Petroleum Potentiality and Petrophysical Evaluation of Late Triassic Baluti Formation, Northern Iraq

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Abstract

Source rock potentiality and reservoir characteristics of the Baluti Formation (Late Triassic), Northern Iraq were examined in order to determine the hydrocarbon generation potential and reservoir properties. A combination of geochemical analyses, stable carbon isotope, 1D-basin modeling and digital log data were used to evaluate the formation. The Total Organic Carbon ratios range from 0.39 to 0.61 wt%, while the quantity of free hydrocarbon and residual hydrocarbon are low (0.05-0.11, 0.40-0.90 mg/g respectively). The average of oxygen index is 318 mg CO₂/g TOC, while the hydrogen index is less than 200 mg HC/g TOC, which indicates type III kerogen. The outcomes of the pristane/phytane and Pr/n-C17 with Ph/n-C18 ratios suggest that the formation was deposited under oxic environment. This conclusion is also supported by trace elemental data. According to the average of Ro% of 0.58 and Tmax of 430.1°C, the formation is in immature to early mature stage. From a plot of 1D-modeled Ro% versus time, it is inferred that the organic matter of the formation had reached early maturation in the Early Paleocene (63Ma). The Baluti is waxier formation and the degree of waxiness ranges from 1.99-2.55. Regarding to, Trriterpanes (Tm/Ts) and regular sterane C27-C29 the studied formation has deposited in terrestrial environment with high terrigenous input with hot and arid to semiarid climates. This result is supported by stable carbon isotopic data and clay mineralogy. Porosity of the dolomite beds is 10-15%. Based on the cutoff results, the Baluti Formation has only 1.13 m net pay of 72m thickness, which means that the formation has poor porosity and permeability in the reservoir beds.

Keywords: Baluti Formation; Late Triassic; Early mature; Porosity, Iraq

1. Introduction

The Triassic successions is more than 2500m thick on the northern Arabian Platform with promising source, reservoir and cap rock lithology. They form treasure for hydrocarbon exploration in southwest and northwest Iraq and eastern Syria (Sadooni, 1995).

In Iraq, the Late Triassic sequence is represented by Mulussa and Zor Hauran formations in the Rutha subzone of western Iraq and by Kurra Chine and Baluti formations in various outcrops and wells from other parts of Iraq (Jassim and Goff, 2006). The current study is focused on the Baluti Formation in both Shaikhan Oilfield and Warte outcrop section in northern Iraq (Fig. 1).

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The formation consists of dolomites and anhydrites with interbedded limestone, breccia, conglomerate and thin grey to green shales (Buday, 1980). They were mainly deposited in shallow marine settings with local salina in arid and semi-arid conditions that were affected by basement block faulting (Sadooni, 1995). Because of its economic significance, the Baluti Formation has been described in numerous papers (Tobia and Mustafa, 2019; Asaad and Omer, 2020; Hussain et al., 2021; Edilbi et al., 2021), the majority of which focus on lithofacies, depositional environments, mineralogy and inorganic geochemistry. However, palynology and source rock potential for the Baluti Formation in other locations have been also studied (Hanna, 2007; Edilbi, 2016; Akram and Naqshabandi, 2018). Petrophysics evaluation is a major application in studying reservoirs for the hydrocarbon industry, whereas, source rocks potentiality is able to estimate the total volume and quality of exploitable hydrocarbons in a sedimentary basin. The study aims to determine the hydrocarbon generation potential and reservoir properties of the Late Triassic Baluti Formation in both subsurface and surface sections using data from organic geochemistry supported by stable carbon isotopic data and Petroleum Systems Modeling Software (PetroMod 1D program).

2. Geological Setting

Iraq is divided into two basic tectonic units, the Arabian Shelf and Zagros Suture Zone (Jassim and Goff 2006). The two main units of the Arabian Shelf are the Stable Shelf and Unstable Shelf (Jassim and Goff 2006). The study area of the Late Triassic Baluti Formation existed in the Zagros Fold Belt of the Kurdistan Region of Iraq. The belt extends 1800km on the north eastern margin of the Arabian Plate and formed from the convergence between the Arabian and the Eurasian Plates (Searle et al., 1980; Omrani et al., 2008; Aswad et al., 2011). This belt is a host to one of the world's prevalent petroleum provinces, containing about 49% of the well-known hydrocarbon reserves in the world (Cooper, 2007). The Baluti Formation cropped out as isolated patches in the cores and limbs of several anticlines in the high folded,
imbricated and northern thrust zones of Iraq. The formation was also recorded from various subsurface sections in Iraq (Buday, 1980; Jassim and Goff, 2006).

Rifting along the Zagros occurred in Early Triassic led to formation of the Neotethys Ocean (the eastern margin of the Arabian Plate) (Beydoun, 1991). During Late Triassic, uplifting occurred in the Rutba area of western Iraq, whereas, submergence took place in the rest of the Stable Shelf creating three common facies; carbonates and clastics facies (Mulussa and Zor Hauran formations) existing in the inner shelf of the Stable Shelf zone of Iraq, carbonates and evaporates facies dominating the Foothill zone and restricted lagoonal facies (Kurra Chine and Baluti formations) in the High Folded Zone of the Unstable Shelf of Iraq (Jassim and Goff, 2006). The subsurface section of the Baluti Formation in well Shaikhan-1B appears at depth interval 2301-2373m (72m thick). This well is located 60km north-west of Erbil City, while it has only 37m thick in the Warte outcrop section which is located 145km northeast of Erbil City (Fig. 1). The formation in the Warte surface section consists of dark grey shale, brecciated dolomite and slightly dolomitized limestones, while in the subsurface section it is mostly shale and anhydrite with some beds of dolomite. Based on well logs data, the Baluti Formation is overlain by the Butmah Formation and underlain by the Kurra China Formation in well Shaikhan-1B. Whereas, In Warte section, the upper contact with the Early Jurassic Sarki Formation is distinguished by the change in lithology from dark grey shale of the Baluti to well bedded limestone of the Sarki Formation, whereas the lower contact with Kurra China Formation is conformable.

3. Materials and Methods

3.1. Organic Geochemistry Analysis

Sixteen shale samples from the Baluti Formation, from both surface and subsurface sections, are subjected to Rock-Eval pyrolysis at Humble Geochemical Services Group, Shenandoah, Texas USA and the Scientific Research Center, Soran University, Iraq. Fifty grams from each sample was weighted and crushed to clay size powder. Later, the powder was heated to 300 °C for 3 minute and to 650 °C for 25 minutes respectively to release S1 and S2 peaks then the temperature was increased to 850 °C to discharge S3 peak. The pyrolysis results are presented in Table 1. Tmax, S1, S2, S3 and TOC, and calculated (petroleum potentiality PP, hydrogen index HI, and oxygen index OI) parameters are used to determine maturity level, types of organic matter and the number of hydrocarbons previously formed or that can be produced from the rock samples. Total organic carbon (TOC) and pyrolysis S2 yield have been used to determine the quantity of organic matter and the future production of hydrocarbons. The TOC generative potential of the rocks in this study is deduced based on (Tissot and Welte, 1984; Hunt, 1996) classifications. Also, kerogen types were identified by using HI vs. OI crossplot (Tissot and Welte, 1984). Thermal maturity of the analyzed samples is determined by Tmax, HI and Ro% relationship (Peters and Cassa, 1994). The selected rock samples were also analyzed by gas chromatograph mass spectrometer (GC/MS) at Ministry of Natural Resources laboratory, Kurdistan Region, Erbil, Iraq (Table 2). Seven rock samples from the well Shaikhan-1B and five samples from Warte section were carefully chosen from the shale beds for the organic geochemical study. In this procedure, the mixture flow through a narrow column, and the different chemical elements of a sample pass in a carrier gas (mobile phase) at dissimilar charges depending on their several physical and chemical properties and their interaction with a specific column called the stationary phase. As the chemicals leave the end of the column, they are sensed and recognized electronically. In the column, the main role of the stationary phase is to separate each component, and to make them all depart the column at a different time (retention time).

Chromatography-mass spectrometry (GC/MS) analyses of C15+ branched/cyclic and aromatic hydrocarbon fractions were used to evaluate the distribution of Sterane and Terpanes biomarkers using
the Agilent 7890A GC (split injection) interfaced to the 5975Q GC mass spectrometer. The flow rate of helium through the analysis should remain steady. The J & W DB5 column is temperature programmed from 100 °C to 325 °C at 3 °C/min for aromatics and from 150 °C to 325 °C at 2 °C/min (for branched/cyclic).

### Table 1. Rock-Eval pyrolysis results of the Balutii Formation in both sections

| Sections | Samples | S1 mg/g | S2 mg/g | S3 mg/g | T_max °C | TOC Wt% | HI | OI | PP | PI | Ro |
|----------|---------|---------|---------|---------|----------|---------|----|----|----|----|----|
| Well Shaikan-1B | 2308 | 0.10 | 0.55 | 1.15 | 431 | 0.47 | 117 | 245 | 0.65 | 0.15 | 0.60 |
| | 2315 | 0.11 | 0.90 | 1.16 | 429 | 0.45 | 200 | 258 | 1.01 | 0.11 | 0.56 |
| | 2320 | 0.09 | 0.80 | 1.02 | 433 | 0.49 | 163 | 208 | 0.89 | 0.10 | 0.63 |
| | 2325 | 0.08 | 0.78 | 1.05 | 426 | 0.48 | 163 | 219 | 0.86 | 0.09 | 0.51 |
| | 2330 | 0.09 | 0.58 | 1.08 | 432 | 0.44 | 132 | 245 | 0.67 | 0.13 | 0.62 |
| | 2347 | 0.07 | 0.61 | 0.97 | 430 | 0.61 | 100 | 159 | 0.68 | 0.10 | 0.58 |
| | 2347 | 0.09 | 0.52 | 0.98 | 428 | 0.50 | 104 | 196 | 0.61 | 0.15 | 0.54 |
| | 2354 | 0.08 | 0.75 | 1.24 | 425 | 0.39 | 192 | 318 | 0.83 | 0.10 | 0.49 |
| | 2361 | 0.06 | 0.58 | 1.18 | 431 | 0.52 | 112 | 227 | 0.64 | 0.09 | 0.60 |
| | 2370 | 0.10 | 0.50 | 1.22 | 430 | 0.39 | 128 | 313 | 0.60 | 0.17 | 0.58 |
| | 8 | 0.09 | 0.77 | 1.00 | 432 | 0.44 | 175 | 227 | 0.86 | 0.10 | 0.62 |
| | 12 | 0.07 | 0.85 | 0.87 | 429 | 0.51 | 167 | 171 | 0.92 | 0.08 | 0.56 |
| | 20 | 0.09 | 0.50 | 0.91 | 434 | 0.41 | 122 | 222 | 0.59 | 0.15 | 0.65 |
| | 27 | 0.05 | 0.40 | 0.83 | 430 | 0.37 | 108 | 224 | 0.45 | 0.11 | 0.58 |
| | 33 | 0.10 | 0.72 | 0.75 | 428 | 0.39 | 185 | 192 | 0.82 | 0.12 | 0.54 |

S1: Volatile hydrocarbon (HC) content; S2: Remaining hydrocarbon generative potential; S3: Carbon dioxide content; T_max: Maximum Temperature; HI: Hydrogen Index; OI: Oxygen Index; GP: Genetic Potential; PI: Production Index.

### Table 2. GC/MS results of the Balutii Formation in the studied sections

| Sections | Samples | Pr/Ph | Pr/Ph-C_{17} | Ph-n-C_{18} | CPI | C7 | C8 | C9 | 20S/(28S-20R) | C_{22S} | C_{22S}/22R-22S | Tm/Ts | Saturated | Aromatic |
|----------|---------|------|-------------|------------|-----|----|----|----|----------------|--------|-----------------|-------|-----------|---------|
| Well Shaikan-1B | 2308 | 2.99 | 2.25 | 0.41 | 1.34 | 2.1 | 30 | 19 | 51 | 0.29 | 0.49 | 1.07 | -30.2 | -25.9 |
| | 2315 | 3.02 | 2.33 | 0.52 | 1.35 | 2.5 | 31 | 15 | 54 | 0.31 | 0.51 | 2.02 | -29.4 | -25.6 |
| | 2320 | 2.98 | 2.47 | 0.47 | 1.30 | 2.0 | 33 | 17 | 50 | 0.28 | 0.48 | 2.08 | -29.9 | -26.2 |
| | 2325 | 3.13 | 2.14 | 0.33 | 1.12 | 2.2 | 32 | 18 | 50 | 0.33 | 0.53 | 1.06 | -30.3 | -26.1 |
| | 2330 | 3.02 | 2.74 | 0.39 | 1.13 | 2.4 | 30 | 17 | 53 | 0.29 | 0.52 | 2.55 | -29.8 | -25.4 |
| | 2347 | 2.95 | 2.65 | 0.37 | 1.21 | 2.6 | 31 | 19 | 50 | 0.31 | 0.48 | 2.33 | -28.9 | -24.9 |
| | 2347 | 3.01 | 2.55 | 0.45 | 1.30 | 2.4 | 33 | 16 | 51 | 0.32 | 0.47 | 1.34 | -30.2 | -25.8 |
| | 2354 | 2.99 | 2.39 | 0.36 | 1.14 | 2.5 | 32 | 18 | 50 | 0.34 | 0.46 | 1.56 | -29.5 | -25.6 |
| | 2361 | 3.03 | 2.47 | 0.44 | 1.23 | 2.2 | 30 | 17 | 53 | 0.33 | 0.5 | 1.11 | -29.9 | -25.1 |
| | 2370 | 2.98 | 2.19 | 0.42 | 1.22 | 2.3 | 29 | 18 | 53 | 0.28 | 0.48 | 0.83 | -30.1 | -25.4 |
| | 2 | 3.02 | 1.58 | 0.29 | 1.31 | 2.5 | 31 | 16 | 53 | 0.31 | 0.51 | 2.51 | -29.7 | -26.1 |
| | 8 | 3.12 | 1.6 | 0.32 | 1.37 | 2.2 | 32 | 20 | 48 | 0.28 | 0.49 | 1.43 | -30.1 | -26.2 |
| | 12 | 2.99 | 1.59 | 0.36 | 1.30 | 2.1 | 33 | 19 | 48 | 0.29 | 0.47 | 2.00 | -29.9 | -25.2 |
| | 20 | 3.01 | 1.61 | 0.3 | 1.32 | 2.5 | 30 | 14 | 56 | 0.31 | 0.49 | 1.11 | -28.9 | -25.4 |
| | 27 | 2.99 | 1.49 | 0.29 | 1.36 | 2.5 | 32 | 14 | 54 | 0.32 | 0.5 | 2.5 | -28.2 | -24.8 |
| | 33 | 2.98 | 1.55 | 0.31 | 1.33 | 2.3 | 31 | 17 | 52 | 0.30 | 0.5 | 1.00 | -29.6 | -25.5 |

Pr: Pristane; Ph: Phytane; CPI: Carbon Preference Index; Ts: 18α(H),21β(H)-22,29,30-trisnorheptane, Ts, (C_{27}) ; Tm:17α(H),21β(H)-22,29,30-trisnorheptane, Tm, (C_{27}) ; C_{32} 17α(H),21β(H)-30,31-bishomohopane (22S)
17α(H),21β(H)-30,31-bishomohopane (22R); C29 5α(H),14α(H),17α(H) sterane (20S); C29 5α(H),14β(H),17β(H) sterane (20R); C29 5α(H),14β(H),17β(H) sterane (20S); C29 5α(H),14α(H),17α(H) sterane (20R).

3.2. Carbon Isotope Analysis

Sixteen cutting samples were analyzed using stable carbon isotope analysis. Stable isotope ratios are determined using mass spectrometry, which distinguishes the various isotopes of the material on the bases of their mass-to-charge ratio. Isotope ratio mass spectrometry (IRMS) is a proxy of mass spectrometry in which mass spectrometric methods are used to measure the relative abundance of isotopic in a given sample. The analysis of stable isotopes is normally concerned with measuring isotopic variations arising from mass-dependent isotopic fractionation in natural systems. While, radiogenic analysis involves measuring the abundances of decay products of natural radioactivity and is used in most long-lived radiometric dating methods. For nitrogen carbon and sulfur isotope analyses depend on the bulk combustion of the sample, followed by separation of products, which are sent to the isotope ratio mass spectrometer for ionization, separation and detection.

3.3. PetroMod 1D Program

The PetroMod 1D program can be used to calculate the present-day heat-flow values by calibrating them with the subsurface geothermal gradients determined from bottom hole temperature (BHT) and thermal conductivity of the rock units. The basic methods to model the thermal evolution of a sedimentary basin have three boundary conditions (Paleo-Water Depth (PDW), the Sediment-Water Interface Temperature (SWIT) and Paleo Heat Flow (PHF). The paleo-water depth in this analysis was modeled on the basis of a variation of known values (Edilbi, 2016). In addition, for erosion or hiatus occurrences, a value of 0.0m has been considered. For carbonate rock, a water depth of 20-30m was added to the model. The PetroMod-1D program tests SWIT values over geological time depending on the Wygrala (1989) approach. This path is taken geological age and differences in mean surface paleotemperature versus latitude and geological time; and water depth during deposition time (Yalcin et al., 1997). The SWIT of this study was identified as the paleo-latitude of the Middle East and 38N (Kurdistan Iraq zone according to UTM in northern part). A Paleo-heat flow was believed to differ over geological time, based on rifting events and the formation of the basin. Regarding erosion, we should plot the reflection of the vitrinet against the depth. If the points plotted for VR are equal and less than 0.3, it means we have no erosion but if we have more than 0.4, then it means the formation is mature and some beds are eroded, on the other hand, zero is a gap because we don't know the value of the gap at all.

3.4. Petrophysical Evaluation

To determine reservoir properties of the formation, the interactive petrophysics program (IP) has been used. The LAS file which includes gamma ray, shallow and deep resistivity with porosity logs was imported, and the vertical resolution of these logs are 0.1524 m. The correction processes have been done for each of gamma ray, resistivity; neutron (CNL neutron) and density logs that are more influenced by the borehole condition, using standard Schlumberger method. After correction process, gamma ray method is used to estimate volume of shale, and porosity loges are used to determine porosity, lithology and mineralogy of the formation, resistivity logs for saturation in the dolomite beds.

3.5. Mineralogical and Inorganic Geochemical Analyses

X-ray diffraction (XRD) analysis, a tool to determine the mineralogical constituents of the Baluti shales, was conducted as powder preparation in a D8 Advance from the company Bruker AXS GmbH, whereas, trace elements geochemical analysis was performed using X-ray fluorescence (XRF) with an
AXI AXIOS from the company PANalytical GmbH. Both analyses were achieved in the Institut für Geowissenschaften-Geologie, Bonn University, Germany.

4. Results and Discussion

4.1. Source Rock Characterization

4.1.1. Source rock characterization from pyrolysis results

The organic matter of shale rocks within the Baluti Formation was regarded as poor-fair with TOC values changes from 0.39-0.61% in well Shaikhan-1B to 0.37-0.51% in Warte outcrop section. The formation’s remaining hydrocarbon (S2) is 0.5-0.9 mg HC/g rock in the subsurface segment and 0.40-0.85 mg HC/g rock in the outcrop portion. Overall, the TOC and S2 matters exposed by these shales, fall within the fair category which reveals a fair hydrocarbon generative potential for Baluti Formation in both parts (Fig. 2a). Kerogen forms were deduced from crossplot of hydrogen index (HI) versus oxygen index (OI) (Fig. 2b), the maximum value of HI reached to 200 mg HC/g TOC (ranging between 100-200 mg HC/g TOC) in both parts, while OI values were greater than HI and ranged from 159-318 mg CO2/g TOC suggesting the type III variety and capable of producing gas in an acceptable situation. The same conclusion has been reached by Akram and Naqshabandi (2018) in well Atrush-1. Thermal maturity is evaluated using Vitrinite reflectance and Tmax pyrolysis results (Fig. 2c). The values of Tmax and vitrinite range from 425-434 °C and 0.49-0.65%, respectively. Overall, both parameters indicate the ripening profile of the Triassic-Baluti Formation in the studied sections, the chosen rock sequence being positioned in the immature to early mature window at both locations.

Fig.2. (a) TOC versus S2 (b) HI versus OI (c) HI versus Tmax showing type of kerogen and maturity of the Baluti Formation in the studied sections
4.1.2. Source rock characterization from biomarkers

More geochemical studies for the selected rocks were conducted in both sections to gain more information on the organochemical properties of the Baluti Formation. Complex molecular fossils extracted from biochemical, especially lipids in thriving organisms are biomarkers (Peter et al., 2005). Various biomarker applications are widely used by geochemists in the sense of hydrocarbon exploration, development, and processing. They are frequently used for defining of organic facies, conditions of deposition, and thermal maturity of organic matter present in source minerals, crude oils, and bitumen. The n-alkanes, isoprenoids, monomethyl-branched alkanes (MMAs), and cyclic alkanes are characteristic biomarker groups isolated from gas chromatograms. The n-alkanes make up a major portion of organic matter in oils and rock extracts.

A population of monomethyl-branched alkanes (MMAs) are originated from plant waxes (C25-C31) or cyanobacteria (C13-C19) (Robinson and Eglinton, 1990). To establish the origins of OM and the environment for deposition, the distribution of such n-alkanes hydrocarbons may be used (Philp, 1985). In rock extracts and oil samples, the greater influence of higher plants (lipids) and terrestrial content are attributed to C27-C33 long-chain n-alkanes enrichment (Tissot and Welte, 1984). In the C21-C25 range (mid-chain n-alkanes); submerged/ floating aquatic plants exhibit enriched (Mead et al., 2005) short-chain distribution of C15-C19 n-alkanes indicating marine development from algal and bacterial biomass (Peters and Moldowan, 1993). The chromatograms (GC) of the analyzed samples reveal the distribution of n-alkanes within the C25-C33 range (long-chain), suggesting the terrestrial source content. Low MMAs and high carbon preference display quite proximal facies with a maximum terrestrial contribution.

The degree of waxiness as an environmental criterion is generally used for organic geochemical classification of source rocks and oils. It is represented by \[ \frac{\sum(n-C21-n-C31)}{\sum(n-C15-n-C20)} \] and indicates the volume of land derived from sediments and oils relative to marine organic matter (Bakr, 2009). The studied formation could be differentiated as a waxier with a degree of waxiness between 1.99-2.55 (Table 2 and Fig. 3a). This is a strong indicator that there is a great contribution of terrigenous OM in the formation, which is generally consistent with the n-alkanes distribution findings. As an example of the redox settings, the ratio of pristane/phytane (Pr/Ph) is used throughout the phases of sedimentation and diagenesis (Escobar et al., 2011), and as a proxy for the source of organic matter then the depositional state in which the OM accumulated (Large and Gize, 1996). Reducing/hypersaline environments can always yield values below one accumulating predominantly aquatic organic material (evaporates/ carbonates), whereas values greater than three represent oxygenated circumstances indicative of terrestrial habitats rich in field plants (coal and peat swamps) (Peters and Moldowan, 1993). The ratios of Pr/Ph of 1-3, illustrate the intermediate settings (oxic-suboxic) of the depositional climate (Wang et al., 1997).

The values of the Pr/Ph ratio for the studied formation changes from 2.95-3.13, with an average 3.01, indicating terrestrial oxic condition in the studied sections (Fig. 3a). The results are uniform with the degree of normal alkane and waxiness. The isoprenoids (Pr, Ph) over n-C17 and n-C18, respectively, have been widely used to classify the ecosystem of the organic source and type of organic matter deposited in the region (Shanmugam, 1985), this plot indicates that the Baluti Formation is dominantly part of the type III kerogen, a typical region of terrestrial settings (Fig. 3b). Terpanes and Steranes have also been used by geochemists in the sequence of biomarker classification of source rocks and basic oils. The GC-MS parameters used in this respect are displayed in Table (2). Triterpanes are plagiaristic primarily from microorganisms (bacteria) and are also used as markers for digenetic conditions and depository (Waples and Machihara, 1991). Generally, tricyclic terpanes can be applied in oil-source rock correlations; source rock descriptions and maturation evaluation (Seifert et al., 1980). As a result, they are found in rocks deposited in both lacustrine and marine settings (Philp and Gilbert, 1986). In
general, the Baluti Formation is low of definite tricyclic such as the C23 in rock cuttings which has continuously been recognized to marine statement environments; Abundance of C19 and C20 members in the selected samples are widely dispersed in terrestrial sources. The Tm/Ts ratio is expressed as Tm/Ts or Ts/Tm. Subsequently, this parameter can also be applied as a maturity indicator. However, Robinson (1987) believed that the Tm/Ts levels are extraordinary in terrestrial, medium in marine and low in lacustrine oils. In the analyzed samples of the Baluti Formation, the Tm/Ts ratios displayed high values for both the Shaikhan-1B well and the Warte outcrop section.

The rearranged hopanes C30 (H)-diahopane (C30D) and C29 (H)-30-nornerohopane (C29T) or compounds C14 and C15, respectively, are produced by the transition in oxic, clay-rich sediments from the originator hopanoid. Abundant C29Ts hopanes indicate terrigenous source material the sediments and oils (Volkman and Maxwell, 1986). In this research, Baluti Formation's shale intervals were highly enriched with rearranged hopanes as an indicator and marker of the oxic quality of its depositional environment and hence a higher clay content. Six structural units of isoprene making saturated biomarkers steranes which were produced by degradation of diagenetic, catagenetic processes and saturation from the eukaryotic membrane and hormone steroids; steranes can be used to conclude deposition condition and the OM form (Volkman and Maxwell, 1986). Table 2 shows the Sterane distributions of the analyzed rocks. To constrain the form of species, present in organic matter, relative abundances of standard C27-C29 sterane have been used. The C29 sterane is known to be terrestrial. The higher normal C27 sterane are indicative to marine organic matter supply (Mendonça Filho et al., 2012). The higher C28 sterane has a high phytoplankton and lacustrine algae content and may also indicate marine sources (Waseda and Nishita, 1998).

Generally, the sterane distribution of the analyzed rock extracts of Baluti Formation showed significant C29 homologs in the proximal facies of terrestrial (III) as evidence for strong terrigenous input. According to the diagram of sterane triangular which was formed by Huang and Meinschein (1979), the normal distribution of steranes typically shows the same three sets; alkanes, isoprenoids, and terpanes of biomarker groups. The extracts from the Late Triassic-Baluti Formation indicate comparatively advanced diasterane content showing further enhancement of clay and includes some clastic facies. Pregnancies in depository settings are believed to be indicative of higher salinity; generally, low pregnanes in oxic environments are associated with high diasterane levels and with major terrigenous input into clay-rich source rocks. A high pregnane/little diasterane arrangement reveals limited, sulfur-rich anoxic carbonates (Guangli et al., 2015). Normal sterane content and comparable pregnancies in the training area are noted for the Late Triassic (Baluti Formation), which is compatible with raised diasterane configurations (m/z 218). This is a strong indication that these shales are rich in terrigenous content and have been stored in clay-rich environments and oxic.The presence of illite (Fig. 4) suggests terrestrial conditions with hot and arid to semiarid climates during the deposition of the Baluti sediments (Hussain et al., 2021). Terrestrial conditions are also favored by common presence of clastic-origin grains such as quartz and feldspars.
Fig. 3. (a-d), Degree of waxiness kerogen types, maturity and different source material of the Baluti Formation in the studied sections based on biomarkers parameter.

Fig. 4. X-ray diffractogram of representative sample from the Baluti Formation, Warte section.

The Sr/Cu and Ga/Rb ratios are considered as key paleoclimate indicators (Cao et al., 2012; Yandoka et al., 2015; Cusack et al., 2020). The high Sr/Cu ratio, greater than 5.0, depicts an arid-hot
climate, whereas its ratio between 1.3 and 5.0 exhibits warm and humid paleoclimate. The Sr/Cu ratios vary from 4.9 to 12.4 (average = 7.66) suggesting an arid-hot climate (Table 3). The Ga/Rb ratio is also used to deduce the paleoclimate. Generally, Rb is closely related to illite, inferring to a cold and arid climate. Therefore, sediments containing lower values of Ga/Rb are indicative of cold and dry climates. The Ga/Rb ratios vary from 0.13 to 0.34 (average = 0.23) confirming arid-hot climate. The presence of illite as a common clay mineral also reinforces arid climatic conditions (Chamley, 1989). Whereas, other geochemical indices such as Ni/Co, V/Cr and V/Ni are used to evaluate palaeoredox conditions (Jones and Manning, 1994). Ni/Co and V/Cr values are 1.9-2.3 (average= 2.1) and 2.0-2.3, 1.0–3.0 (average= 2.12), respectively (Table 3) which reflect oxic conditions of deposition. V/Ni ratio also is used to determine the type of environment in which organic matter was deposited and establishing the paleoenvironmental redox conditions (Galarraga et al., 2008). According to these authors, V/Ni ratios, higher than 3, indicate marine organic matter deposited under anoxic conditions, from 1.9 to 3 in disoxic–oxic conditions with precursor organic matter of mixed origin (continental and predominantly marine), ratios lower than 1.9 show terrestrial organic material with prevailing oxic conditions. In the present study, the V/Ni ratios have shown an average value of about 2.16 (Table 3) which reveals the deposition under disoxic–oxic conditions for the Baluti sediments.

Table 3. Trace element ratios, paleoenvironmental sensitive ratios and redox proxies for selected samples of Baluti Formation, Warte section

| Samples | Sr/Cu | Ga/Ba | Ni/Co | V/Cr | V/Ni |
|---------|-------|-------|-------|------|------|
| 2       | 12.4  | 0.34  | 2.3   | 2.3  | 1.9  |
| 8       | 4.9   | 0.13  | 1.9   | 2.0  | 2.4  |
| 11      | 5.7   | 0.24  | 2.1   | 2.1  | 2.2  |

The biomarker maturity of the rock samples is explored in this study by adding triterpane and sterane isomerization parameters: 22S/(22S+22R) of homohopane C32 and 20S/(20S+20R) of sterane C29 respectively. When putting the analyzed extracts in the immature to early mature period for the chosen samples in both pieces, Biomarker maturity data would suggest complete compatibility with those of the pyrolysis findings. The ratio of homohopane C32 increases significantly during the maturation period from 0.0 to 0.60 (equilibrium level = 0.62), with values from (0.5 to 0.54) suggesting early generation of oil, and (0.57 to 0.62) representing maturation of the oil window (Seifert and Moldowan, 1986). Although, the C29 sterane 20S/(20S+20R) ratio rises with thermal maturity from 0.0 at the immature stage to almost 0.55 at peak oil generation with equilibrium at 0.52-0.55 (Alian, 1983). Nevertheless, the isomerization maturity, sterane and terpanes of the analyzed samples is consistent with the pyrolysis Tmax values, however, Ro maturity demonstrates immature to early mature window phase for the Late Triassic-Baluti Formation (Fig. 3d).

4.1.3. Source rocks C-isotopes composition:

Powerful fractionation of stable carbon isotopes takes place during the ingestion of carbon into organic matter (Peters et al., 2005). Weak δ13C values (-25.2 to -35.5 PDB) are seen by Sapropelic lacustrine organic matter, whilst the humic value is comparatively heavier with values in the range of (-22.6 to -28.0 PDB). For the analyzed rock extracts shown in (Fig. 5), the carbon isotopic composition suggests that the Late Triassic is isotopically heavier (-24.8 to -30.3) being plotted in the field of terrestrial organic matter. This plot is in complete concordance with the various biomarker signs mentioned above as supporting evidence of terrestrial input during the Late Triassic period in Northern Iraq.
4.1.4. Basin modeling of source rock

Basin growth evaluation requires information on stratigraphic section lithologies, formation dates, and times of deposition, as well as non-deposition/erosion. (Cao and Lerche, 1990). The burial and thermal histories are very important for the Late Triassic source rock to forecast the timing of hydrocarbon generation and expulsion. The studied well was modeled using Schlumberger's PetroMod one dimensional (1D) Modeling Software. One of the popular commercial simulation tools, used in this analysis for the reconstruction the burial and temperature histories of the Shaikhan-1B well, is the 1D burial history model. The formations penetrated from the oldest to youngest within the Shaikhan-1B well section are: Late Triassic Baluti Formation, Early Jurassic Butmah, Adaiyah, Mus, Alan formations, Middle Jurassic Sargelu Formation, Barsarin and Chia Gara Late Jurassic Formations. The Cretaceous units include; Garagu, Sarmord, Qamchuqa, Kometan, Wajna and Aqra formations. These are overlain by Tertiary Kolosh Formation. During the time intervals (161-154 Ma, 99.9-94.7 Ma, 75-54.8 Ma and 30-0.0 Ma) 1400m erosional thickness in Shaikhan-1B well has been recorded. The burial history of Shaikhan-1B well shows that during Jurassic (~195-136 Ma) sedimentation was characterized by relatively low subsidence rates of about ~ 12.5 m per million years leading to a present thickness of about 1100 m. Subsidence and sedimentation continued during Cretaceous (~144-64 Ma), when the subsidence rate increased to approximately 11.96 m per million years, leading to a present thickness of about 1145 m. The younger Tertiary unit has low average subsidence rate of about (4.69 m per million years) in the well. The Late Triassic formation is supposed to be more mature than it is. It seems that the thickness of overburden rocks (2300 m in Shaikhan-1B well), have not contributed to sufficient temperature rise to cook organic matter present in Baluti Formation. However, as noticed from Fig. 5, there was non-deposition of Oligocene and erosion of Middle-Upper Eocene-Pleistocene sediments in the well. The history of source rocks maturity depends on pyrolysis information (TOC, HI, Tmax and VR), subsurface geothermal gradients calculated from BHT in addition to the thickness and lithology of formations, all of which required the studied well to create historical profiles. Therefore, the Rock-Eval pyrolysis Tmax values were used to quantify the estimated vitrinite reflectance (Ro%) data (Table 2), using this formula:

\[ Ro = 0.018 \times Tmax - 7.16 \]  

(1)
In order to calibrate the paleo-heat wave, the measured figures were subsequently used to balance the modeled values as defined by Simple Ro% (Sweeney and Burnham, 1990). In this study, the reasonable fit of measured and vitrinite reflectance (Ro%) of Sweeney and Burnham was achieved from erosion of 1400m of sediments from top of Kolosh Formation (Fig. 6a). Compared to the Low Folded Zone, the geothermal gradients in the Kurdistan Area are slightly lower in the High Folded Zone, which may be due to changes in rock thermal conductivity and groundwater movement (Abdula, 2018). In the High Folded Region, the low temperatures are possibly due to the high thermal conductivity of Cretaceous carbonate rocks (Yandoka et al., 2015). In comparison, the heavily fragmented rocks in the High Folded Region allow more extreme groundwater flow. For the selected well the best fit between bottom hole temperature and present-day temperature was set as 35 °C (Fig. 6b). The burial and thermal maturity histories profiles for the studied section (Fig. 6c) show that the generation zone was simulated based on calculated vitrinite reflectance for Baluti Formation is immature to early mature (0.49-0.65% Ro). It is clear that the geothermal gradients are not uniform through the entire borehole (Fig. 6d). The gradient anomalies typically reasoned to variety of heat transporting routes and entrapment (Sonam and Kumar, 2013). In addition, such anomaly may be related to presence or absence of clay and hot shales also, and presence of a very tight seal. Black shales and clays generally show a higher heat generation than sandstones and limestones. The modeled generation mass of the Late Triassic formation and its TR associated with geologic time of the studied well indicated that the Baluti Formation didn’t reach the early phase of oil generation (TR < 0.1) (Fig. 6).

4.2. Reservoir Properties

Almost all stratigraphic succession that contains low amount of shale can be considered as a good reservoir for hydrocarbon accumulation, otherwise the formations that have more than 20% of shale might not have capacity for collecting hydrocarbons (Darwin and Julian, 2007). To calculate the volume of shale in the Baluti Formation, gamma ray log is the best indicator. In carbonate rocks, such as limestone, dolomite and anhydrite, the gamma ray kick reading is low while opposite the shale beds it has a big value (Asquith and Krygowski, 2004). The process set out by calculation gamma ray index (IGR) through the Equation 2 then Larionov method was used for the old rocks (Mesozoic and Paleozoic formations) (Eq. 3). The results showed that the formation generally contains 34% of shale, particularly, in its upper part. On the other hand, the M-N crossplot has been used to determine the mineralogy of the Baluti Formation. The crossplot would be available when we have sonic log in the wells. According to M-N crossplot, the formation mainly consists of clay minerals and anhydride with the presence of dolomites (Fig. 7a). Regarding to the different types of lithology (Fig. 7b), the studied formation in well Shaikhhan-1B has been divided into four zones. Almost all shale and anhydrite beds are displayed in the zone number 1 and 3, which have significant role as a cap rock in the subsurface section. The zones number 2 and 4 are distinguished from the other two mentioned zones by the presence of some dolomite beds. In some cases, the porosity in these beds ranges from 10-15%. Therefore, these beds can be considered as fair-good reservoir rocks for hydrocarbon accumulation.
Fig. 6. Burial history and maturation period for the Late Triassic Baluti Formation in well Shaikhan-1B.
Archie equation (Eq. 4) was used to determine type of fluid (water and hydrocarbon) within the dolomite beds of the formation. In the plot of the true formation resistivity versus effective porosity (Fig. 7c), the Archie’s parameters were determined (a=1, m=1.97 and n=2). The red line passed through points that have maximum porosity values and minimum deep resistivity, the area around that line represents the water zone at which water saturation equals one. The slope of the line represents the porosity exponent (m) and the intercept represents the formation water resistivity (Rw) which is equal 0.047 in this well. Based on equations 5 and 6, most hydrocarbons which accumulated in the dolomite beds are residual hydrocarbon; the Baluti Formation has 12 m reservoir net out of total 72 m thick and only 1.13 m net pay in whole formation regarding to the cutoff results (Fig. 8).

\[
\text{IGR} = \frac{G_R \log - G_R \text{min}}{G_R \text{max} - G_R \text{min}} \quad (2)
\]
\[
V_{sh} = 0.33(2^{2^{GRI}} - 1) \quad (3)
\]
\[
S_w = \left( \frac{a \cdot \frac{R_w}{R_t}}{\beta m} \right)^{\frac{1}{n}} \quad (4)
\]
\[
S_{hc} = 1 - S_w \quad (5)
\]
\[
S_{hc} = S_{hr} + S_{hm} \quad (6)
\]

Where:

- IGR: Gamma ray index
- Vsh: Shale volume
- Sw: Water saturation
- Rt: True resistivity
- Rw: Water resistivity
- Shc: Saturation hydrocarbon
- Shr: Residual hydrocarbon
- Shm: Movable hydrocarbon

**Fig.7.** (a) The M-N crossplot (b) Neutron-density crossplot (c) True formation resistivity versus effective porosity (Pickett plot) of the Baluti Formation in well Shaikhan-1B.
Fig.8. Computer Processed Interpretation (CPI) for the studied formation in well Shailhan-1B, the figure from number 1-5 is related to input data which are the obtained logs while from number 6-10 is our output (results) number 6 showed by black bar and the value of net pay for this formation in the studied well, numbers 7, and 8 are showing both water saturation and both total and effective porosity respectively, number 9 reflected to change of lithology.
5. Conclusions

The hydrocarbon generation potential and reservoir properties of the Late Triassic Baluti Formation in well Shaikhan-1B and Warte outcrop sections have been investigated using organic geochemical analyses supported by stable carbon isotopic data and Petroleum Systems Modeling Software (PetroMod 1D program). In the proven and potential source rock, the average oxygen index is 227 mg CO2/g TOC and the Pr/Ph values are greater than 3 with abundant of C29 sterane, which is known to be the terrestrial oxic environment and the terrigenous supply in both parts. This also supported by mineralogical and trace elemental analyses. Furthermore, due to the hydrogen index, that was around 200 mg HC/g TOC and the average of Tmax, Ro% and TOC reached 430.1 °C, 0.58 and 0.46%, respectively. The studied formation has kerogen type III and capable to generate some gas in appropriate condition. According to the neutron density crossplot, the porosity of these beds reached 5-10%, suggesting standard porosity in the subsurface portion to accumulate hydrocarbons. In the respect of proven and potential cap rock, the M-N and neutron-density cross plots are concerned, the formation has more anhydrite beds that play a major role to act as a cap rock.

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