

Petrophysical Reservoir Characterizations of the Zubair Formation and Equivalents of the Hauterivian-Aptian Basin

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Abstract

This study presents a comprehensive petrophysical and stratigraphic synthesis of the Zubair Formation and its Hauterivian–Barremian equivalents across five adjacent petroleum provinces: Iraq, Kuwait, Saudi Arabia, the United Arab Emirates, and Iran. Published core plug measurements (effective porosity, absolute permeability, shale fraction) were depth matched to high-resolution wireline logs (gamma-ray, density, neutron, sonic, resistivity) via core-tie workflows. Porosity was obtained from density-neutron overlays; clay volume was obtained from the gamma-ray log. Facies discrimination combined gamma-ray vs. density and neutron to classify intervals into fluvial-deltaic, shoreface, or lagoonal belts, while sequence-stratigraphic panels were constructed by correlating key flooding surfaces and sand–shale boundaries. Results demonstrate that Iraqi and Kuwaiti delta-front sands commonly exhibit the highest porosities (18-23 %) and permeabilities (200-600 mD), whereas deeper foreland equivalents in Iran display broader variability (8-22 % porosity, 5-500 mD permeability) due to enhanced compaction and cementation. Diagenetic influences, such as carbonate cementation in the Biyadh Formation (Saudi Arabia) and the Lekhwair Formation (UAE), as well as illite overgrowths in the Lower Zubair (Kuwait), further control reservoir quality. This integrated petrophysical and stratigraphic framework not only elucidates heterogeneity across national boundaries but also provides targeted insights for optimized field development and enhanced recovery planning within this prolific Lower Cretaceous petroleum system.

Keywords: Zubair Formation; Petrophysical properties; Lower Cretaceous; Reservoir; Stratigraphy

1. Introduction

The Zubair Formation is one of the most important oil reservoirs in Iraq and occupies a distinguished stratigraphic position in the geological section. It consists mainly of thin to medium-bedded sandstone intercalated with siltstone and mudstone (Awadh et al., 2019). The Zubair Formation in Iraq is a significant oil reservoir, particularly in the Zubair, Rumaila, and West Qurna fields, as well as in Kuwait. In Saudi Arabia, it is known as the equivalent formation (Biyadh) within the Ghawar field. In the UAE, it is known as Lekhwair, and in Iran, it is known as Gadvan (Adabi, 2012). The spatial distribution of these formations is presented in Fig.1.

The significant Lower Cretaceous period has not been studied comprehensively across geographical boundaries but rather locally in each country. This constitutes a scientific knowledge gap that requires study. For example, the Zubair Formation in the Arabian Peninsula and adjacent regions records critical changes in Cretaceous sea level and palaeogeography, the Lekhwair Formation, one of the most laterally extensive Barremian units, remains poorly integrated into regional syntheses. Previous

work has characterized the Thamama Group in central Oman, where the Lekhwair interval was first defined in the Lekhwair-7 well (Hughes Clarke, 1988) and subsequently refined through high-resolution sequence stratigraphy (van Buchem et al., 2002). Aksharan and Nairn (1986) correlated Barremian carbonates across Oman, Qatar, and the United Arab Emirates but did not explicitly tie the Lekhwair to its equivalents in Kuwait, southern Iraq, or southwest Iran. Setudehnia (1978) documented similar marl-grainstone cycles in the lower Sarvak Formation of Iran, suggesting synchronous eustatic fluctuations, but regional chronostratigraphic correlation remains uncertain. This gap in knowledge hinders our understanding of both the lateral continuity of Barremian carbonate deposition and the controls on reservoir quality across national boundaries.

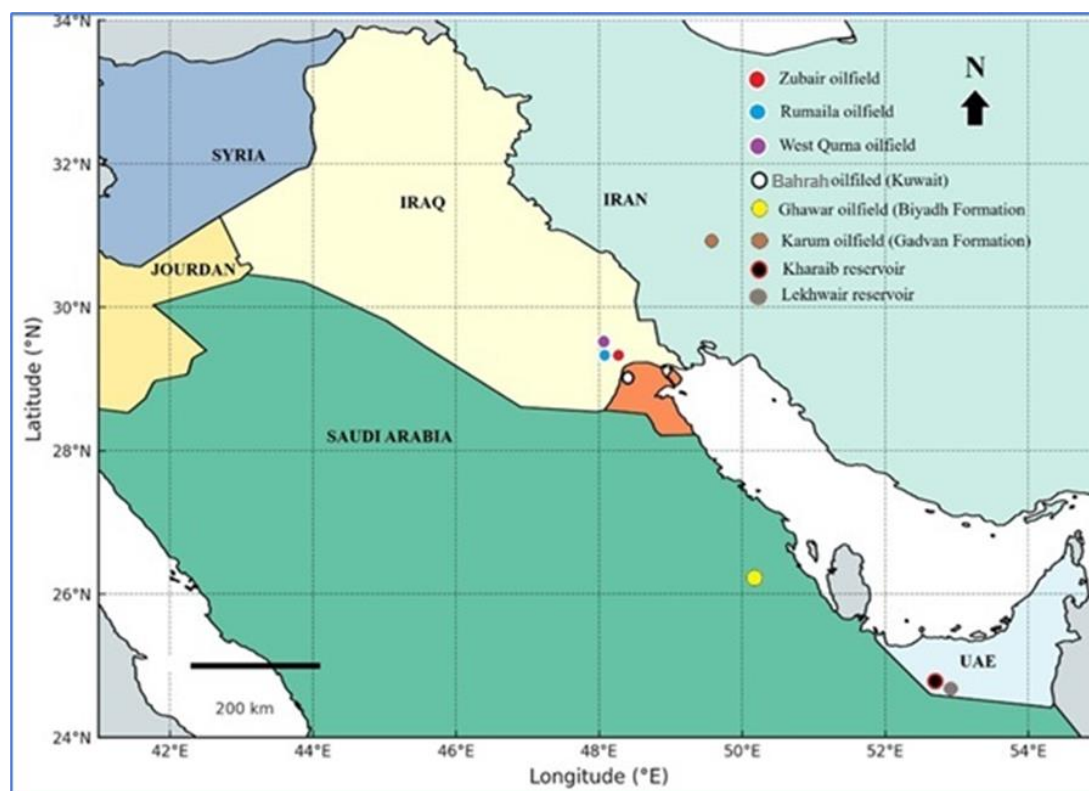


Fig. 1. Location Map of the Zubair Formation in Iraq and equivalents in Kuwait, Saudi Arabia, UAE, and Iran

The Lower Cretaceous reservoirs span a vast area across Iraq, Kuwait, Saudi Arabia, and the United Arab Emirates (UAE), yet most petrophysical studies have been confined within national boundaries. In southern Iraq, the Zubair Formation exhibits effective porosities of 18–20% and permeabilities of 50–200 mD, with net pay thicknesses of 30–50 m under a strong water-drive system and oils averaging ~34° API (Abdulaziz et al., 2017). Across the border in Kuwait's Bahrah Field, Casey et al. (2024) report similar porosities (17–19 %), permeabilities (60–180 mD), and mixed water/gas drive, while the Biyadh Formation of Saudi Arabia and the UAE shows slightly lower porosities (14–18 %) and permeabilities (50–150 mD) with 20–60 m net pay and 30–32° API oils (Aqrabi et al., 2010). Despite these valuable individual datasets, a regional synthesis of petrophysical facies, drive-mechanism variation, and fluid-property trends across Iraq, Kuwait, Saudi Arabia, and the UAE remains lacking. Without such cross-border correlation, exploration models cannot reliably predict reservoir quality heterogeneity or optimize recovery strategies at the basin scale. Moreover, the impact of structural compartmentalization on the continuity of effective porosity and permeability has not been quantified

across the Zubair basin complex. The petrophysical characterizations of the rock are influenced by the lithology, rock mechanical parameters, rock behavior, and depositional environments, which are estimated using well-log data to enhance production (Abdul Aziz et al., 2024). The current study targeted the Albian-Hauterivian interval of the Lower Cretaceous, focusing on the Zubair Formation in Iraq and its equivalents in Kuwait, Saudi Arabia, the United Arab Emirates (UAE), and Iran. This study, therefore, integrates well logs and cores to establish a unified petrophysical correlation framework for the Zubair and its Hauterivian-Barremian equivalents, aiming to understand regional variations in porosity and permeability. The outputs recommend optimized field development for this prolific Lower Cretaceous petroleum system, which will directly inform cross-border exploration and enhanced oil recovery.

2. Geological Setting

2.1. Stratigraphic Correlation and Reservoir Quality

The Zubair Formation in southern Iraq is typified by 120–200 m of fine- to medium-grained sandstones deposited in a deltaic–shoreface system, with proximal fluvial channels grading basinward into shallow-marine shelves (Jassim and Goff, 2006; Al-Ameri et al., 2011). Its lateral equivalents include the Biyadh Formation in Saudi Arabia, which attains 140–180 m in delta-front and coastal-plain facies (Bellen et al., 1959), the Fahad Member (Lower Zubair Sandstone) in Kuwait at 60–110 m of fluvio-deltaic sands (Khalifa and Al-Mutairi, 2010), the Lekhwair and overlying Kharaib formations in the UAE comprising 50–100 m of delta-prodelta and lower-shoreface deposits (Morton & Hudson, 1995), and the Gadvan Formation in southwestern Iran with thinner (30–60 m) shoreface to prodelta sandstones (Adabi et al., 2012). Across all these basins, high net-to-gross, well-sorted sands within deltaic to shallow-marine environments underpin the prolific reservoir quality of the Zubair-equivalent intervals. Shale intervals alternating with reservoir sands in the Barremian–Hauterivian Zubair sequence of southern Iraq function as the main source beds, where the middle part of the formation has good reservoir properties (Al-Ameri et al., 2011; Idan, 2017). In Abu Dhabi, the Nahr Umr and overlying Kharaib units together form 50 m of calcareous mudstones with 1–4 % TOC and HI values above 300 mg HC/g TOC, thereby supplying most of the hydrocarbons to overlying sands (Morton and Hudson, 1995). In the Zagros Basin, the Gadvan shales encompass 30–100 m of prodelta to distal-shelf marls with 0.5–3 % TOC and maturity firmly within the oil window, making them a key charge source for Karun-area reservoirs (Adabi et al., 2012). Across its lateral extent from southern Iraq through Kuwait and eastern Saudi Arabia into southwestern Iran, Zubair (and its equivalents) exhibits consistent depositional characteristics but varying reservoir quality due to facies changes and diagenetic features. Table 1 shows the Hauterivian-Barremian sandstone of the Zubair Formation in southern Iraq, which is laterally equivalent to the Biyadh Formation in Saudi Arabia, the Zubair interval in Kuwait, the Lekhwair Formation in the UAE, and the Gadvan Formation in southwest Iran. For further stratigraphic information, Fig. 2. Illustrates the stratigraphic correlation of Lower Cretaceous Zubair-equivalent units across the Arabian–Iranian domain. In southern Iraq, the Zubair Formation rests directly atop the Ratawi Formation (Hauterivian –Lower Cretaceous). Within Zubair, the Lower Zubair Member (mB) constitutes the main reservoir interval, characterized by thick, clean delta-front sands, whereas the overlying Upper Zubair Member (mA) contains thinner sand bodies with more frequent carbonate cement (Al-Hashim and Abed, 2021). This mB interval correlates seamlessly across the Kuwait border with the Lower Zubair Sandstone (Al-Hashim and Al-Jassar, 2020). The Hauterivian–Barremian Biyadh Formation of eastern Saudi Arabia occupies a modest stratigraphic slot above the Buwaib Formation (Hauterivian) and beneath Aptian–Albian Shu’aiba limestones (Al-Ghamdi and El-Diri, 2022). In the United Arab Emirates, the Lekhwair Formation (Hauterivian) records a shallow marine carbonate ramp within the Thamama Group. These early Barremian carbonates extend into Qatar and correlate

northward with the Kharaib Formation (Barremian), marking a continuous shelf-wide carbonate belt established during Barremian eustatic highstands (van Buchem et al. 2002; Alsharhan and Nairn, 1986). In southwestern Iran's Zagros foreland, the late Barremian–early Aptian Gadvan Formation overlies Jurassic Sargelu shales (or equivalent Lower Cretaceous units) and is succeeded by Aptian Dariyan mudstones. This positioning makes Gadvan the local correlative to Zubair's deltaic sandstones (Gholipour and Ziaie, 2020), completing the stratigraphic linkage of Hauterivian-Barremian reservoir systems from southern Iraq through Kuwait, Saudi Arabia, the UAE and into Iran (Boukhamsin et al., 2022).

Table 1. Stratigraphic equivalents of the Zubair Formation and related oilfield with ages.

Country	Equivalent Formation	Age	Oilfield	Latitude (°N)	Longitude (°E)
Iraq	Zubair	Hauterivian-Barremian (Early Cretaceous)	Zubair	30.45	47.92
			Rumaila	30.03	47.84
			West Qurna	30.29	47.4
Kuwait	Zubair	Barremian (Early Cretaceous)	Bahrah	29.64	48.07
UAE	Lekhwaib	Hauterivian (Early Cretaceous)	–	24.15°N	52.40°E
	Kharaib	Barremian (Early Cretaceous)	–	–24.20°N	52.30°E
Saudi Arabia	Biyadh	Barremian (Early Cretaceous)	Ghawar	25.99	49.49
Iran	Gadvan	Barremian (Early Cretaceous)	Karun	31.35	49.27

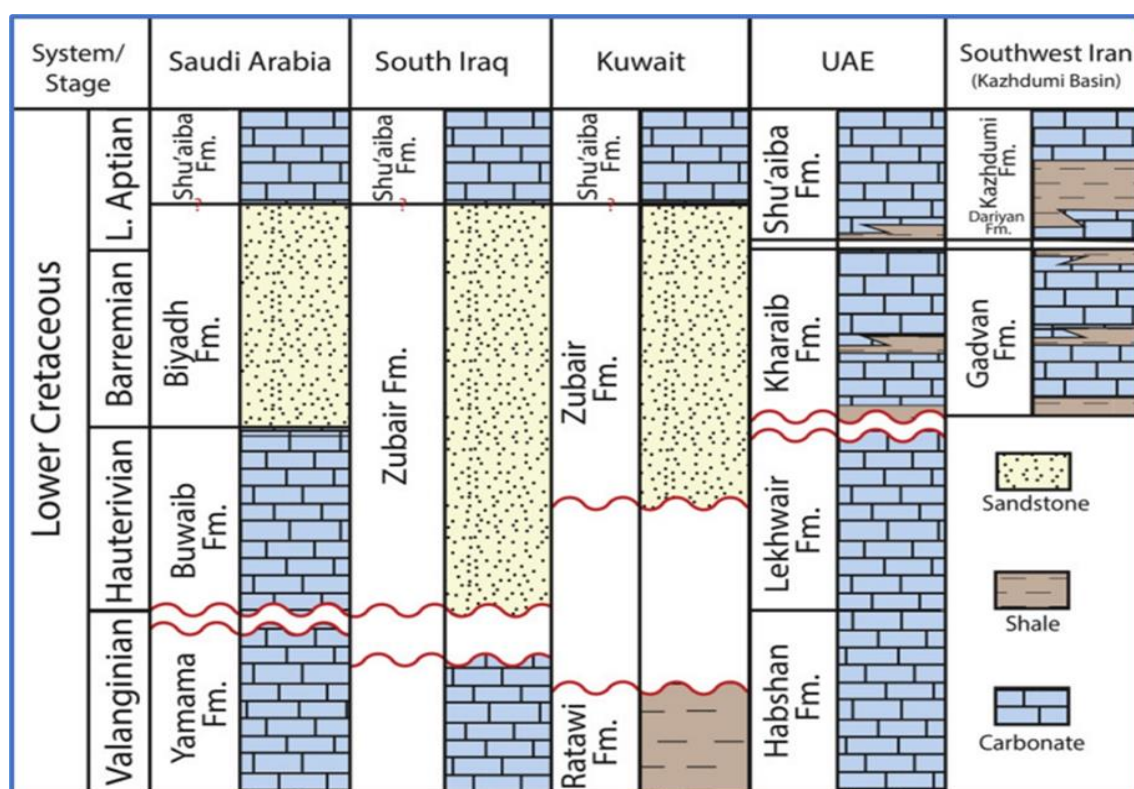


Fig. 2. Stratigraphic correlation of Lower Cretaceous Zubair-equivalent units across the Arabian–Iranian domain, showing Hauterivian–Barremian sandstones (Zubair, Biyadh, Lekhwair, Kharaib, Gadvan) and associated marine shale and carbonate intervals (Boukhamsin et al., 2022)

2.2. Regional Tectono-Sedimentary Framework

During the Early Cretaceous (Hauterivian–Barremian to Early Aptian), the northern Arabian-Iranian Basin evolved from a passive Neo-Tethyan margin into a complex foreland setting. Thermal subsidence of the Arabian Plate created a broad accommodation space that, in southern Iraq and Kuwait, transitioned into the Mesopotamian foredeep under the influence of incipient Zagros convergence to the northeast (Gholipour and Ziaie, 2020). This flexural basin hosted progradational deltaic systems that drained into the Arabian Gulf embayment (Al-Hashim and Abed, 2021). Further south, rapid subsidence along the Rub' al Khali margin of eastern Saudi Arabia supported deposition of the contemporaneous Biyadh clastics (Al-Ghamdi and El-Diri, 2022), while across the Arabian Platform, the rising Zagros orogen flexed the crust to form the Khuzestan embayment, a depocenter for the Gadvan delta systems of southwestern Iran (Gholipour and Ziaie, 2020).

2.3. Lithofacies and Diagenesis

The Zubair Formation and its lateral equivalents have a predominant deltaic type, although local changes in sediment supply, subsidence, and marine energy formed a patchwork of facies. In southern Iraq and Kuwait, coarse- to medium-grained distributary channel and delta-plain sands several meters thick, well-sorted and cross-bedded interfinger with overbank silty shales (Al-Hashim and Al-Jassar, 2020; Al-Hashim and Abed, 2021). Basinward, these give way to planar- trough cross bedded delta front and mouth bar deposits, which in the Biyadh Formation locally record tidal rhythmites and rippled drift lamination under more substantial wave and tidal currents (Al-Ghamdi and El-Diri, 2022). Beyond the main sand bodies, low-energy prodelta and offshore mudstones accumulated, corresponding in Iraq to the finer interbeds of the Upper Zubair and underlying in Iran to the shale intervals that separate Gadvan sand packages (Gholipour and Ziaie, 2020). Along embayed shorelines of eastern Saudi Arabia, coastal mudstones and tidal-flat facies developed, often cemented by early anhydrite nodules.

Superimposed on these original facies are diagenetic modifications that crucially influence reservoir quality. Common carbonate cementation calcite and subordinate dolomite in Upper Zubair and Biyadh sands locally occlude pore space and reduce permeability (Al-Hashim and Abed, 2021; Al-Ghamdi & El-Diri, 2022). Illite and kaolinite overgrowths in Lower Zubair (**Kuwait**) line pore throats and diminish effective porosity (Al-Hashim & Al-Jassar, 2020). In the deeper foreland of the Zagros, Gadvan sands have undergone moderate mechanical compaction and pressure-solution suturing, further lowering primary porosity but sometimes enhancing pore-throat connectivity in cleaner intervals (Gholipour and Ziaie, 2020).

Thickness patterns reflect these processes and the paleogeographic setting. In southern Iraq, Zubair accumulates 200–400 m of deltaic strata, thickening into depocenters such as Rumaila (Alsultan et al. 2024; Al-Dujaili et al. 2024), whereas Kuwait's Lower Zubair reaches up to 250 m in Bahrah before tapering where channels pinch out under wave-dominated shoreface influences (Al-Hashim & Al-Jassar, 2020). The Biyadh Formation spans 100-200 m in Ghawar and thins toward the Rub' al Khali interior (Al-Ghamdi & El-Diri 2022). The Gadvan Formation in Karun exceeds 300 m adjacent to the Zagros front, thinning to below 150 m toward the Arabian Platform (Gholipour & Ziaie, 2020). Together, these facies, diagenetic histories, and thickness trends map a southwest-trending delta complex system that extends from southern Iraq into Kuwait, eastern Saudi Arabia, the UAE, and southwestern Iran.

3. Data and Methodology

The study begins by integrating data from the Zubair Formation and its stratigraphic equivalents across five key hydrocarbon provinces, Iraq, Kuwait, Saudi Arabia, the United Arab Emirates, and Iran to capture both lateral and vertical variability in depositional settings (Fig. 1). The published core-plug

measurements (effective porosity, absolute permeability, and shale fraction) were compiled from published references; such as Alsultan et al. (2024), Al-Dujaili et al. (2024), and Al-Hashim and Abed (2021) for Iraq; Al-Hashim and Al-Jassar (2020, 2023) for Kuwait; Al-Ghamdi and El-Diri (2022) and Boukhamsin et al. (2022) for Saudi Arabia and the UAE; and Hosseini et al. (2018) and Gholipour and Ziaie (2020) for Iran and depth-corrected these values to align precisely with the wireline log datum. The high-resolution gamma-ray, density, neutron, sonic, and resistivity logs for all selected wells were digitized. Porosity depended on neutron density overlays, while clay volume was based on the normalized gamma-ray index, with clean-sand baselines delineating shaly intervals. Archie's equation provided water saturation, computed from the given references. The gamma-ray versus resistivity helps in separating sand-rich from clay-rich intervals, and overlaid density neutron plots distinguish sandstones, siltstones, and carbonates. Each interval was then assigned to one of three shallow-marine depositional belts, fluvial-deltaic, shoreface, or lagoonal, following established genetic facies models. Oilfields were petrophysically evaluated based on the porosity and permeability values.

4. Results and Discussion

4.1. Comparative Reservoir Characteristics

4.1.1. Zubair Formation, Southern Iraq

The petrophysical properties of the Zubair Formation and Equivalents are presented in Table 2. The Hauterivian–Barremian Zubair Formation in southern Iraq comprises two main units: the clean, thick delta-front sands of the Lower Zubair Member (mB), which serve as the region's primary reservoir, and the thinner, carbonate-cemented sandstones of the Upper Zubair Member (mA) (Al-Hashim and Abed, 2021).

Table 2. Petrophysical properties of the Zubair Formation and Equivalents.

Formation Country	Effective Porosity (ϕ_e) %	Permeability (K) mD	Shale Volume (Vsh) %	Net Pay (m)	$^{\circ}\text{API}$	Primary Drive Mechanism	References
Zubair Iraq	3.7– 23	1 – 194	2 - 23.5	200 – 400	27 – 34	Bottom-water drive; solution-gas drive	Alsultan et al. (2024); Al-Dujaili et al. (2024)
Zubair Kuwait	16.7	200 – 600 420 (av.)	16	150 – 300	24 – 32	Waterflooding; gas injection	Al-Hashim & Al-Jassar (2023)
Lekhwaib UAE	14–18	120–450	8–18	150–300	29–36	Bottom-water drive; water injection	Al-Hosani & Al-Mazrouei (2021)
Kharaib UAE	10–15	50–300	5–15	100–250	32–38	Bottom-water drive; water injection	Al-Kaabi & Al-Abri (2020)
Biyadh Saudi Arabia	12 – 20	50 – 400	10 - 20	100 – 200	30 – 38	Bottom-water drive; water injection	Al-Ghamdi & El-Diri (2022)
Gadvan Iran	8 – 22	5 – 500	5 - 25	300 – 400	25 – 35	Water injection; gas injection	Gholipour & Ziaie (2020); Hosseini et al. (2018)

Core plug and log analyses across Zubair, Rumaila, and West Qurna fields reveal shale volumes of 2-23.5 %, effective porosities from 2.7 up to 23 %, and permeabilities spanning 1.0 mD to 194 mD (Alsultan et al. 2024; Al-Dujaili et al. 2024). In the best delta-front facies, porosity peaks at 12-20% with permeabilities in the hundreds of millidarcies, supporting production rates of tens of thousands of barrels per day under a strong bottom-water drive and occasional solution-gas expansion. The produced oils are medium to heavy (27-34 API $^{\circ}$), sourced from deeper Jurassic–Cretaceous shales of early mature source rocks (Awadh and Al-Mimar, 2023). The fluids of hydrocarbons and brine migrated upwards

from the Sargelu Formation to the Zubair reservoir through cracks and fractures in the Gotnia Formation, as indicated by the Cl/Br geochemical indicator (Awadh et al., 2019). Cumulatively, Lower Zubair sands account for roughly 50 %-60 % of southern Iraq's oil output.

4.1.2. Lower Zubair Sandstone (Bahrah Field), Kuwait

Across the Iraq–Kuwait border, the Lower Zubair Sandstone mirrors Iraq's mB interval, deposited as a prograding delta plain during the Hauterivian–Barremian. In Bahrah Field, core and log data indicate average shale volumes near 16 %, effective porosities of ~16.7 %, and permeabilities around 420 mD within the cleanest distributary-channel and mouth-bar sands (Al-Hashim & Al-Jassar 2023). These channel bodies can exceed 200 m net thickness, forming a laterally continuous, high-quality reservoir. Moderate to heavy calcite cement locally reduces permeability below 50 mD. Lower Zubair oils in Kuwait are relatively heavy (24–32 API°) under a gravity-assisted water-drive system.

4.1.3. Lekhwair Reservoir (UAE)

The Upper Lekhwair succession in Southeastern Abu Dhabi, laid down on an expansive, shallow carbonate ramp during the Hauterivian, exhibits reservoir-quality intervals within bioclastic grainstones and rudist shoals. Well-logs and core analyses report shale contents ranging from 8 to 18%, average effective porosities of nearly 16%, and matrix permeabilities of 120 to 450 mD in the cleanest facies (Whitcomb et al., 2024). These shoal complexes stack to more than 250 m of net pay in places. Pore-filling calcite locally diminishes permeability to below 100 mD. The crude oils produced are moderate to light, with API gravities of 29–36°, driven primarily by natural bottom-water influx and supplemented by targeted water injection (Whitcomb et al., 2024). The Kharaib Reservoir in Abu Dhabi sits stratigraphically above the Lekhwair. The Barremian Kharaib Formation comprises coarsening-upward carbonate cycles deposited on the same ramp platform. Data from cores and logs indicate shale volumes of 5-15%, effective porosities of 10-15 %, and permeabilities of 50-300 mD in well-sorted grainstone and packstone intervals (Al-Kaabi and Al-Abri 2020). Net-pay thicknesses typically range from 100 to 250 m within laterally extensive shoal bodies. Dolomite cement locally occludes pore throats, reducing permeability below 50 mD. Oils here are relatively heavy (32-38°API) and are produced under a natural bottom-water drive, later enhanced by water-injection systems (Al-Kaabi and Al-Abri 2020).

4.1.4. Biyadh Formation (Ghawar Field), Eastern Saudi Arabia

The Biyadh Formation (Barremian) in eastern Saudi Arabia overlies the Buwaib Formation (Hauterivian) and is overlain by Shu'aiba Formation (Al-Ghamdi and El-Diri 2022). In the Ghawar basin, delta-front sands reach net pay thicknesses of 50-150 m, with porosities ranging from 12 to 20% and permeabilities from 50 mD to 400 mD in the best facies. Local carbonate cementation can reduce porosity to as low as 8% and permeability to below 20 mD. Production across Ghawar and Shaybah fields, driven by bottom-water support and water injection, contributes several hundred thousand barrels per day of light oil (30-38 API°) (Al-Ghamdi and El-Diri 2022).

4.1.5. Gadvan Formation (Karun Field), Southwestern Iran

In the Zagros foreland, the Gadvan Formation (Barremian) underlies Dariyan mudstones (Gholipour and Ziaie 2020). Gadvan delta-front sands in Karun Field often exceed 300 m thick, recording shale

volumes of 5-25 %, effective porosities of 8-22 %, and permeabilities from 5 mD in clay-rich facies to over 500 mD in clean high-energy sands (Hosseini et al., 2018). Net Pay ranges from 300-400 m, but only discrete facies are produced under bottom-water and targeted water-alternating-gas injection. Majnoon Field, straddling the Iraq–Iran border, taps both Gadvan and Iraqi Lower Zubair intervals, with Iranian facies averaging ~15 % porosity and ~250 mD permeability. Gadvan oils are medium-sour (25-35 API°) and require desalting and H₂S removal.

4.2. Comparative Petrophysical Well-Log Analysis

4.2.1. Zubair Formation in Iraq

A well-logging panel from the Zubair reservoir in the Zubair oil field, Basra, evolving SP, GR, shallow/deep resistivity (LLS/LLD), density (RHOB), neutron porosity (NPHI), sonic transit time (DT), and interpreted facies (H3–N) with major sand and shale oil intervals was interpreted (Fig. 3). At approximately 3370 ft, the spontaneous-potential swings strongly to a negative value, indicating clean, water-bearing sands. Moving down to the 3380-3390 ft interval, gamma rays (20-40 gAPI) indicate the presence of sands rich in hydrocarbons, supported by the sharp divergence of the shallow and deep resistivity tracks to about 2000 Ω m. At 3410 feet, a gamma-ray spike rises, marking the K-shale marker. Here, the resistivity drops toward brine levels, and the density- neutron curves overlap, indicating a water-saturated, clay-rich layer. From 3420 feet to approximately 3430 feet, the shallow laterolog again pulls away from the deep curve, albeit at a lower magnitude, while the neutron and density separate to yield 12% porosity, pointing to compact but still hydrocarbon-charged sandstone. Continuing downward into the 3430–3450 ft interval, the density minimum at 1.95 g/cm³ and the concurrent neutron maximum produce a positive crossover of some 20 %, and the sonic transit time falls to 55 μ s/ft, indicating a porous, gas-bearing layer. The 3450–3470 ft slice exhibits mixed lithology, including silty sandstone, where neutron and density separation become narrower and resistivity separation weakens, suggesting partial water saturation. Finally, at the base, near 3480 ft, both resistivity curves align with the clay baseline again; the gamma-ray rises, and the sonic slows (up to 100 μ s/ft), marking a return to tight sands and shale. Eventually, based on the information above, there are two main reservoir zones above the shale barrier, followed by a sequence of tighter pay intervals, each with a distinct log fingerprint (Fig. 3) (Al-Jafar and Al-Jaberi, 2019).

4.2.2. Zubair Formation in Kuwait

The well-log data from the Zubair reservoir in Kuwait reveal a sequence of predominantly clean (Fig. 4) (Aladwani et al., 2023) quartz-rich sandstones interspersed with minor clay streaks, which together define the hydrocarbon-bearing intervals of the highest reservoir quality. The gamma-ray curve remains low throughout most of the interval, indicating minimal shale content and a largely siliciclastic framework. At the same depths where the gamma-ray signature drops, the deep resistivity rises sharply, often exceeding ten ohm-meters, signalling zones of elevated hydrocarbon saturation. Simultaneously, the sonic transit times decrease and the neutron-density porosity overlay converges to porosity values of 18-25%, confirming that these sands are not only clean and well-sorted but also possess excellent storage capacity. A predominance of quartz with only minor kaolinite and illite, suggesting limited pore-throat blockage and good permeability continuity (Awadh et al., 2014). Together, these log responses delineate discrete, laterally continuous sand bodies with both high porosity and high resistivity, which are the main sweet spots for oil production in this section of the Zubair Formation.

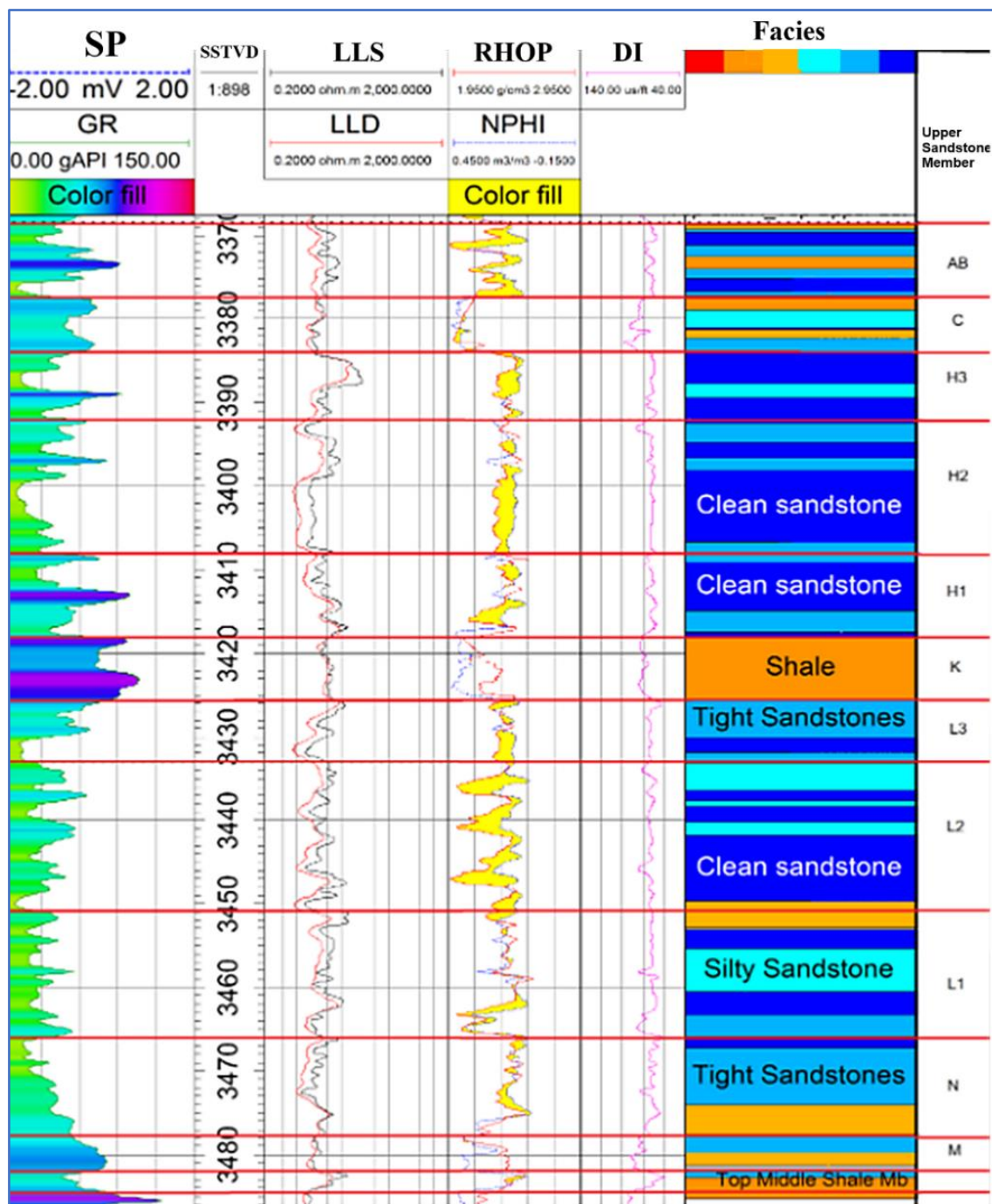


Fig.3. High resolution well log panel from the Upper Sandstone Member of the Zubair Formation, Basrah (after Al-Jafar and Al-Jaberi, 2019)

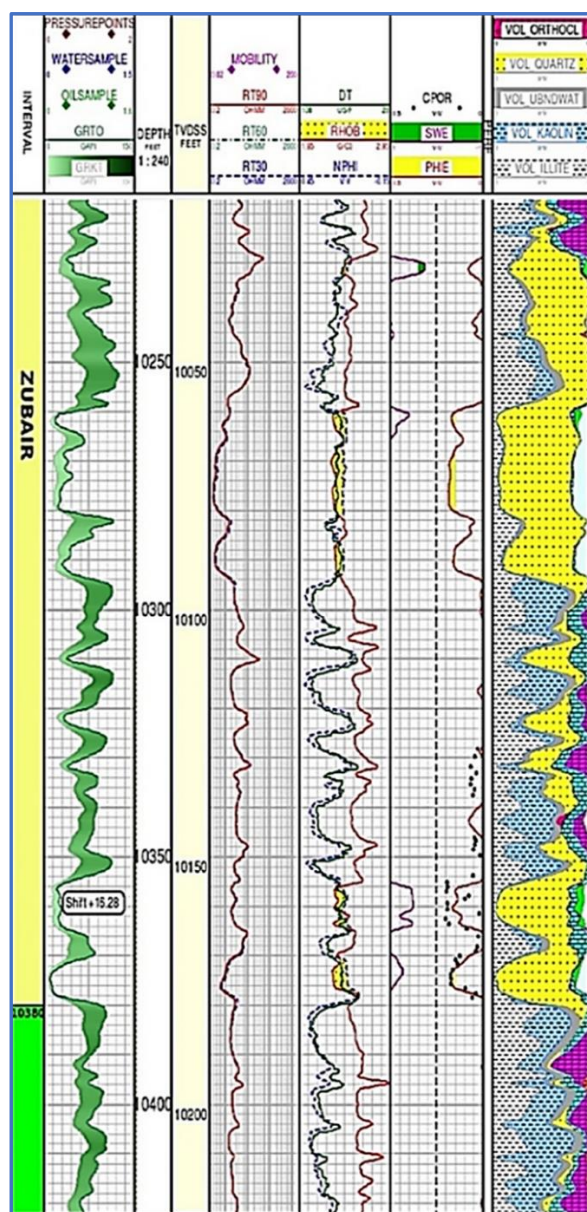


Fig. 4. Composite well log of the Lower Zubair reservoir in Kuwait (after Aladwani et al., 2023)

4.2.3. Kharaib Formation in The UAE

The composite section through the Kharaib Formation in the UAE shows that at the base, the KH-1B and KH-1C intervals have moderate gamma-ray values, permeability in the 50-200 mD range, and porosities less than 15 %, indicating fair reservoir quality (Gatel et al., 2024) (Fig.5) . Moving upward into the KH-2A through KH-2C.2 packages, gamma-ray minima coincide with the KH-2 Dense and KH-2B grainstone intervals, where porosity peaks at 20% and permeability locally exceeds 500 mD. These zones are tied to laterally continuous, rudist, orbitoline dominated packstones whose tight interparticle contacts have been enhanced by field wide dolomite cement and stylolite dissolution, preserving excellent pore throat connectivity. In contrast, the KH-2D and KH-2E units return slightly elevated gamma ray readings and reduced permeability in the mixed-fauna facies, reflecting minor argillaceous influx and more pervasive microporosity. The overlying KH-2G grainy intervals again exhibit low radioactivity, 18-22% porosity, and high permeability (300-600 mD), indicating laterally persistent shoal buildups. Finally, the Hawar cap at the top of the succession exhibits higher gamma-ray

values, low porosity (<10%), and low permeability (<50 mD), consistent with a shaly, stylolitic wackestone that seals the section (Gatel et al., 2024). Throughout this vertical profile, the coupling of low gamma-ray, elevated porosity and permeability, and rudist-rich lithologies identifies the prime pay zones, those laterally extensive grain and packstone facies that constitute the Kharaib's highest-quality reservoir intervals. However, the composite well log of the Kharaib Formation (UAE) illustrates, from left to right, gamma-ray response showing fluctuating clay content across transgressive–regressive cycles; neutron-density derived porosity curves indicating 10-20 % porosity peaks in grainy facies; permeability profile (1-1 000 mD) highlighting high quality intervals in KH-2 Dense and KH-2B packstones Gatel et al., 2024).

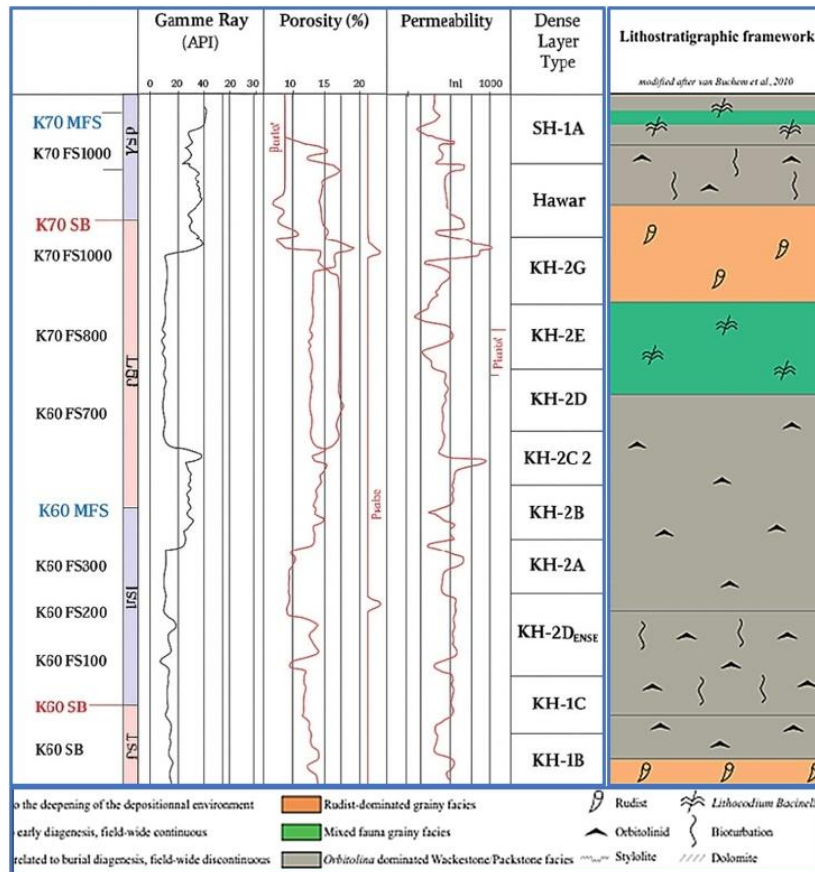


Fig. 5. Composite well-log of the Kharaib Formation (UAE) (after Gatel et al., 2024)

4.2.4. Ghawar oil field in Saudi Arabia

Fig. 6 shows (left to right) the gamma-ray track highlighting low clay intervals, the sonic transit-time curve indicating stiff, cemented sands, the neutron-density overlay with positive porosity crossover (18–24 %), and the reservoir zone column delineating five major pay packages (1, 2A, 2B, 3A, 3B, 4). The well-log from the Ghawar oil field in Saudi Arabia displays a succession of clean carbonate and siliciclastic intervals, whose petrophysical signatures collectively pinpoint the best reservoir zones (Fig 6). Across the gamma ray track, repeated troughs dipping below 20 API units mark sands and limestones with minimal clay content, and these same depths coincide with pronounced spikes in the sonic track where transit times fall to 50 μ s/ft or lower, signalling stiff, tightly cemented rock frames that transmit acoustic energy rapidly. In the adjacent neutron–density overlay, the neutron porosity curve falls below the density porosity curve in these low-gamma troughs, producing a positive porosity crossover of 18-

24% clear evidence of hydrocarbon fill rather than water. Between 6,850 ft and 7,150 ft, the log delineates four main reservoir zones (labelled 2A, 2B, 3A, and 3B) where this convergence of low gamma-ray, low sonic transit time, and positive neutron–density separation repeats in laterally extensive packages. A fifth deeper zone around 7,200 ft exhibits weaker crossover and slightly higher gamma-ray levels (30–40 API), indicating diminished reservoir quality due to increased argillaceous content. Overall, the logs show that Ghawar’s prime intervals are those thick, laterally continuous beds where minimal shale, fast sound velocities, and robust porosity crossover coincide. These represent the highest-quality pay zones in the field (ECG, 2015).

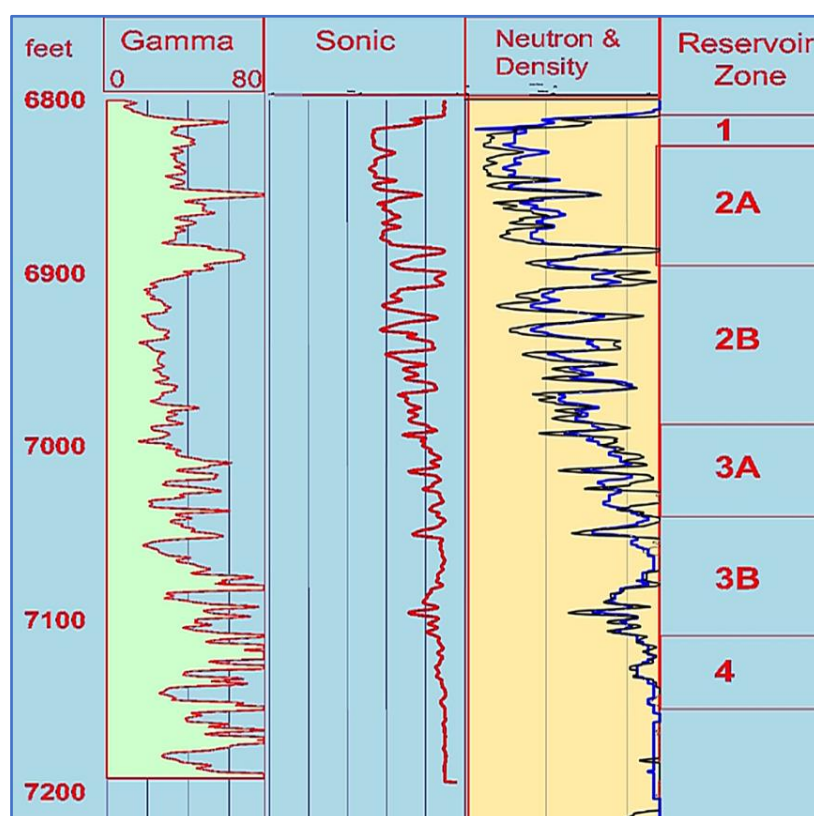


Fig. 6. Composite well log from the Ghawar Field (Saudi Arabia) (ECG, 2015)

4.2.5. Gadvan Formation in Iran

The well log for the Gadvan Formation in well C, Zagros Basin, Iran, describes from (left to right) spontaneous potential and gamma-ray tracks lithology column differentiating sandstone, limestone, and marl units; deep resistivity and sonic transit time logs (Dt); density–neutron porosity overlays with total organic carbon (TOC); and the baseline marker (Fig. 7). The composite well log from the Gadvan Formation in Iran illustrates a rhythmic alternation of carbonate and siliciclastic intervals, whose petrophysical signatures collectively define the optimal zones for hydrocarbon production (Fig. 7). Along the gamma-ray track, distinct troughs dropping below 40 API units correspond to cleaner, sand prone horizons, whereas peaks above 80 API mark marl or chalk beds with minimal reservoir potential. At the same depths where gamma-ray minima occur, the porosity sensitive neutron curve diverges from the density curve, producing positive crossover values of 15–25%, indicating gas or oil filled pore space rather than water. The sonic transit time decreases from over 100 μ s/ft in shaly layers to 70–80 μ s/ft in these cleaner intervals, reflecting stiffer, more consolidated rock frames that support good permeability.

The lithology column confirms that well-sorted sandstones dominate these sweet spot intervals, interbedded with oolitic and bioclastic limestones. The positive density–neutron separation coincident with low gamma ray and fast sonic transit times delineates the main productive intervals within the delta-front to prodelta succession. The intervals of low-gamma, high-porosity windows indicate that these packages effectively trap hydrocarbons, showing that the Gadvan reservoir quality is controlled by laterally continuous, low-shale sand bodies with both high porosity and reduced acoustic transit time sandwiched between tight, clay rich seals.

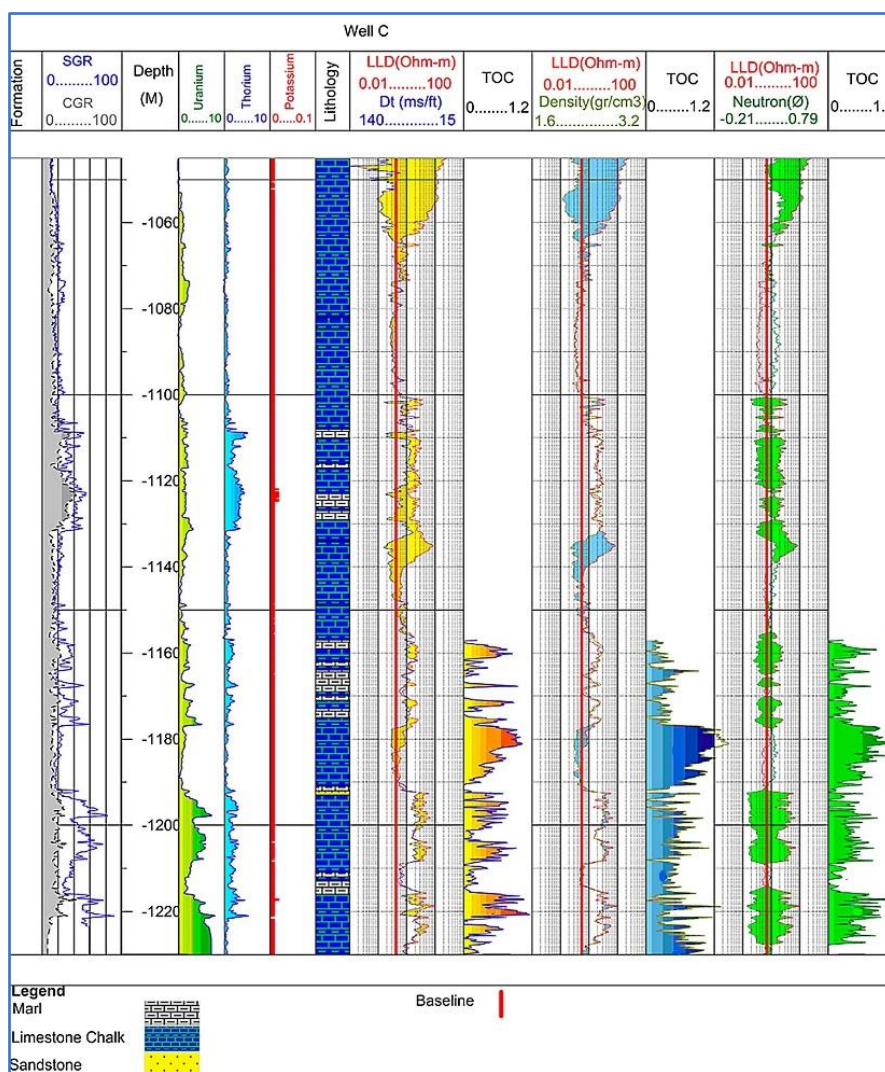


Fig. 7. Composite well-log for the Gadvan Formation (Well C, Zagros Basin, Iran) (after Khoshnoodkia et al., 2011)

5. Conclusions

The Zubair Formation (Early Cretaceous, Barremian) represents one of the most significant deltaic sandstone reservoirs in the northern Arabian–Persian Basin. Although it never acted as a primary source rock, Zubair sands serve as the main reservoir and production interval for hydrocarbons generated in deeper units. By unifying core data, wireline logs, and sequence-stratigraphic correlations, this study establishes a coherent petrophysical portrait of the Zubair Formation and its lateral equivalents across southern Iraq, Kuwait, eastern Saudi Arabia, the United Arab Emirates (UAE), and southwestern Iran. Delta-front and mouth bar sands of Iraq and Kuwait consistently deliver the best reservoir performance,

marked by net to gross ratios exceeding 50 %, porosities up to 23 %, and permeabilities in the hundreds of mD. In contrast, more distal foreland facies in Iran and carbonate-rich belts in Saudi Arabia and the UAE demonstrate wider property ranges due to diagenetic overprint and mechanical compaction. The results confirm that these inter basin variations are significant, underscoring the need for region-specific development strategies. The methodology used in this study, which combines petrophysical properties and their quantitative comparison, offers a reproducible template for cross-border reservoir evaluation. Ultimately, enhanced recovery strategies tailored to each reservoir facies and diagenetic history will maximize recovery from this key Lower Cretaceous play.

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