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Petrography and Depositional Evolution of Zubair Succession in Rumaila and West-Qurna Oilfields, Southern Iraq

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Abstract

This study encompasses the petrography, lithofacies analysis, and depositional development of the Zubair Formation in four boreholes (Ru-X1, R-X2, WQ-X1, WQ-X2) located within the Rumaila and West-Qurna oil fields. The Zubair Formation depositional basin was located in the Mesopotamian Foredeep during the Barremian age.

Zubair succession mainly consists of sandstone, specifically quartz arenite (or orthoquartzite), with about 93% or more quartz grains. Rocks containing over 20% lithic-fragments and minor feldspars are classified as lithic-arenites, and those containing over 30% clay content along with minor lithic fragments are classified as greywackes. Five main lithofacies have been identified within two dominant rock groups across two major successions. The first group, sand-dominated rocks, includes well-sorted, sub-rounded quartz arenite lithofacies; poorly sorted, sub-angular quartz arenite lithofacies; and poorly sorted graywacke lithofacies. The second group, clay-dominated rocks, consists of sandy claystone and shale lithofacies.

Three facies associations are identified in the studied succession: delta plain, shore-face, and back-shore. These associations were deposited over three cycles, dividing the Zubair succession into three units. The lower unit of the Zubair Formation is mainly composed of shale, with thin sandstone beds and lenses separating it into two parts. In the northern part of the study area, the upper part consists of sandstones, while the lower rock unit is dominated by shaly beds. The middle unit of the Zubair Formation is the thickest and features alternating shale-dominated and sand-dominated beds, forming three depositional cycles, most prominent in the southern part of the study area (Rumaila oilfield), whereas the northern part (West-Qurna) has two cycles. The upper unit of the Zubair Formation is mainly composed of well-sorted, sub-rounded quartz arenite lithofacies, indicating deposition in a shoreface environment and marking a sea-level rise in the Rumaila oilfield. In the West-Qurna oilfield, this unit is represented by delta plain and backshore facies associations. This cycle marks the conclusion of Zubair deposition during the transgressive stage, transitioning into the Shuaiba Formation.

Keywords: Petrography, Depositional evolution, Zubair Formation, Rumaila Oilfield, West-Qurna Oilfield.

الصخارية والتطور الترسيبي لتكوين الزبير في حقلي نفط الرميلة وغرب القرنة، جنوب العراق

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الخلاصة

تتضمن هذه الدراسة الصخارية وتحليل السحنات الصخرية وتطور الترسيب لتكوين الزبير في أربع آبار (Ru−X1, R−X2, WQ−X1, WQ−X2) تقع ضمن حقول النفط في الرميلة وغرب القرنة. ترسب تكوين الزبير في نطاق ما بين النهرين خلال المرحلة الباريمية من العصر الطباشيري المبكر.

يتكون تتابع الزبير بشكل أساسي من الحجر الرملي، المصنف على أنه أرينيت كوارتز (أو أورثوكوارتزيت)، يحتوي على حوالي 93% أو يزيد من معدن الكوارتز. يصنف الحجر الرملي الذي يحتوي على أكثر من 20% من الشظايا الحجرية والفلسبار الثانوي على أنها أرينيت حجري، بينما يسمى الحجر الرملي الذي يحتوي على أكثر من 30% من محتوى الطين والصخور الحجرية الثانوية بالصخور الجرايواكي. تم تحديد خمس سحنات صخرية رئيسية ضمن مجموعتين صخريتين مهيمنتين ضمن تتابعين رئيسيين، التتابع الأول تهيمن عليها الرمال والتي تتكون من صخور أرينيت كوارتزية جيدة الفرز شبه مستديرة، وصخور أرينيت كوارتزية سيئة الفرز شبه زاوية، وصخور جرايواكي سيئة الفرز. أما التتابع الثاني فهو صخور تهيمن عليها الطين والتي تتكون من صخور طينية رملية وصخور صخرية من الصخر السجيلي.

يتميز التتابع المدروس بثلاث مترافقات سحنية: سهل الدلتا، وواجهة الشاطئ، والشاطئ الخلفي. وقد ترسبت هذه المترافقات خلال ثلاث دورات ترسيبية، مما أدى إلى تقسيم تتابع الزبير إلى ثلاث وحدات. تتكون الوحدة السفلية من تكوين الزبير في المقام الأول من الحجر السجيلي مع تطبقات مترققة وعدسات من الصخور الرملية تقسمها إلى قسمين. في الجزء الشمالي من منطقة الدراسة، يتكون الجزء العلوي من الحجر الرملي، بينما تهيمن على الجزء السفلي طبقات الصخر السجيلي. الوحدة الوسطى لتكوين الزبير هي الأكثر سمكًا، وتتميز بتناوب طبقات الصخر السجيلي والرمل، وتشكل ثلاث دورات غير متجانسة جانبيًا. وتبرز هذه الدورات بشكل أكثر وضوحًا في الجزء الجنوبي من منطقة الدراسة (حقل الرميلة النفطي)، بينما توجد دورتان في الجزء الشمالي (غرب القرنة). تتكون الوحدة العلوية لتكوين الزبير بشكل أساسي من سحنات صخرية من الكوارتز شبه المستديرة والمرتبة جيدًا، مما يشير إلى الترسيب في بيئة ساحلية ويشير إلى ارتفاع مستوى سطح البحر في حقل الرميلة النفطي. في حقل غرب القرنة النفطي، يتم تمثيل هذه الوحدة من خلال مترافقات سحنات سهل الدلتا والساحل الخلفي. تشير هذه الدورة إلى نهاية ترسب الزبير خلال مرحلة تقدم البحر والانتقال إلى تكوين الشعيبة.

1. Introduction

The Zubair Formation, renowned as a pivotal reservoir unit and source rock for oil during the Early Cretaceous Era, is a focal point of geological inquiry and hydrocarbon exploration. Originating from sedimentary deposits in Iraq and adjoining regions in the northeastern part of the Arabian Plate, the Zubair succession has garnered considerable attention since the inception of oil exploration in southern Iraq, notably marked by the drilling of the inaugural oil well in 1948 by an international oil company.

This study aims to comprehensively investigate the petrographic and changing depositional environment related to the diagenetic development of the Zubair Formation. This study includes petrography, the study of rock textures, mineralogical composition, and sedimentary structures, and provides valuable insights into the formation's depositional environment.

The study area is located in southern Iraq within Mesopotamian Foredeep (Fig. 1). The West-Qurna oil field covers an area of 340 km². The West-Qurna and Rumaila oil fields are significant, playing pivotal roles in Iraq’s oil production and contributing substantially to global energy markets.

West-Qurna oilfield is located in the south of Iraq, West-Qurna ranks among the largest oil fields globally. It lies within the Basra Governorate, approximately 65 km northwest of Basra. West-Qurna is renowned for its vast crude oil reserves, which are estimated to be several billion barrels. Its strategic location and immense resource potential make it a focal point for international oil companies and investors seeking to capitalize on its production (Fig.1).
Rumaila Oil Field, another major oilfield in Iraq, is situated near the city of Basra in the southern part of the country. It is one of the largest oilfields globally regarding reserves and production capacity. Rumaila's significance in the global oil market stems from its massive reserves, estimated to exceed 17 billion barrels of oil. The field covers an extensive area of approximately 1,800 K^2, making it a crucial asset for Iraq's oil industry. Rumaila's strategic location and prolific production make it a cornerstone of Iraq's oil economy and a key focus for international oil companies involved in the region (Fig.1).
Both West-Qurna and Rumaila play vital roles in Iraq's oil production, contributing significantly to the country's economy and global energy supply. Their strategic locations in southern Iraq, near Basra, facilitate their efficient operation and exportation of crude oil to international markets.

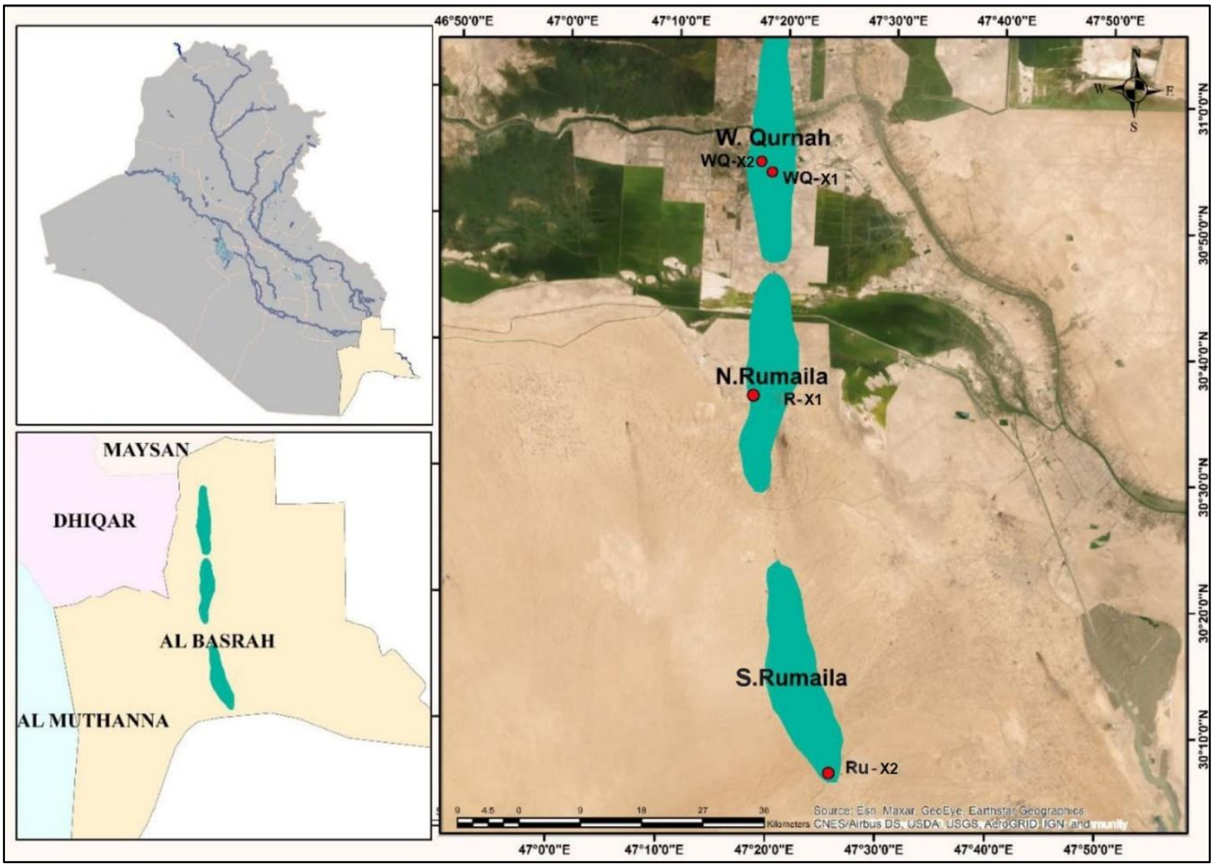

Figure 1: Location map of the studied area showing West-Qurnah, N. Rumaila and S. Rumaila oil fields.

The Zubair Formation represents a Barremian succession which belongs to the Thamama Group within Tithonian - Early Turonian Mega-sequence. This succession was deposited in a vast intrashelf sedimentary basin during a tectonic phase of seafloor spreading in southern Neo-Tethys; this formation experienced differential subsidence and thickness variations along transverse faults. As a result, the basin's axis shifted from the Salman and western

Mesopotamian zones to the eastern Mesopotamian Zone, specifically into the Tigris Subzone [1].
Al-Zaidy [2] studied the lithofacies and association facies related to the stratigraphic development of the Zubair succession in the Majnoon and Suba oilfields. The research concluded that the Zubair Formation in the Suba oil field experienced three phases of sea level rise (transgressive system tracts). These phases ultimately led to shale deposition within well-sorted quartz arenite, marking the peak of sea level rise (maximum flooding surface). In contrast, the Zubair Formation in the Majnoon oil field is characterized by three distinct depositional cycles dominated by delta plain and delta front environments, primarily composed of shale units. Additionally, the study examined the distribution of rock types and the stratigraphic framework of the Zubair Formation in the Kifl oil field. [3].
The clastic shelf sediments of the Zubair and Ratawi succession were subsequently overlain by the carbonate ramp sediments of the Shuaiba Formation. This was followed by a period of progradation (shoreline advance) of the Zubair and Ratawi succession (Fig.2) [4]. Jassim and Buday [1] suggested that the deepest part of the Zubair basin was east of the Salman Zone, with the thickest sediments found north of the study area.

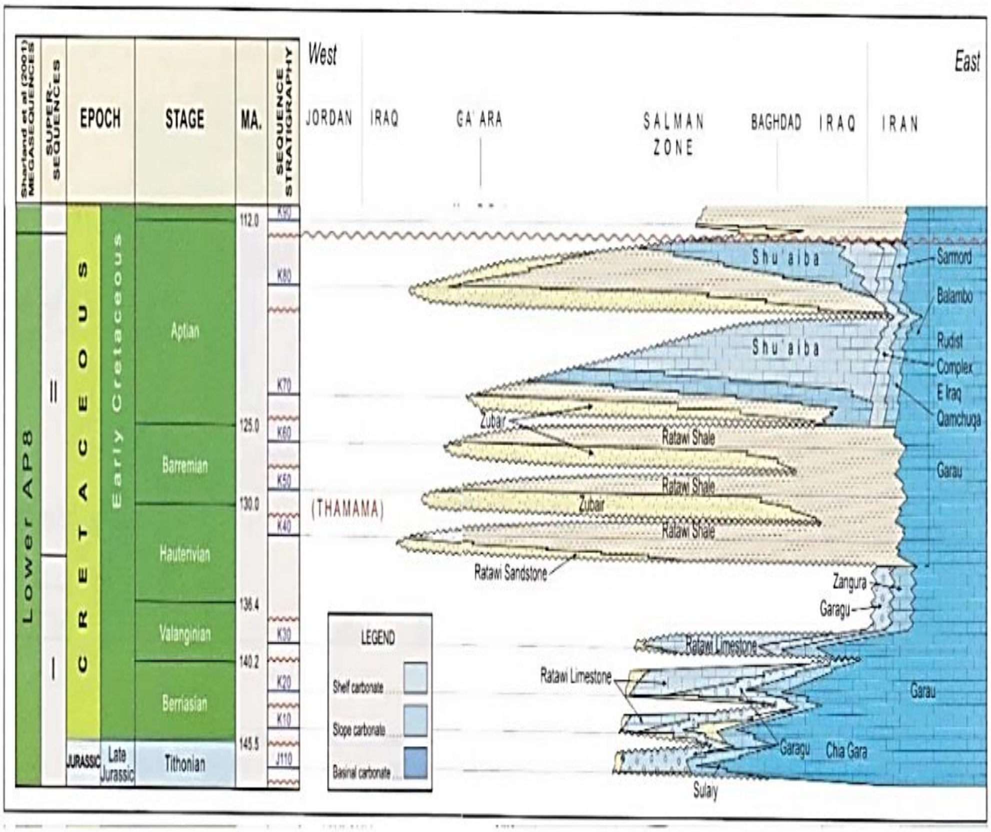

Figure 2: Stratigraphic section showing the lateral and vertical distribution of the Zubair Formation [4].

The upper contact of the Zubair succession with the Shuaiba succession (Albian age) is predominantly a gradational (conformable surface). In contrast, the lower boundary with the Ratawi succession is an unconformity surface [5][6]. This study aims to provide a petrographic description and analyze the lithofacies characteristics of the Zubair rock units in the West-Qurna and Rumaila oilfields to reconstruct the paleo-environments.

2. Methodology

This research focuses on studying the Zubair Formation at specific localities under investigation. The following procedures were undertaken to achieve the objectives of this study:

2.1 Fieldwork

This study integrates the examination of cores and cuttings with the analysis of geophysical logs in the Zubair sequence. Four stratigraphic sections were measured and sampled in North Rumaila and West-Qurna areas. About 500 rock samples were collected from four wells (R-X1, RU-X2, WQ-X1, and WQ-X2) to represent the sections. Observations were made on sedimentary textures, facies changes, and thickness of the Zubair Formation (Table 1).

2.2 Lab work

This work includes two parts:

1. Slides preparation of about 75 thin sections were examined using transmitting-polarizing and reflecting-light microscopes. More than 500 microphotographs were taken showing the textures and the mineral composition of the rock varieties.

The mineralogy and texture types of the samples were identified by the point-counting of the thin sections using the swift model F point counter and JMicroVision, and four hundred counts were made per slide. Also, all the thin sections of the different lithologies are point-counted for grain-size measurements.

2. Analyze the complete set of well logs (provided by SOC), correlating the logs responses with lithology/facies variations and distribution.

Table 1: Studied boreholes with coordinate and thickness of Zubair succession.

Well Name	Easting (m)	Northing (m)	Top (m)	Bottom (m)	Thickness (m)
WQ-X1	720900.03	3420680.42	3074.5	3425.9	351.4
WQ-X2	710518.10	3421000.70	3109.6	3329.7	220.1
R-X1	719480.00	3389175.00	3114.8	3321.8	207.0
RU-X2	743416.00	3330956.00	3209.4	3447.0	327.6

3. Petrography

Several factors influence the composition of sandstone, such as the mineral makeup of the source rocks, the distance sediments travel before reaching their final depositional basin, the duration detritus spends in environments other than the final deposition site, the climate in the source area, and the diagenetic processes affecting the sediments post-deposition [7].

Texture is utilized to describe sedimentary rocks (sandstones) to interpret depositional mechanisms and environments. It also serves to assess porosity and permeability percentages, proving valuable in analyzing potential hydrocarbon-rich sand bodies.

3.1Quartz

Quartz is the dominant mineral among the primary component grains, as determined using JMicroVision, focusing only on quartz, feldspars, and lithic fragments. The quartz content of the Zubair Formation varies significantly, ranging from over 93% in well-sorted, rounded quartz arenite sandstone to less than 20% in shale-dominated units. According to Wentworth (1932) [8], the quartz grain size ranges from medium to very fine, and Powers' visual chart

indicates a roundness ranging from subangular to rounded. The dominance of quartz grains can be attributed to factors such as reworking, long distance transport, or prevalent tropical weathering [9].
The variation in grain size and roundness results in the formation of different types of quartz grain contacts, including long edges, concave to convex, and Y-shaped contacts. Occasionally, floating and point contacts are also present, becoming more prevalent in sandstones with high calcite crystal content. This increase in carbonate cement causes grains to be forcefully wedged apart [10]. Two types of quartz particles or grains are identified in the studied succession:
1. ***Monocrystalline quartz*** with straight to slightly undulose extinction, exhibits deformation bands of plutonic sources [11], or metamorphic sources and/or formed during folding and faulting in sediments. The undulosity of quartz grains may be associated with deep burial conditions, where the influence of lithostatic pressure in producing undulose quartz is not significant [12] (Plt.1A).
2. ***Polycrystalline quartz*** grains (average 0.7%) show straight to slightly undulose extinction and straight to sutured boundaries between individual crystals (Plt. 1B). Grains with straight intercrystalline boundaries and slightly undulose extinction may indicate schistose origin [11]. The polycrystalline grains are fine and medium grain-size and generally composed of more than three individual crystals with uniformly sized grain shapes.

3.2 Feldspar

The feldspars constitute 0 to 1% (average 0.5%) of the framework composition, which is more abundant in the North Rumaila section. The scarcity of feldspars is expressed by the high maturity index of sandstone, according to Pettijohn et al. [8].
Untwined orthoclase is the predominant feldspar (Plt. 1E) with trace amounts of plagioclase (Plt. 1F) and grid-twinned microcline (Plt.1G). The stability conditions of feldspars in these samples are highly variable; some grains are fresh, whereas others have been severely degraded. Feldspar alteration includes leaching, kaolinization and calcination. The survival of feldspars appears to be a function of both the intensity of the decay process and the time or duration of the action.
Leaching of detrital feldspar grains occurred progressively ranging from small dissolution pits to completely dissolved grains. Due to its lower hardness than quartz, feldspar is partially dissolved along fractures and cleavage planes, leaving intragranular porosity. Complete dissolution of feldspars is evidenced by oversized pores with rims of clays marking the original grain boundary (Plt.1H).
Kaolinite replaced grains (kaolinitization) in sandstones with abundant leached feldspars (Plt. 2C).

3.3 Rock fragments

The rock fragments are rare, with an average of 0.2% of the framework grains. Sedimentary rock fragments are more abundant than metamorphic and plutonic ones.
Sedimentary rock fragments (SRFs) are mainly chert, megacrystals of quartz in clay matrix and detrital carbonate grains.
Chert grains are the most common rock fragments (Plt. 2D), composed mostly of well-rounded microcrystalline quartz. Chert tends to survive abrasive action; hence, a short transport is implied for those sandstones containing abundant chert grains.

The percentage of rock fragments in these sandstones indicates the high maturity index, which can be expressed as the ratio of chert (durable)/non-chert (less durable), as well as the ratio of quartz/(feldspar + rock fragments). These ratios show the progress towards the ultimate end-type pure quartz sand in these samples.

Although not common, metamorphic and igneous rock fragments (Plt. 2E) were observed in some samples. Metamorphic rock fragments (MRFs) are represented by kaolinite-replaced mica. The very small veinlet shape of megacrystals of quartz is possibly derived from a plutonic source [12].

3.4 Micas

Detrital micas (0-0.2%) are locally observed in finer sandstones and include both muscovite (Plt. 2F) and biotite (Plt. 3A). Muscovite is the most mica species present in these sandstones due to its greater resistance to chemical weathering, whereas biotite is not common.

3.5 Heavy minerals

Heavy minerals in the present sandstones comprise 0-1% with a mean value of 0.5% and are more abundant in the West-Qurna section. The non-opaque heavy minerals include amphiboles, pyroxene, zircon, tourmaline, rutile, epidote, and kyanite, in descending order of abundance (Plt.1C, Plt.2G, H).

3.6 Glauconite

Glauconite is locally observed in three thin sections with a percentage of 0.1%. Glauconite ranges from pale green to greenish yellow (Plt. 3C). When oxidized, the grains turn brownish or brown. These rounded grains are generally uniform in size and typically lack structure. Under Crossed Nicols, glauconite appears as microcrystalline aggregates.

3.7 Matrix:

The whole framework of the studied sandstone samples is embedded in an argillaceous matrix (up to 1%) with occasionally fine-grained quartz silt and carbonaceous matter that occupy some of the pore spaces. Biotite and muscovite tend to form within the clay matrix [13].

The interstitial clay matrix in some samples is engulfed (Plt. 3B). In other samples, the argillaceous matrix contains isolated calcite spare.
Kaolinite is the principal clay mineral comprising the matrix. Some ductile argillaceous grains are deformed between adjacent quartz grains in a manner that resembles matrix-filled pores, making it difficult to distinguish between the matrix and altered rock fragments (Plt. 2A).

The samples possessing considerable amounts of calcite cement are matrix-free or with rare amounts of matrix. The calcite cementation inhibits matrix formation, but in a non-calcareous bed, the rock fragments can be altered to a diagenetic matrix [13], then referred to as pseudo-matrix.

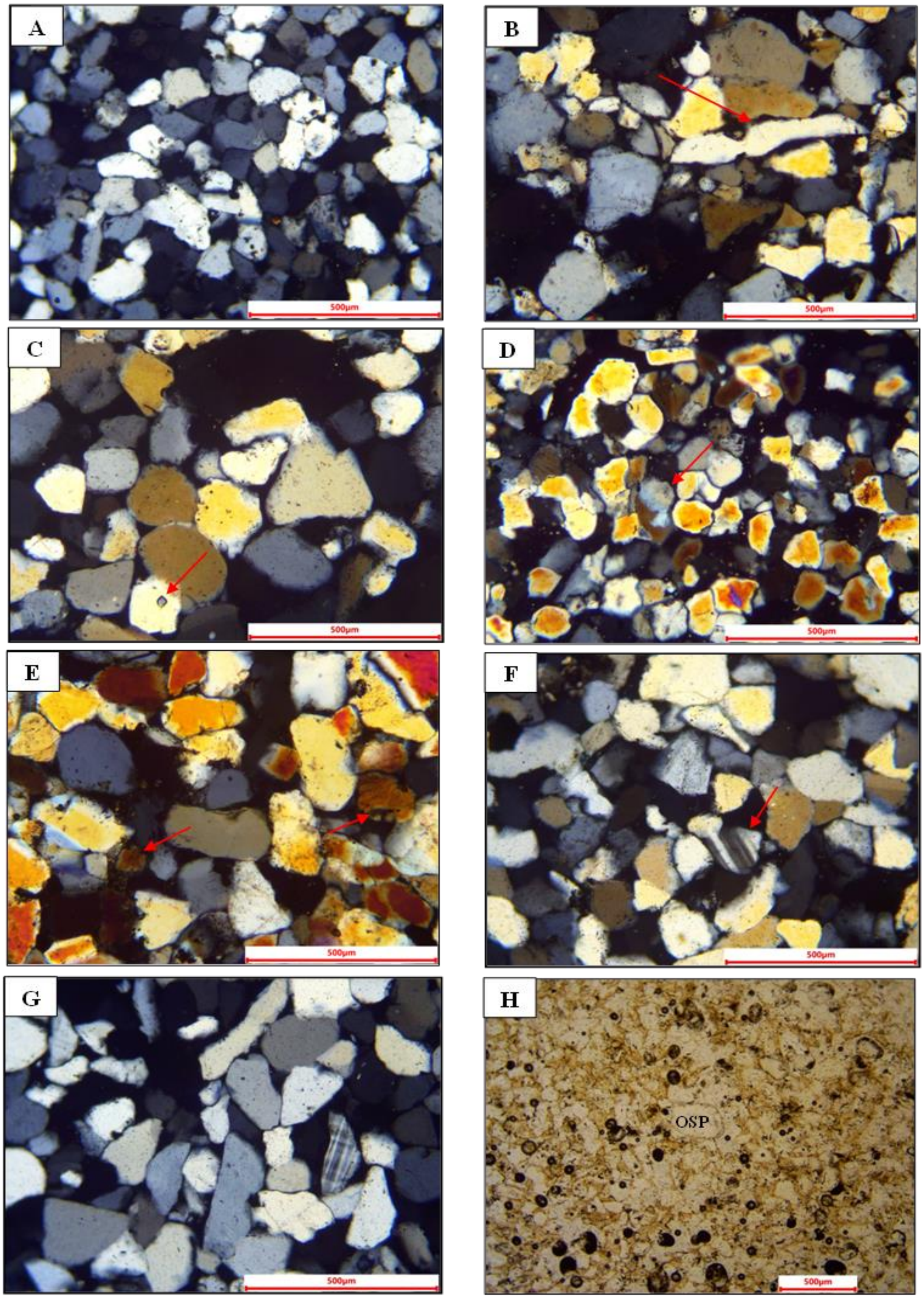

Plate 1

A. Fine-to-medium, subrounded to subangular quartz grains. RU-145 (3256-3257).
B. Elongated quartz grain. WQ-3 (3222-3223).
C. Heavy mineral inclusion inside quartz. RU-25 (3154-3155).
D. Polycrystalline elongated quartz grain. RU-145 (3328-3329).
E. Partial dissolution of K-feldspar grains. RU-145 (3327-3328).
F. Plagioclase. RU-25 (3136-3137).
G. Microcline**.** RU-25 (3136-3137)
H. Oversized pore (OSP). WQ-3 (3223-3224).

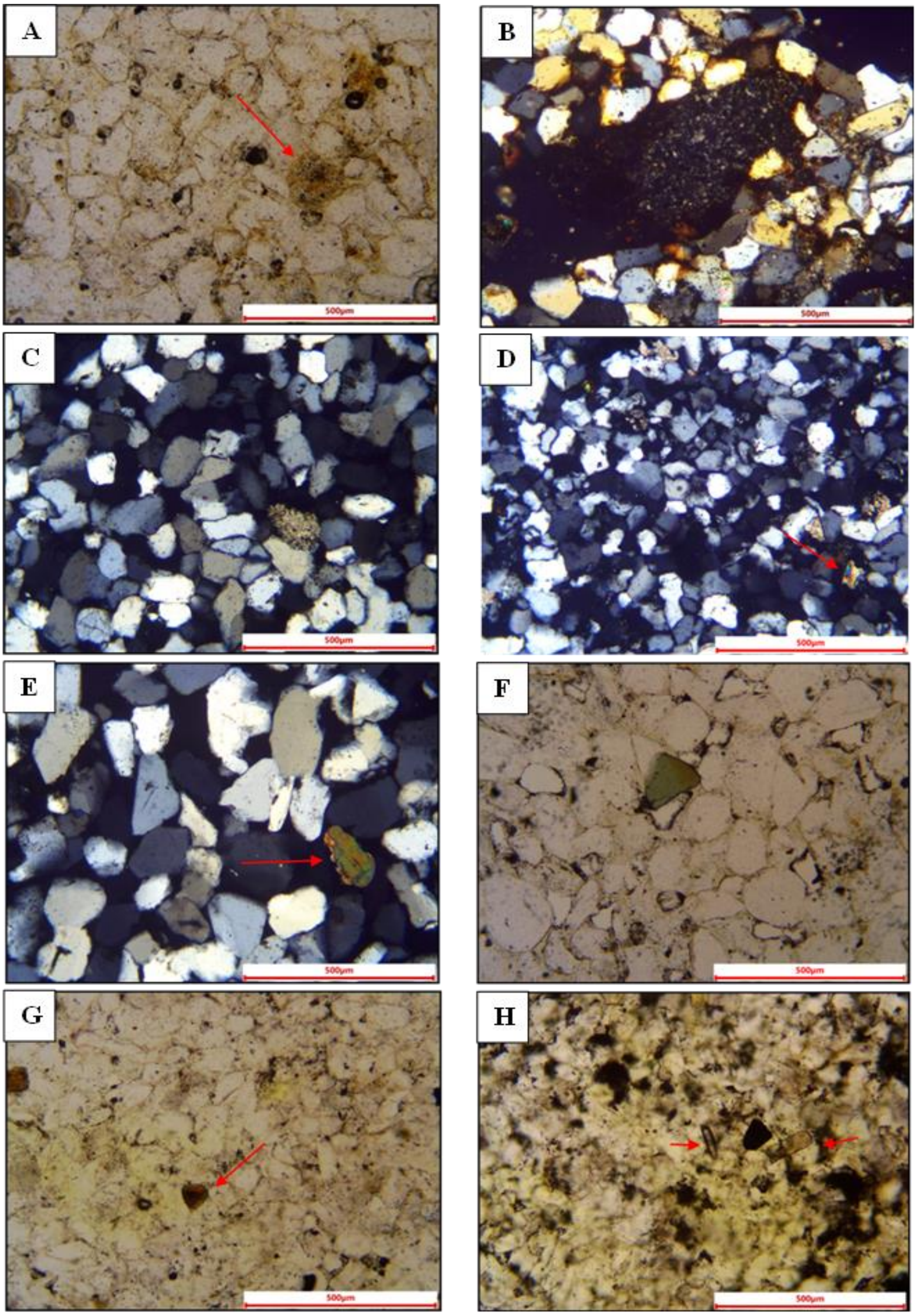

PLATE 2
A. Kaolinite-replaced grain, most probably feldspar. RU-145 (3251-3252)
B. Well rounded chert. RU-145 (3234-3235).
C. Well rounded igneous rock fragment. RU-145 (3256-3257).
D. Muscovite. RU-25 (3109-3110).
E. Biotite, note cleavage. RU-25 (3100).
F. Hornblend crystal (Hbl). RU-25 (3100)
G. Rutile. RU-25 (3100-3101)
H. Euhedral long prismatic zircon (left) and epidote (right). RU-25 (3100-3101).

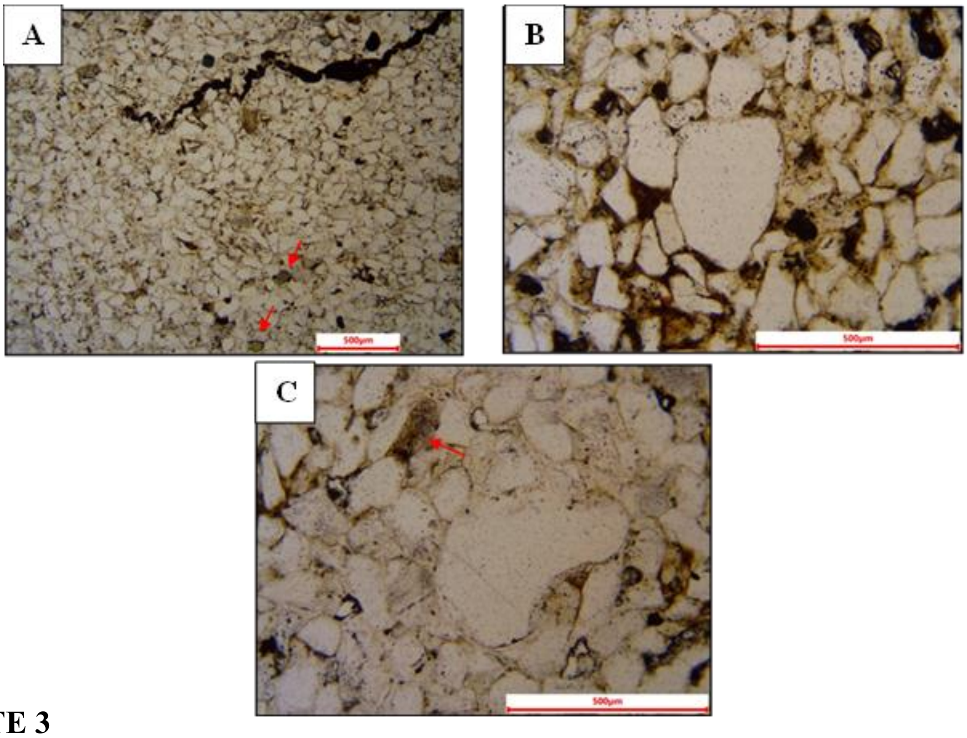

PLATE 3
A. Glauconitic pellets. RU-145 (3234-3235
B. Clay matrix. WQ-1 (3193-3194).
C. Altered rock fragments. WQ1 (3193-3194).

4. Sandstone classification

The sandstones of the Zubair Formation are primarily quartz arenites. They contain minor amounts of feldspars and rock fragments. Most feldspar grains, rock fragments, and possibly some other unstable detrital particles have completely dissolved. The point counting data of the studied sandstone samples are used to construct the QFR plot (Fig. 3). Figure (3) shows that the sandstones at North Rumaila and West-Qurna are predominantly quartz-arenites with average compositions of $Q_{95.3}$ $F_{0.7}$ R_4 and $Q_{96.4}$ $F_{0.6}$ R_3 respectively.

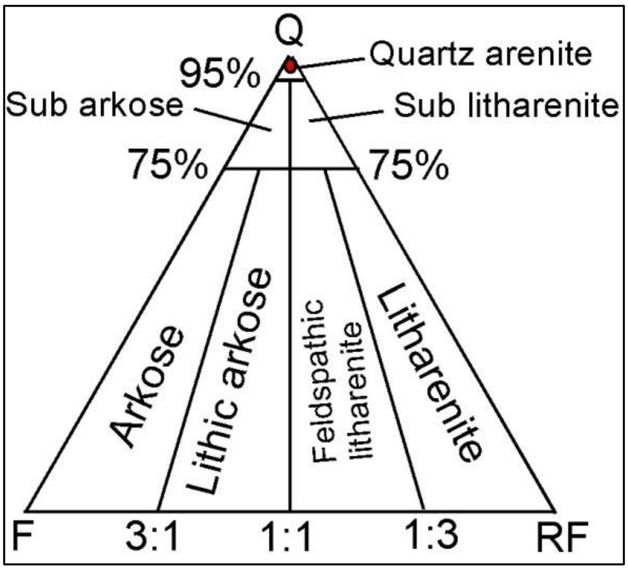

Figure 3: Ternary plot showing the composition of Zubair sandstones. Classification of Folk (1974)[11].

5. Lithofacies Identification

The depositional settings and fabric characteristics of the clastic rocks are influenced by a combination of tectonic activity, sea-level fluctuations, sediments supplying rates, the physical processes and biological activities influencing sediment transporting and deposition, and climatic conditions. At the depositional basins, these factors interact to shape the geometry distribution and arrangement of the various environments or stratigraphic rock units over time, a concept known as the basin's stratigraphy architecture [13].

One of the initial steps in analyzing clastic succession facies involves describing and interpreting available conventional core samples [14, 15]. A key outcome of core descriptions is the identification and classification of core samples into lithofacies. Lithofacies are defined as subdivisions of a study succession based on lithologic type, grain-size distribution, physical and biologic sedimentary structures, and stratifications, all of which are directly related to the processes of deposition and environments that formed them. Lithofacies and facies associations serve as the fundamental units for interpreting the paleoenvironments.
Therefore, Zubair succession is characterized by two major successions, including five lithofacies in the studied boreholes, which are described according to the availability of these parameters (Figs.4, 5, 6, 7).

4.1 The sandstone dominated lithofacies

On the basis of the detailed petrographical and mineralogical study, the sandstones could be subdivided into three lithofacies.
1. ***Lithofacies Zf.1*** Well-sorted quartz-arenite sandstone lithofacies: This lithofacies is characterized by fine-grained, well-sorted sandstone with sub-angular to sub-rounded grain shapes. Composed of over 90% quartz, it is classified as a quartz arenite sandstone. In the middle rock unit, these lithofacies is identified by very-low values of GR and high resistivity response, displaying a box-shaped GR log pattern, as well as spontaneous potential logs (Plate 4A).
2. ***Lithofacies Zf.2*** Poorly-sorted quartz-arenite sandstones lithofacies: These lithofacies exhibit a wide range of sandstone grain-size, from fine to coarse, with well-rounded to sub-rounded grains. Composed of over 90% quartz, they are classified as quartz-arenite. This is diagnosed in the upper rock unit of the Zubair succession, which characterized by bad sorted and exhibits very low gamma ray values that decrease upward, forming a bell-shaped gamma ray log pattern, along with low acoustic log values (Plate 4B).
3. ***Lithofacies Zf.3*** Poorly-sorted graywackes sandstones lithofacies: These lithofacies consist of mud and sand-dominated rock units primarily composed of quartz. It is characterized by poorly sorted graywacke sandstone (Plate 4C) with moderate gamma ray values, displaying a funnel-shaped gamma ray log pattern. This lithofacies is found in the upper unit of the Zubair Formation.

4.2 The shale dominated lithofacies

The dark laminated shales of the Zubair Formation are distributed at different intervals within the studied sections. It is the most common facies, followed in abundance by the sandstone. This lithofacies is characterized by fissile and poor marine faunal content consisting of small molluscan shell fragments. It is sandy or silty, slightly bioturbated, or well-laminated structures consisting of an alteration of dark lamina (up to 1 mm thick) enriched in organic compounds and lighter lamina (millimeters to centimeters thick).
1. ***Lithofacies Zf.4*** Sandy shale lithofacies: The fourth lithofacies occurs within the sandstone rock units as lenses of shale, which characterizing by high V-shale values with funnel-shaped gamma ray log pattern. The primary contents of these facies are mud dominated rock units with

angular quartz grains (Plate 4D).

2. *Lithofacies Zf.5* Shale lithofacies: This facies is present throughout the Zubair rock units. It is primarily consists of shale rocks (Plate 4E) and exhibits high gamma ray values with a bell-shaped gamma ray log pattern.

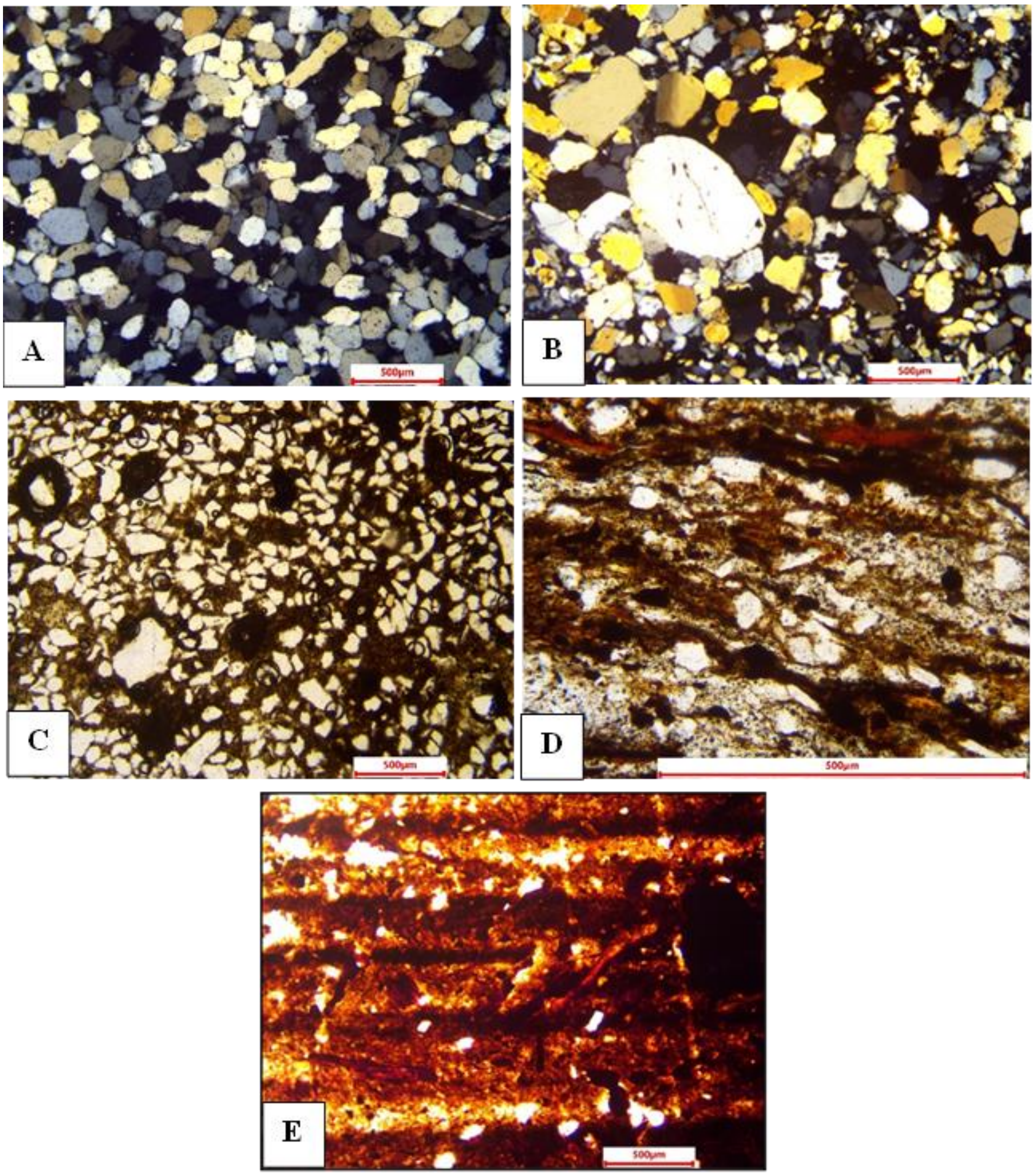

PLATE 4
A. Well-sorted quartz-arenite sandstones Lithofacies. WQ-1 (3194-3195)-0026.
B. Poorly-sorted quartz arenite sandstones Lithofacies. Ru-25 (3168)m.
C. Poorly-sorted graywacke sandstones lithofacies. WQ-1 (3254-3255)-0216.
D. Sandy shale lithofacies, R-25 (3174-3175)h.
E. Shale lithofacies, WQ-3 (3224-3225).

5. Depositional environments

Three main associations of deltaic facies are recognized in the studied succession:

1. Delta plain: Upper delta plain - floodplain deposits
2. Shore-face: Wave-dominated shoreface sands
3. Back-shore: Lower delta plain - lacustrine delta fill

The Zubair Formation is deposited in delta plain, shore-face, and back-shore environments, according to studies [14], [15], [16], and [17]. Furthermore, well logging tools such as GR, SP, and DT logs are used to identify minor lithofacies changes and the overall trend of sediment grain size [18, 19].

5.1 Lower unit

The lower unit mainly consists of shale and thin beds of sandstone, which are divided it into two parts. In the north of the study area (WQ-X1), the uppermost section is sandstones, while the lower part of Zubair suction is dominated by shale beds. In the southern part, the unit is predominantly shale. The upper part of the unit is primarily composed of sandy shale lithofacies (Zf.4), with fewer thin beds of poorly sorted graywackes (Zf.3). The lower part is characterized by shale lithofacies (Lf.5). This succession is interpreted as having been deposited in a delta-plain environment, a common setting in both the northern and southern parts of the study area (WQ-X2 and Ru-X2). Conversely, the central part of this area (WQ-X2 and R-X1) was closer to a shoreface environment (Figs. 4, 5, 6, 7).

5.2 Middle unit

The thickest unit in the middle section is characterized by alternating shale and sand beds, forming three laterally variable cycles. These three cycles are prominent in the southern part of the study area (Rumaila oilfield), while the northern part (West-Qurna) exhibits two cycles. In the central part of the study area, the middle unit comprises a single cycle of well-sorted, sub-rounded quartz arenite lithofacies (Lf.1), associated with delta front and shoreface environments. This distinctive facies association sets the two-cycle northern section apart from the three-cycle southern section.

In the southern region (R-X1 and Ru-X2), bad sorted quartz arenite (Lf.2) alternates with bad sorted graywacke lithofacies (Lf.3), a sequence not observed in the northern region. As a result, the delta-plain association is more prevalent in WQ-X1 and WQ-X2, represented by successive lithofacies 3, 4, and 5. This association alternates with backshore associations in the northern region (R-X1 and R-X2) (Figs. 4, 5, 6, 7).

5.3 Upper unit

The well sorting, sub-rounding quartz-arenite lithofacies (Lf.1) is the dominant feature of this rock unit, indicating deposition in a shoreface environment and signifying a sea level rise in the Rumaila oilfield. In the West-Qurna oilfield, this unit exhibits delta plain and backshore facies associations (Lf.4 and Lf.5). This deposition cycle marks the final depositional stage of Zubair succession during the transgressive phase, leading into the Shuaiba Formation (Figures 4, 5, 6, 7).

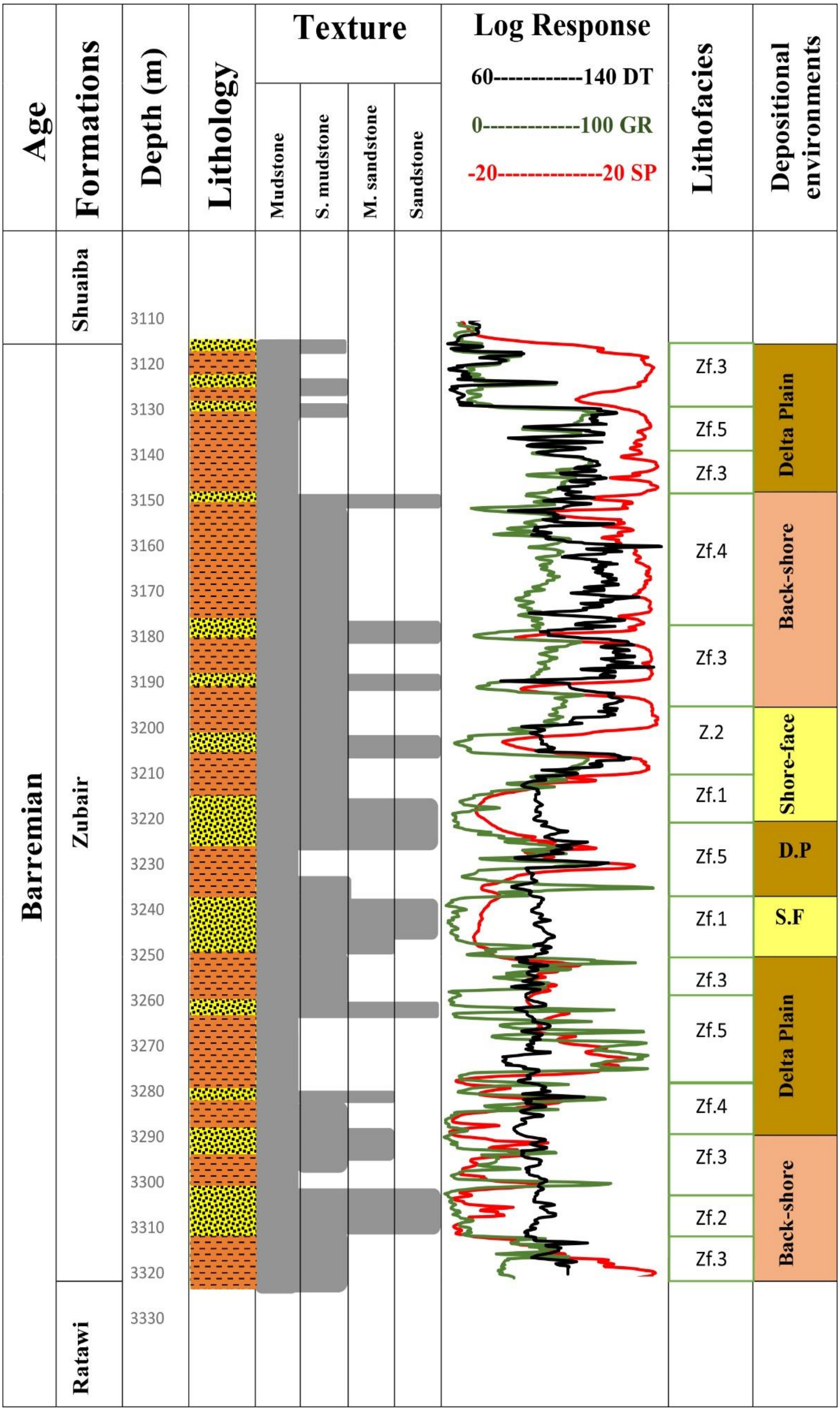

Figure 4: Columnar section showing lithofacies distribution and facies associations of R-X1 in North Rumaila oilfield.

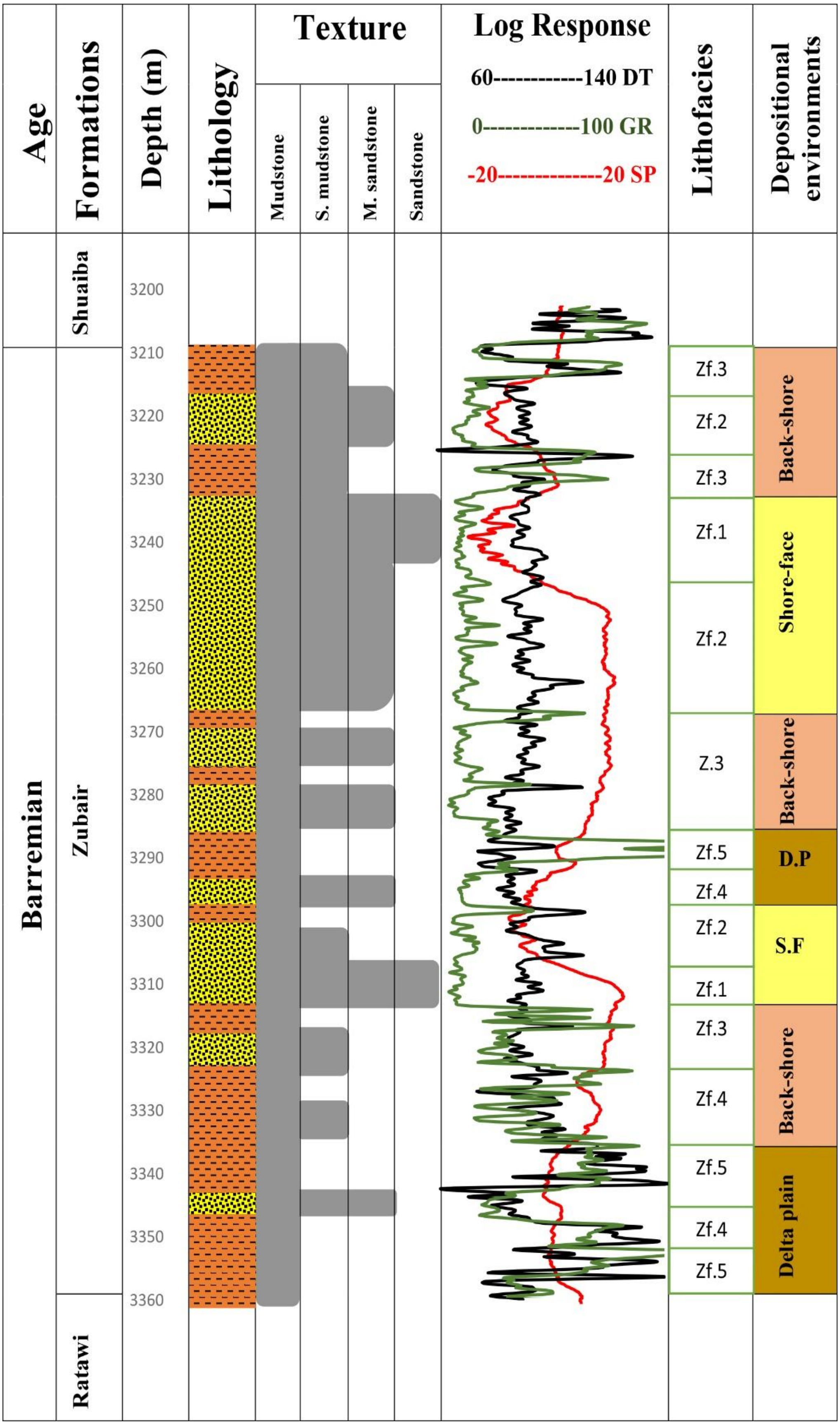

Figure 5: Columnar section showing lithofacies distribution and facies associations of Ru-X2 in South Rumaila oilfield.

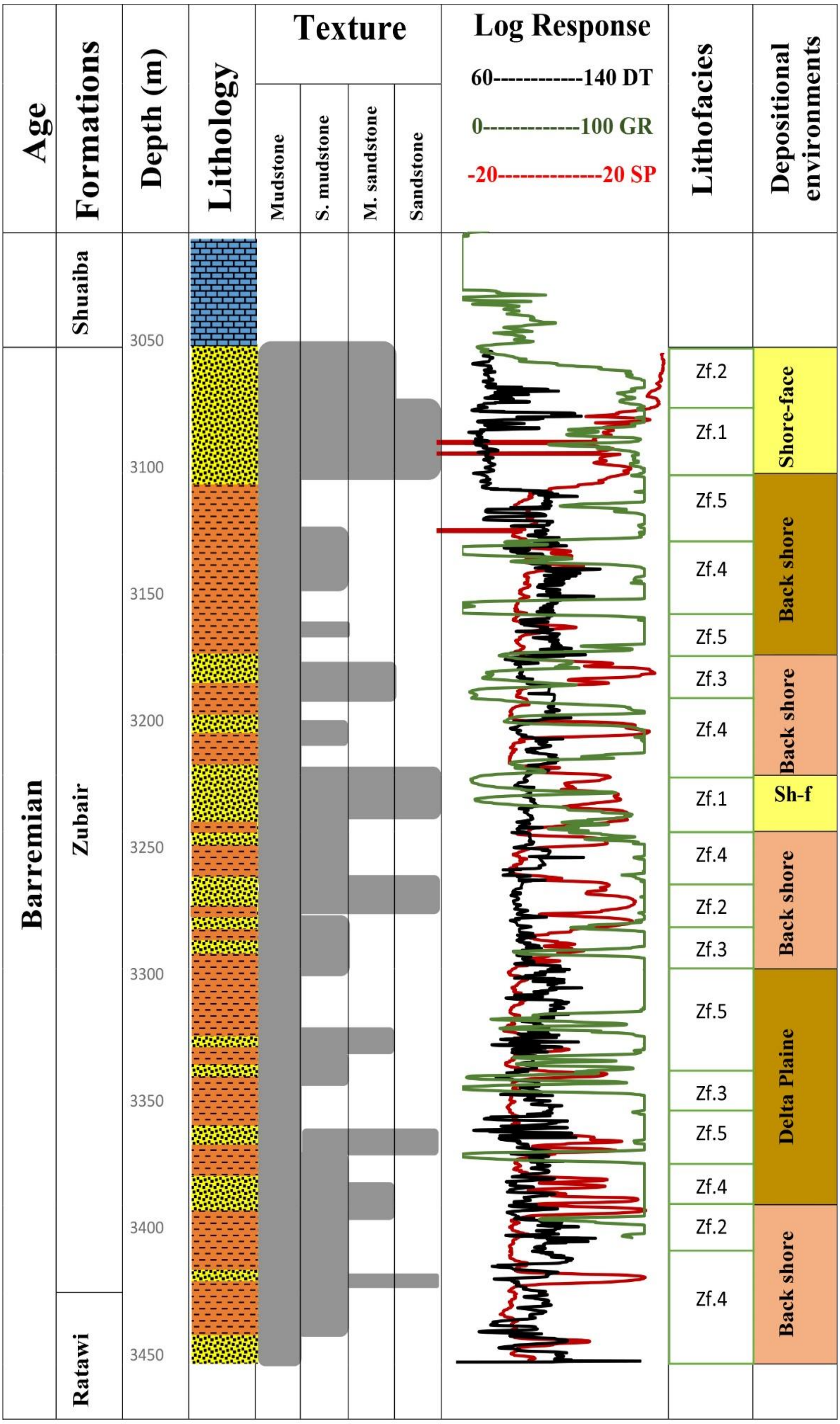

Figure 6: Columnar section showing lithofacies distribution and facies associations of WQ-X1 in West-Qurnah oilfield.

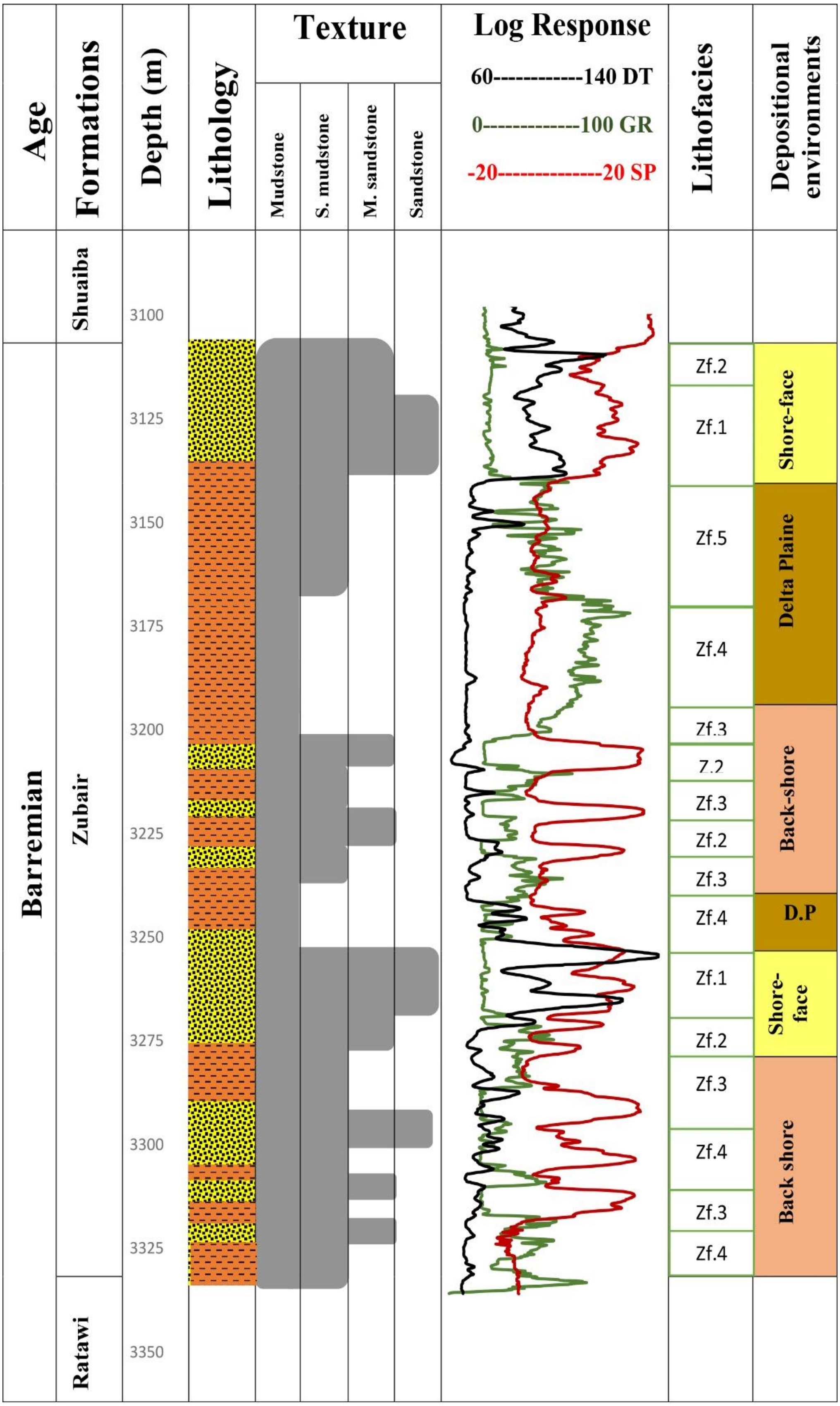

Figure 7: Columnar section showing lithofacies distribution and facies associations of WQ-X2 in West-Qurnah oilfield.

6. Conclusions

This study investigates the petrography, lithofacies analysis, and depositional evolution of the Zubair succession in four boreholes (Ru-X1, R-X2, WQ-X1, WQ-X2) located in the Rumaila and West-Qurna oilfields. The Zubair Formation was deposited in the Mesopotamian Foredeep during the Barremian age (Early Cretaceous epoch).

The Zubair rock unit predominantly consists of sandstones, classified as quartz-arenite (ortho-quartzite), containing more than 93% quartz grains. Rocks with over 20% lithic fragments and minor grains of feldspar are classified as lithic-arenites, while those with over 30% clay and minor lithic fragments are classified as graywacke.

Two primary rock groups, which are divided into five lithofacies, have been identified in this succession:

A. Sand-dominated rocks:

1. Well-sorted, sub-rounded quartz-arenite lithofacies
2. Poorly-sorted, sub-angular quartz arenite lithofacies
3. Poorly-sorted graywacke lithofacies

B. Clay-dominated rocks:

1. Sandy claystone lithofacies
2. Shale lithofacies

Three association facies have been diagnosed in the studied succession: delta plain, shore-face, and back-shore. The lithofacies identification and paleoenvironmental reconstruction of the Barremian basin in the studied area identified three stages corresponding to the observable units. These associations were deposited during three cycles, which divided the Zubair succession into three units. The lower rock unit of the Zubair Formation is mainly composed of shale, with thinly bedded lenses of sandstones dividing it into two rock units. In the northern part of the study area (WQ-X1), the upper rock unit consists of sandstones, while the lower rock unit is dominated by shales. In the southern part of the study area, the unit is predominantly shale. The upper part is characterizing by sandy-shale lithofacies (Zf.4) with thin beds of poorly sorted graywackes (Zf.3), while the lower part is characterizing by shales lithofacies 5. This sequence is identified as having been deposited in a delta-plain association, which is predominate in both northern and southern parts of the study area (WQ-X2 and Ru-X2). The central part of the area of study (WQ-X2 and R-X1) was closer to a shoreface environment.

The middle unit of the Zubair Formation is characterized by thick and alternating shaly and sandy rock units, creating three depositional cycles. These cycles are most prominent in the southern part of the study area (Rumaila oilfield), while in the northern part (West-Qurna), there are two cycles. At the center of the studied area, the middle rock unit is represented by a single well-sorted cycle, sub-rounded quartz arenite lithofacies 1, indicative of delta front and shore-face associations facies. This distinctive facies separates the two cycles in the north from the three cycles in the south. In the southern part (R-X1 and Ru-X2), the unit consists of alternating bad sorted quartz arenite (lithofacies 2) and bad sorted graywacke lithofacies (lithofacies 3). Meanwhile, the northern part (WQ-X1 and WQ-X2) is dominated by delta plain associations with successive lithofacies 3, 4, and 5, alternating with backshore associations in the north (R-X1 and R-X2).

The upper rock unit of the Zubair succession primarily consists of well-sorted, sub-rounded quartz arenite lithofacies (Lf.1), indicating deposition in a shoreface environment and marking a sea level rise in the Rumaila oilfield. In the West-Qurna oilfield, this unit is represented by delta plain and backshore facies associations (Lf.4 and Lf.5). This cycle marks the final depositional stage of Zubair succession, coinciding with the transgressive phase of the Shuaiba Formation.

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