RESEARCH ARTICLE

Petroleum System Modelling of the Akri-Bijeel Oil Field, Northern Iraq: Insights From 1-Dimensional Basin Modelling

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Received: 18-06-2020 **Accepted:** 16-07-2020 **Available online:** 31-12-202

ABSTRACT

The petroleum system of the Akri-Bijeel oil field shows that the Palaeogene formations such as the Kolosh Formation seem to be immature. However, the Jurassic–Lower Cretaceous source rocks such as those from the Chia Gara, Naokelekan, and Sargelu formations are thermally mature and within the main oil window because their vitrinite reflectance (Ro%) values are >0.55%. The Triassic Kurra Chine and Geli Khana formations are thought to be in the high maturity stage with Ro values ≥1.3% and within the wet and dry gas windows, whereas the older formations are either within the dry gas zone or completely generated hydrocarbon stage and depleted after the hydrocarbons were expelled with subsequent migration to the reservoir rock of the structural traps.

Keywords: Akri-Bijeel, Bekhme-1, Hydrocarbon maturation, PetroMod, Kurdistan Region

1. INTRODUCTION

The Akri-Bijeel Block is 1 of 55 oil exploration blocks in the Kurdistan network Region of northern Iraq. The Bekhme-1 Well was drilled as an explorer or wildcat, and it is the second exploration well being drilled in the Akri-Bijeel Block, 20 km northeast of the Bijeel-1 Discovery Well (the P50 operator estimates that there is a total 2.4 billion barrels of oil on site) (Csontos et al., 2011). The area of the Akri-Bijeel Block covers 889 km2 and the Bekhme-1 Well targets possible intervals in the Jurassic and Triassic periods with a predicted depth of 3000 m (Csontos et al., 2011). From a topographic point of view, the mountain mass is divided into the northern part, which is characterized by the E-W trend of the mountain range with heights up to 1500 m above sea level, and the southern part, a smooth and mountainous region 500 m above sea level on average (Csontos et al., 2011). Abdula et al. (2017) used Rock-Eval pyrolysis to study the potential of generating oil from source rocks from the Bijeel 1 Well, Akri-Bijeel Block, in the Kurdistan Region of northern Iraq. The results showed that the Sargelu and Sehkaniyan configurations contain a marine type IIS kerogen and that the organic matter is thermally mature and in the oil window. In the samples studied, it was determined that the carbonates are richer in organic matter and more susceptible to oil generation than the shale, which seems to be potential sources of natural gas.

Access this article online

DOI: 10.25079/ukhjse.v4n2y2020.pp35-47 **E-ISSN:** 2520-7792

The samples from the Chia Gara, Naokelekan, Sargelu, and Sehkaniyan formations can be considered good source rocks with an average total organic carbon (TOC) content of 1.50, 2.86, 1.44, and 0.63 wt%, respectively, and they contain type II and III kerogens, indicating marine and nonmarine organic matter, which proposes oil and gas prone sources (Ali, 2018). The petroleum system of Jabal Kand oil field (located SW of the study area) shows that formations such as the Kolosh (Palaeocene), the Shiranish (Upper Cretaceous), and the Sargelu (Middle Jurassic) are immature and have not generated any oil with Ro values of <0.55% (Abdula, 2017c). The main aim of this study was to determine the parameters of the petroleum system at Bekhme-1 Well to determine during which time the existing kerogen was changed to oil and became mature and to determine the time at which oil migrated into the reservoir.

The Bekhme-1 Well is located in the highland of the southern part of the Akri-Bijeel Block in the northern part of Iraq. Bekhme-1 Well is located about 10 km northwest of the city of Harir and 50 km north of the regional capital city, Erbil. It is situated at latitude 36° 40' 33.05" North and longitude 44° 17' 47.60" East (Figure 1).

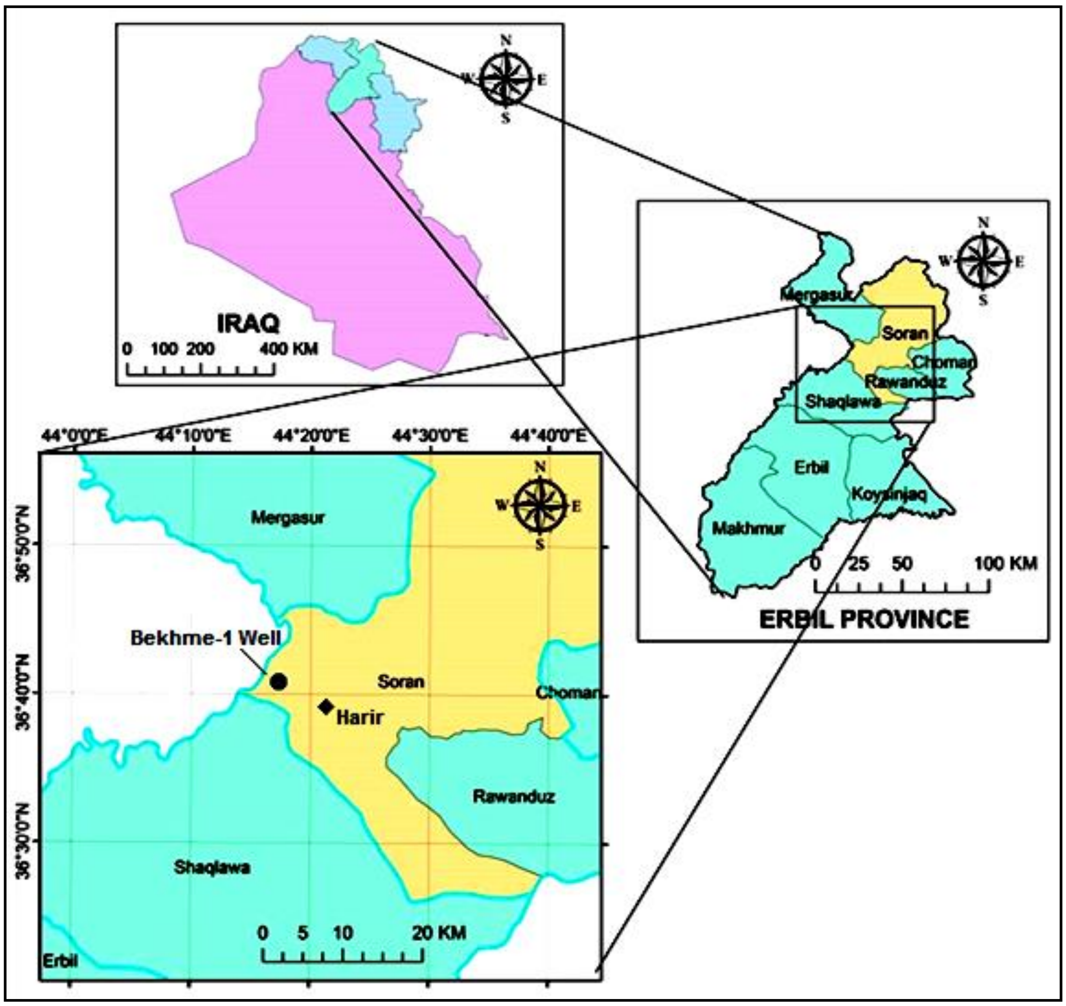

Figure 1. Main map of Iraq showing the Kurdistan Region (A); Enlargement of the outlined area in A marked the Erbil Province (B); Enlargement of the area outlined in B showing the location of the studied well (C)

2. MATERIALS AND METHODS

In this study, 1-dimensional (1-D) basin modelling PetroMod 2011.1 software (Schlumberger, Houston, Texas, USA) was used to determine the burial and thermal history of Bekhme-1 Well. Data was obtained from the Ministry of Natural Resources, Erbil, on November 3, 2019, which included data about the top and base thickness, the lithology of the geological units, and the borehole temperature. The TOC wt%, hydrogen index (HI), and T_{max} of the organic matter from several formations were collected from the study by Ali (2018). The geothermal gradient value in the studied area was obtained from Abdula (2017a) and the sea levels during the deposition of the existing formations were obtained from Jassim et al. (2006). Adobe Illustrator CC 2019 was used to draw the geological column and Geological Information System software was used to draw a regional map of the region.

Formation names with their top and base boundaries, formations thickness, eroded amount, duration of none deposition, the main lithology of the geological units, the role of each formation in the petroleum system, TOC wt%, kinetics, and HI are presented in Table 1. The thermal conductivity and heat capacities are distinguished by the thermal properties of the different types of rocks by the user or programmed by default. The bottom well temperature was obtained from the well log header for the well that was used in the modelling (Figure 2).

Mathematically calculated T_{max} values and their equivalent %Ro values, as determined by Rock-Eval pyrolysis, were used for calibration. The T_{max} values have been reported by Abdula (2015) and Abdula (2017b).

It is reasonable to assume that the heat flow changed over time, but it has not been necessary to make assumptions about when the heat flow changed because the use of a constant heat flow over time has led to an appropriate context visualization of the %Ro value, as determined by EASY%Ro (Sweeney and Burnham, 1990).

The average surface temperature of all the burial history sites was estimated to be 21°C based on data recorded by the Iraqi Meteorological Organization and the Seismology-Kirkuk station for the years from 2010 to 2015 and from the results from this study. This means that the surface temperature is 4°C less than the data used by Pitman et al. (2004) for the southern part of Iraq.

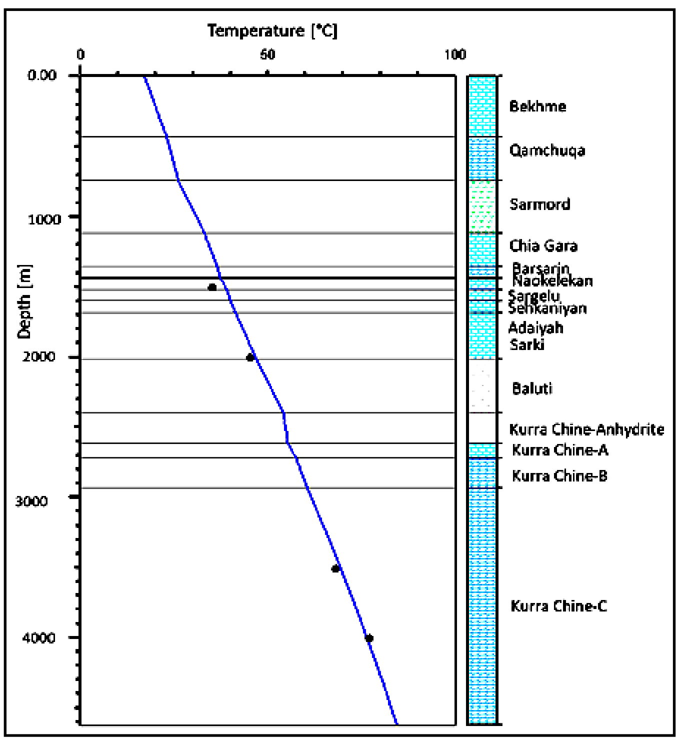

Figure 2. PetroMod software modelling of the temperature vs depth for the Bekhme-1 Well of the Akri-Bijeel Oil Field

Table 1: Formation names with their top and base boundaries, formation thickness, eroded amount, duration of none deposition, main lithology of geological units, the role of each formation in the petroleum system (PSE), TOC, kinetic, and HI values (data from Ali, 2018)

Formation	Top (m)	Base (m)	Thickness (m)	Eroded (m)	Depo. from (Ma)	Depo. to (Ma)	Eroded from (Ma)	Eroded to (Ma)	Lithology	PSE	TOC (wt.%)	Kinetic	HI (mg HC/g TOC)
Bekhme	11	430	419	3500	89.6	75	75	0.1	limestone, dolomitic limestone	Reservoir rock			
Qamchuqa	430	740	310	100	119	99.6	99.6	89.6	limestone, dolomite	Reservoir rock			
Sarmord	740	1120	380		129	119			marl, marly limestone	Reservoir rock			
Chia Gara	1120	1357	237		148	143			shale, limestone	Source rock	1.47	Burnham (1989), TII	152
Barsarin	1357	1435	78		153	148			limestone, dolomitic limestone, anhydrite	Seal rock			
Naokelekan	1435	1440	5		165	153			shaly limestone, dolomite, limestone	Source rock	2.5	Burnham (1989), TII	550
Sargelu	1440	1524	84		177	165			limestone, shale	Source rock	1.6	Burnham (1989), TII	550
Sehkaniyan	1524	1602	78		186	177			limestone, dolomitic limestone	Reservoir rock			
Adaiyah	1602	1687	85		191	186			limestone, anhydrite, shale	Reservoir rock			
Sarki	1687	2015	328		200	191			limestone, shale, anhydrite	Reservoir rock			
Baluti	2015	2397	382		202	200			shale, limestone, dolomite	Seal rock			
Kurra Chine Anhydrite	2397	2615	218	170	209	205	205	202	anhydrite, dolomite	Seal rock			
Kurra Chine-A	2615	2723	108		210	209			anhydrite, dolomite	Reservoir rock			
Kurra Chine-B	2723	2934	211		214	210			dolomite, anhydrite, shale	Reservoir rock			
Kurra Chine-C	2934	4625	1691		227	214			dolomite, shale	Source rock			

Three members (A, B, and C) of the Kurra Chine Formation have been recognized.

They are characterized by 3 broad carbonate evaporation cycles.

3. GEOLOGICAL SETTING

Iraq is located in the northeastern part of the Arabian Plate and has been severely affected by its structural position in the major geological units of the Middle East (Jassim and Buday, 2006). The Akri-Bijeel Block is located in the northeast of Iraq on the border between the Arabian part of the African Platform (Nubia-Arabian) and the Asian branches of the Alps Tectonic Belt (Jassim and Buday, 2006) (Figure 3).

From Bijeel's counterline to Akri and Bakrman (Figure 4), it is very common to find very steep dipping layers in the area with Mesozoic units in the limb of the anticline. Many thrust exposures are found at the southern limb of the Aqra and Pirat anticlines and 1 at the northern limb within both existing anticlines (Figure 4) suggesting that thrusts are underlying the limbs of these major folds (Csontos et al., 2012; Abdula et al., 2017).

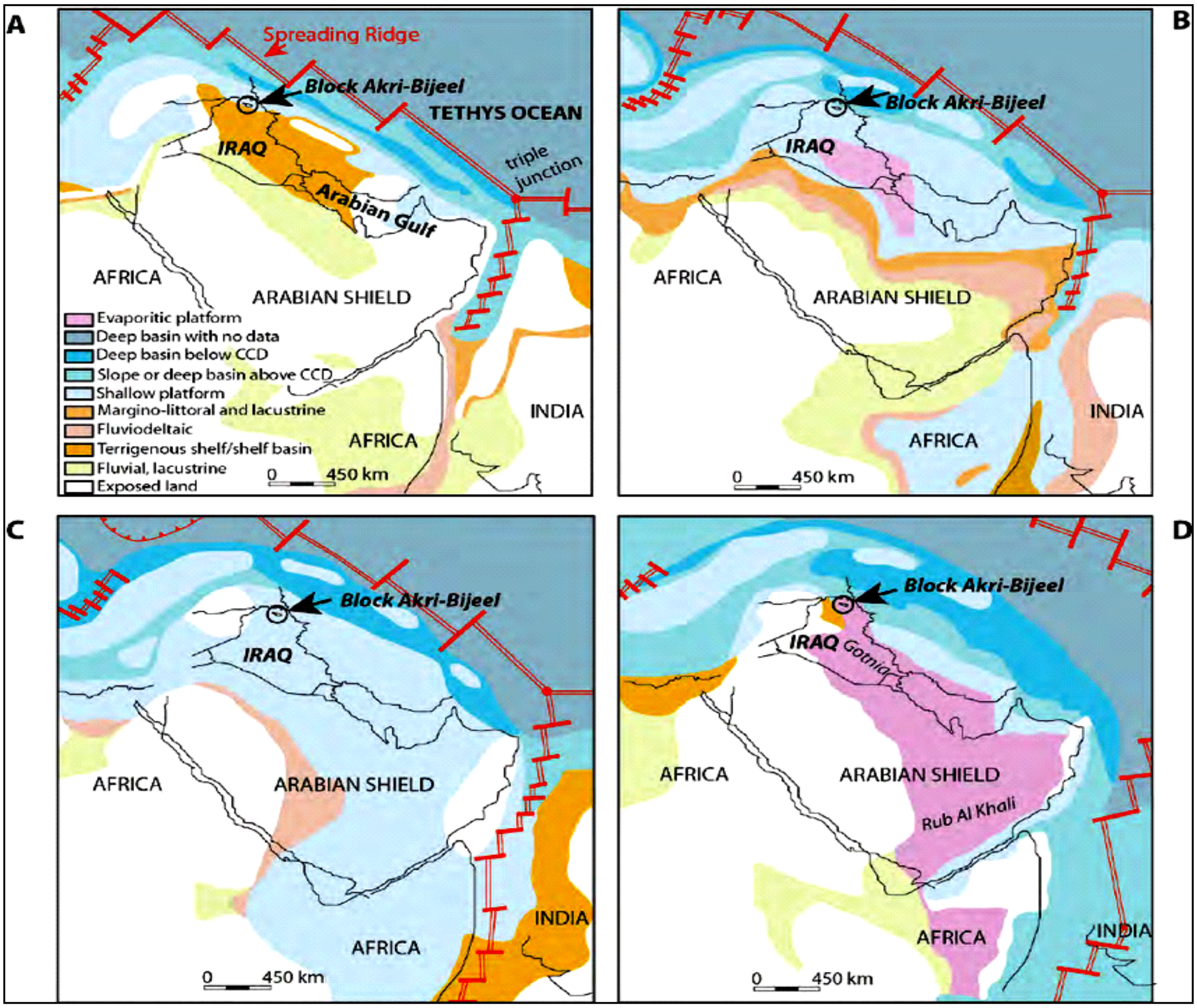

Figure 3. Palaeogeographic reconstruction of the region: Upper Triassic (A); Lower Jurassic (B); Middle Jurassic (C); and Upper Jurassic (D) (according to Al-Husseini, 1997)

3.1. Stratigraphic Setting

At the southern shelf of the Tethys Ocean, the bulk of the Permian-Eocene sequence was deposited. The entire sedimentary succession may be more than 10 km thick and may begin with a ductile Late Precambrian series. It is crowned by a successive series of Palaeozoic with a thickness of several thousands of meters in which shallow-water carbonates in the Chia Zairi (Permian) and Kurra Chine (Triassic) formations form thicker and stiffer units with local anhydrite. The stratigraphy of the Bekhme-1 Well is shown in Figure 5.

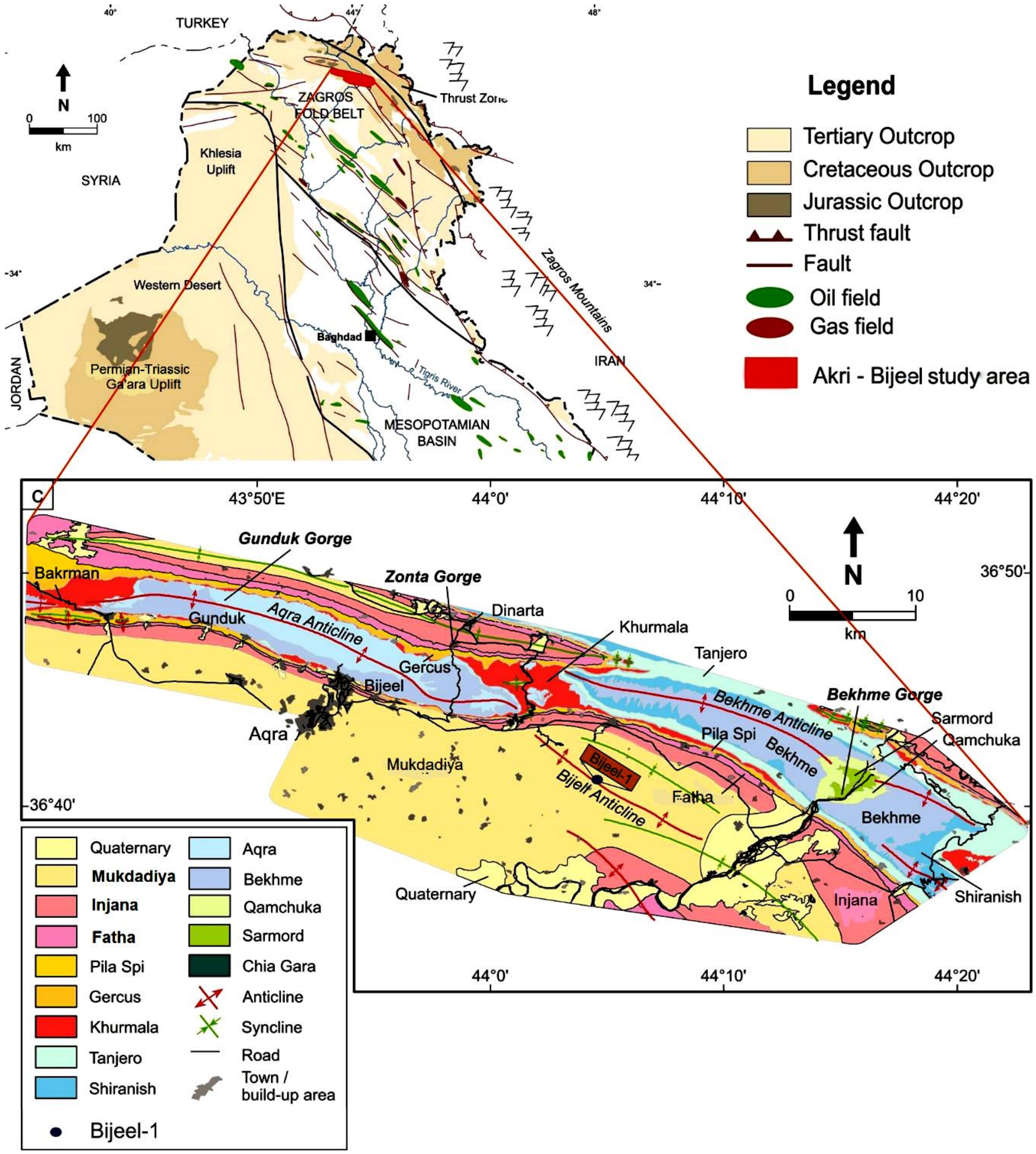

Figure 4. The upper part is a map of Iraq showing the location of the studied well, the folded belt of Zagros, and the main oil and gas deposits of the region (according to Pitman et al., 2004). The lower part is a geological map of the area showing the 2 main anticlines and displaying the Mesozoic formations to the north that correspond to the Aqra anticline (west) and Bekhme (east) (according to Csontos et al., 2012)

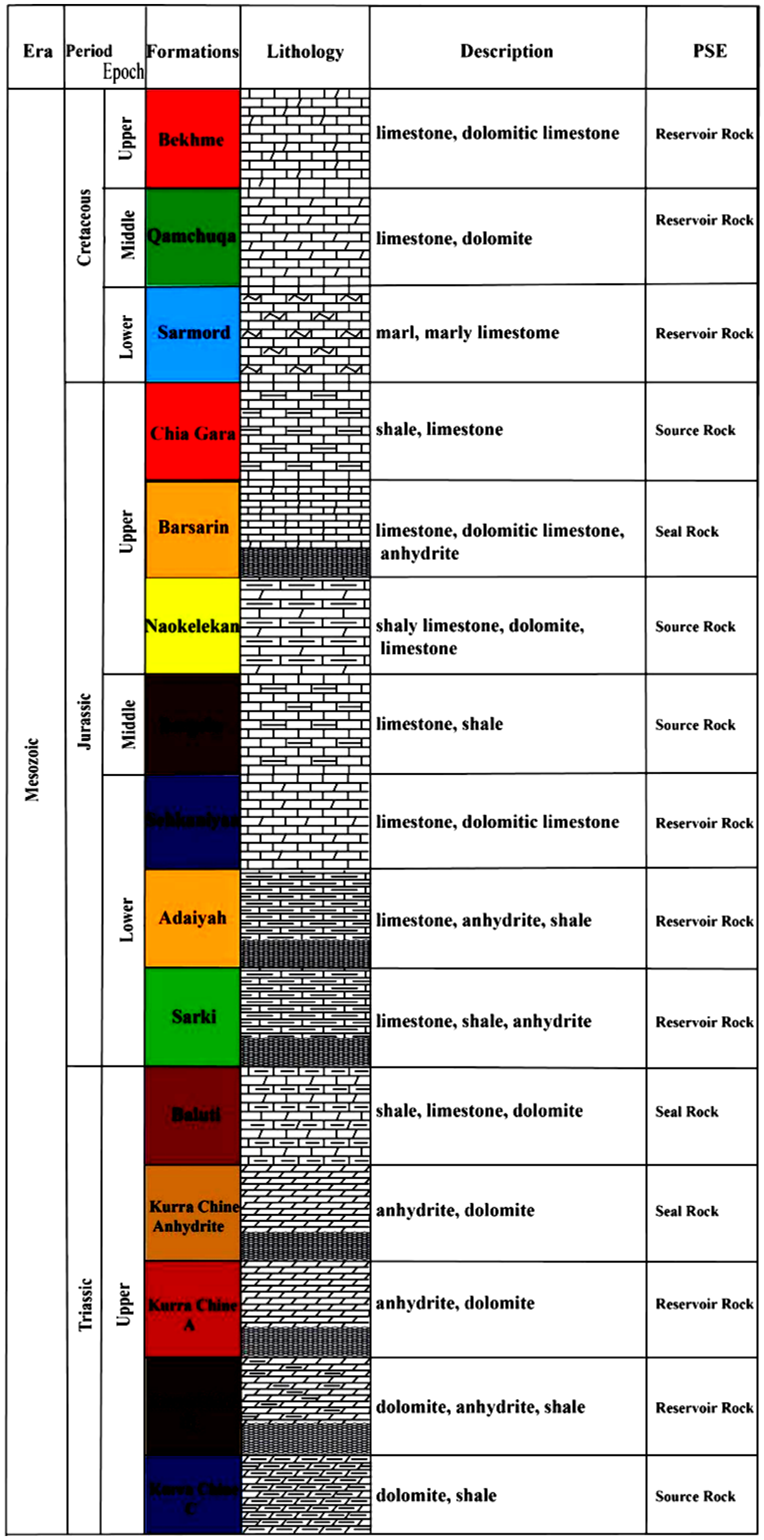

Figure 5. Generalized stratigraphic column of the Triassic-Cretaceous sequences in the Akri-Bijeel oil field

3.2. Structural Setting

The oil exploration area is located at the front of the Zagros compression belt. The structural evolution of the area was affected by the collision of the Arabian Plate with the Eurasian Plate. The deformation can be divided into the following 2 phases: the northwesterly and southwesterly forwarded stress and the subsequent north-south strain (Csontos et al., 2012).

The most important structural elements of the oil exploration area include a considerable north and northeast thrust, the Bijeel anticline in the south of the thrust, and a raised, high anticline in the southern corner of the block, which is the Safeen Mountain. The northern thrust consists of 2 segments, namely the Aqra anticline and Pirat anticline. The larger Bijeel anticline is located between the Bekhme and Safeen structures and their axes cross in a southwestern-northwestern direction (Figure 6).

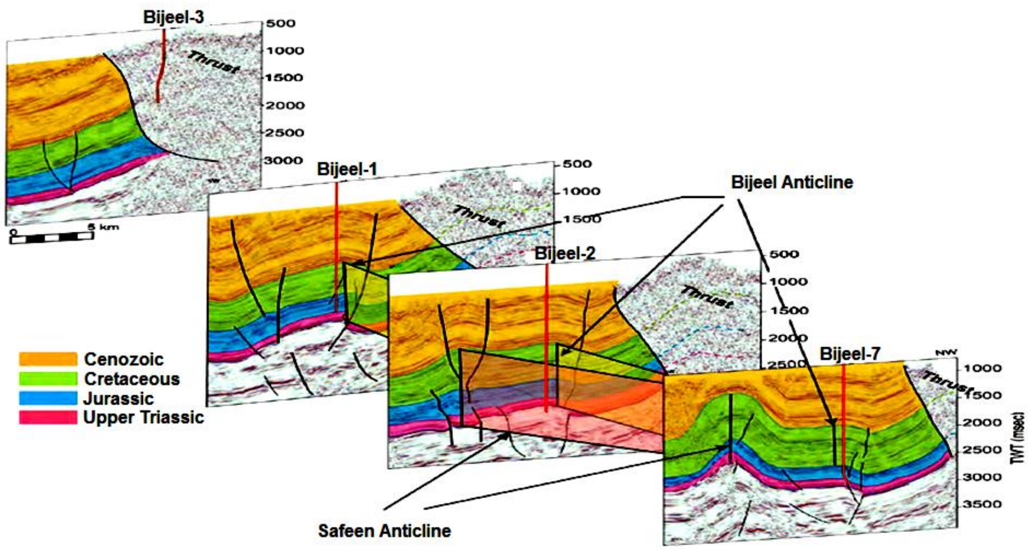

Figure 6. The Akri-Bijeel Block structure based on seismic sections. A total of 3 main elements can be identified as follows: the northeast direction (Bekhme anticline line); a southern retreat, here referred to as the Safeen line; and the central retreat, the Bijeel resistance line. Only the northern part of the Safeen structure is inside the Akri-Bijeel Block (the rest is outside the block); it becomes smaller and plunges in the northwest. The anti-Bijeel axle closes with an outbreak of the Safeen and Bekhme anticlines. Note that the Bijeel oil production structure is bounded by the northwest area of the Bijeel-1 Well and the Shaqlawa area (Al-Husseini, 1997)

4. BASIN MODELLING PARAMETERS

Basin modelling allows calculation of the thermal history and retreat of the basin to predict the quantities and distribution of oil in a given area (Lerche, 1990a, b).

Basin and petroleum systems modelling aim to predict the distribution and movement of petroleum within the basin and determine the generation, migration, and accumulation of hydrocarbon in addition to the temperature and pressure histories (Hantschel and Kauerauf, 2009). The following are the main parameters that were used for the modelling : borehole temperature, paleo water depth (PWD), heat flow, TOC, and other Rock-Eval pyrolysis parameters.

4.1. Borehole Temperature

Borehole temperature is the temperature measured in wells. Although the temperature of the Earth's crust generally increases with depth, the relationship between the temperature and depth is not straight or linear because it changes according to the thermal conductivity of the geological units (Figure 7). The geothermal gradient values depend on thermal conductivity and are therefore linked to rock types that are generally not uniform across the section. It can be determined by the following equation:

Geothermal gradient = (Formation temperature−mean surface temperature)/ (formation depth).

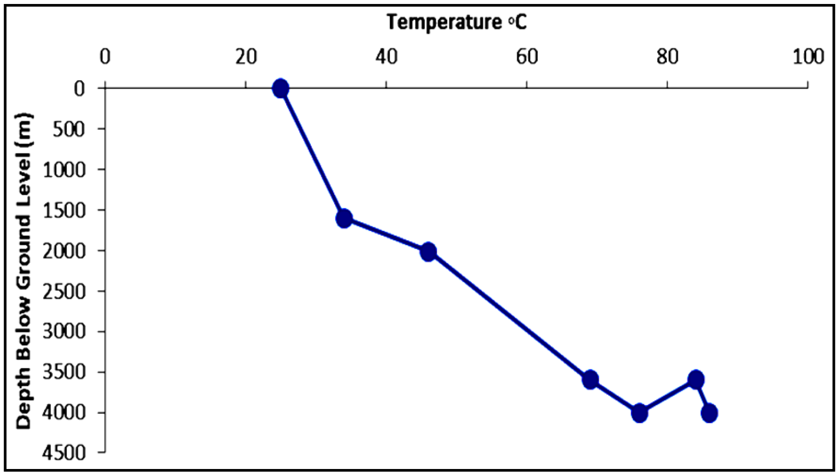

Figure 7. Borehole temperature vs depth for the Bekhme-1 Well

4.2. Paleo Water Depth

Sea level changes have occurred throughout Earth's history. The timing and magnitudes of sea level changes are extremely variable. It offers a good overview of Earth's tectonic and climatic history, but it is still difficult to pin down exactly. The ever-changing tidal currents are small when compared with the long-term fluctuations in Earth's history. Sea levels can change if tectonic forces move the land up or down. A change in sea level must be caused by 1 of the following 2 events: (1) changes in the volume of water in the oceans, or (2) changes in the size of ocean basins. Figure 8 shows the PWD from the Triassic period to the Neogene in the Iraqi Kurdistan Region.

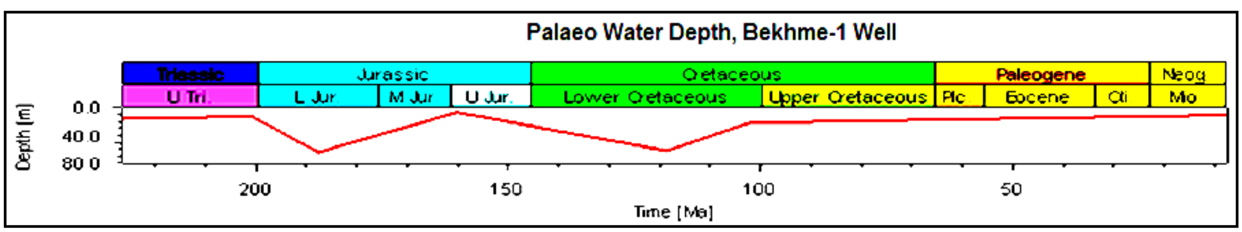

Figure 8. Sea level change from the Upper Triassic period to Neogene in Iraqi Kurdistan Region

4.3. Heat Flow

The heat flow is an important parameter in basin modelling , but it is difficult to define for pervious geologic times. However, the palaeo-heat flow models are usually calibrated using thermal maturity measurements, such as the %Ro values and Rock-Eval pyrolysis T_{max} data (He and Middleton, 2002; Hakimi et al., 2010; Shalaby et al., 2011, 2012; Aldega et al., 2014; Mashhadi et al., 2015). In this study, the palaeo-heat flow for the study area was estimated by calibrating the models to the calculated vitrinite reflectance (%Ro) (from the T_{max}). The paleo-heat flow is the result of the fit between the measured and modeled vitrinite reflectance profiles (He and Middleton, 2002; Hakimi et al., 2010; Shalaby et al., 2011, 2012; Aldega et al., 2014; Mashhadi et al., 2015). However, the palaeo-heat flow, together with the erosion periods, has a significant effect on the modeled maturity (Hakimi and Abdullah, 2015; Hadad et al., 2017; Makeen et al., 2016). The palaeo-heat flow modelling results for the studied well indicate a warm history with a constant change in the heat flow rate during the Upper Triassic to Palaeocene (49–52 mW/m^2), followed by a significant decrease during the Late Palaeocene to Miocene (48–23 mW/m^2). The present-day heat flow values were also estimated and were inferred from obtaining a good fit between the modeled and measured bottom-hole temperatures.

4.4. Total Organic Carbon and Rock-Eval Pyrolysis Factors

Several representative samples from the Bekhme-1 Well were gathered and analyzed. The samples were from the Bekhme, Qamchuqa, Sarmord, Chia Gara, Barsarin, Naokelekan, Sargelu, Sehkaniyan, Adaiyah, Sarki, Baluti, and Kurra Chine formations. By using Rock-Eval pyrolysis, potential hydrocarbon parameters, which include the type and amount of kerogen and thermal maturity, were determined by analyzing the 15 collected samples. The average TOC wt% content of the samples from the Chia Gara, Naokelekan, and Sargelu formations was 1.47, 2.50, and 1.60 wt%, respectively. Consequently, they can be considered as good source rocks. The organic matter belongs to types II and III kerogens that were derived from marine and nonmarine organic materials, and is oil and gas prone. The values for T_{max} range from 441˚C to 450˚C, averaging 446˚C, and the calculated vitrinite reflectance ranges from 0.78 to 0.94 %Ro, with an average of 0.88 %Ro (Ali, 2018).

5. RESULTS AND DISCUSSION

The results of 1-D modelling show the burial history and tectonic subsidence (Figure 9). Based on the geologic model of depositional and erosional events, the burial and subsidence history of sedimentation can be evaluated in absolute time.

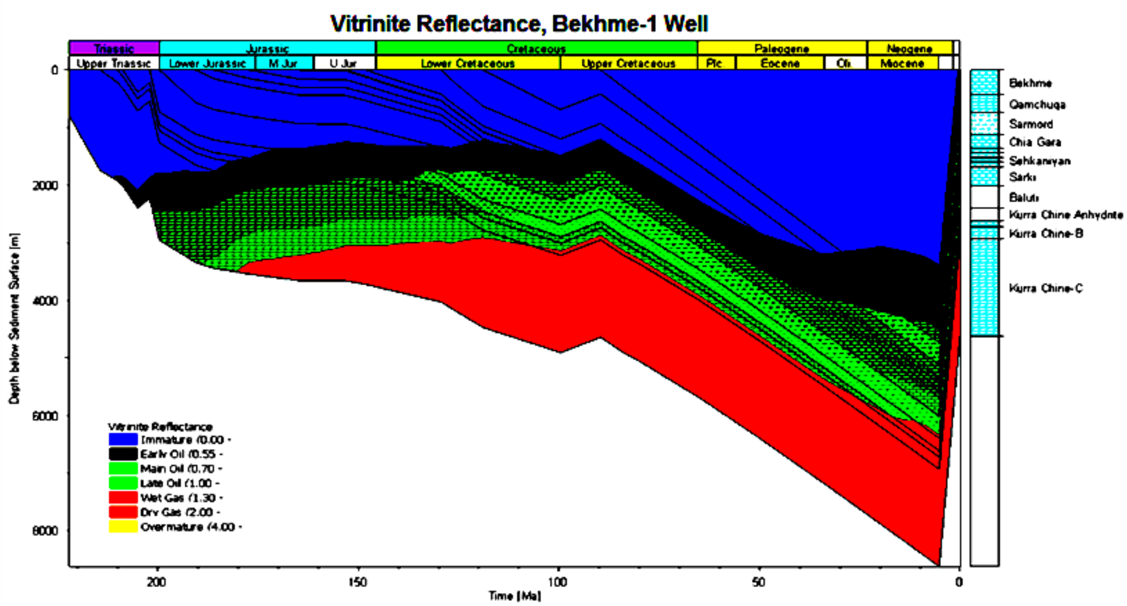

Figure 9. Thermal, burial, and subsidence history curves at the Bekhme-1 Well

The expelled and migrated oil was preserved in the Lower Cretaceous reservoirs (Figure 10). The source rock from the Sargelu Formation was formed by the Middle Jurassic time. The modeled burial and subsidence history curves in the Bekhme-1 Well show that the Triassic Period had a short burial history of approximately 227.76 to 199.60 Ma and is associated with relatively low subsidence rates and a thickness of about 2000 m. From the Jurassic to Lower Cretaceous time (~199.60–127.96 Ma), the subsidence rates and sedimentation rates increased and reached a thickness of 3400 m.

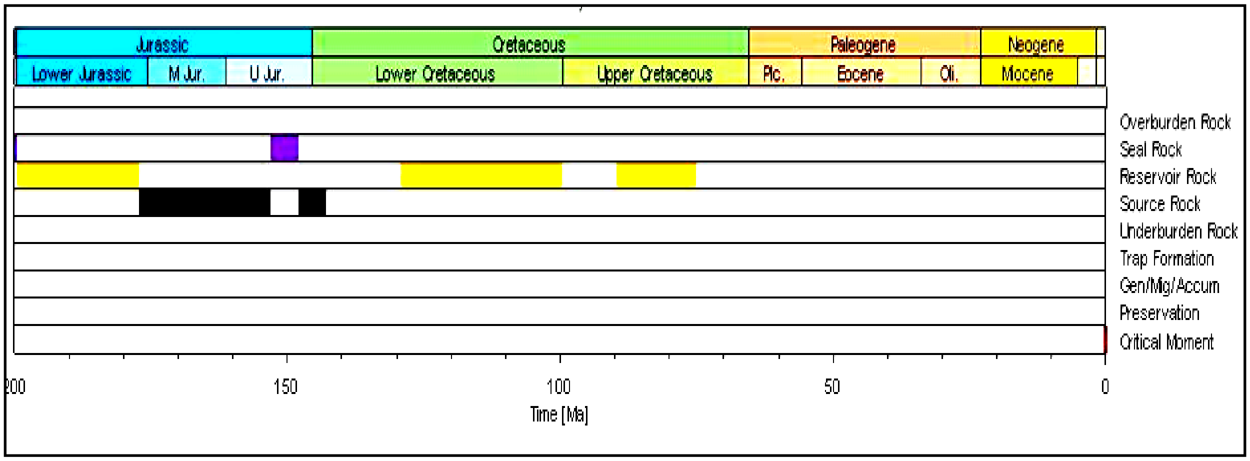

Figure 10. Events chart showing the timing of the essential elements and processes of the complete petroleum system in the Behme-1 Well

During the Upper Cretaceous to the end of the Miocene time (~100.5–5.333 Ma), there was a sharp change in the subsidence and sedimentation rates, which reached nearly 7100 m. The burial and subsidence history curves also indicate 3 main periods of unconformity and erosion events in the Kurdistan Region, namely the Upper Triassic–Lower Jurassic, Upper Cretaceous, and Pliocene. These events and the associated heat flows affected the rate of thermal maturity in the area (Makeen et al., 2016; Hadad et al., 2017).

In the basin modelling software program, the maturity simulation is a kinetic equation that shows the level of maturity. This equation is a function of time and temperature. The model has an average of 1000 m of erosion above the Bekhme Formation, implying that the underlying rocks were buried deeper than its present-day situation. The temperature was higher (50ºC–60ºC) and the rocks became more mature at that depth when compared with the erosion model. The Chia Gara Formation reached the early oil window at around 60 Ma in the Palaeocene, however, the Naokelekan and Sargelu formations entered the early oil window during the Lower Cretaceous at about 108 and 112 Ma, respectively.

Based on the 1-D basin model, the petroleum system of the Akri-Bijeel oil field shows that the Palaeogene formations, such as the Kolosh, is immature.

The Jurassic–Lower Cretaceous formations, such as the Chia Gara, Naokelekan, and Sargelu reached the late oil window during the Late Miocene (%Ro=0.84, 0.88, and 0.90, respectively). Because of uplifting, these source rocks have ceased to mature further in the Bekhme-1 Well (Figure 9 and Figure 11). The Triassic formations, such as the Geli Khana, are thought to have a high maturity, with %Ro values of ≥1.3%, and are thought to be in the wet and dry gases window. The older formations are in an area where hydrocarbons or fully dry gases are produced and depleted after the oil is expelled and carried over to the rock traps in the sedimentation structure.

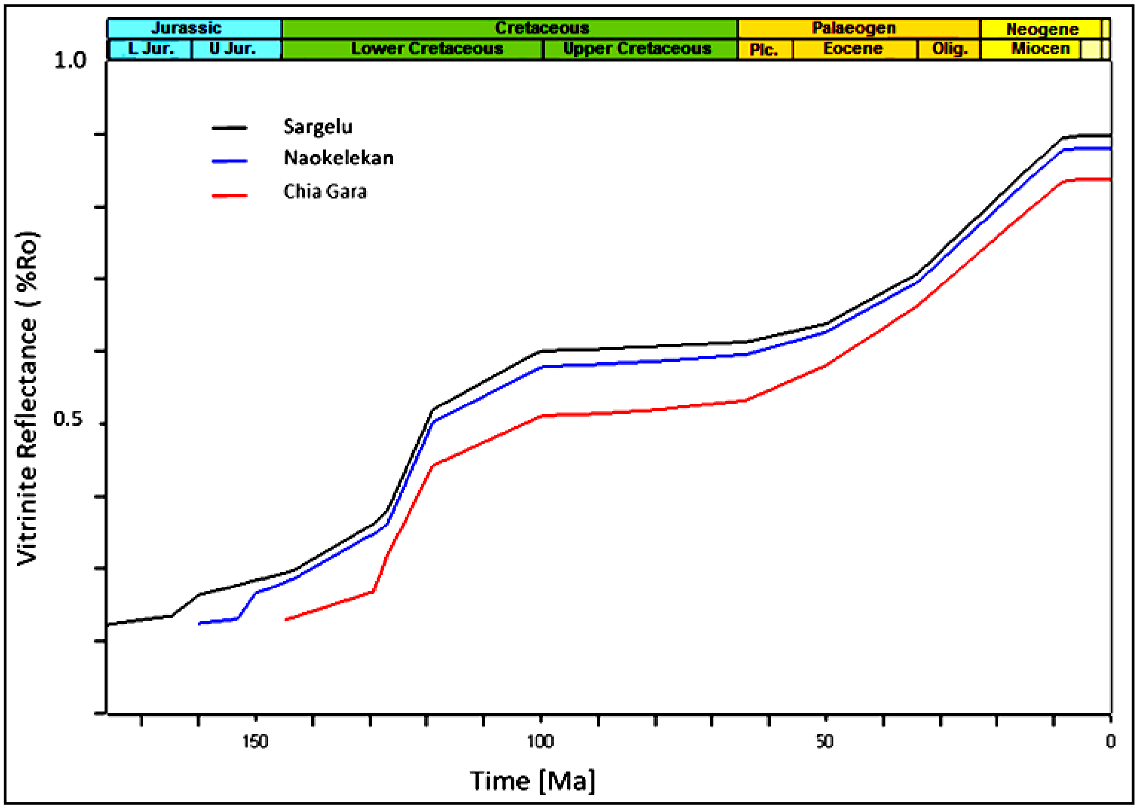

Figure 11. Time plot of the vitrinite reflectance (%Ro) at the Bekhme-1 Well. The data that were used to construct the curve were calculated mathematically from the T_{max} values

6. CONCLUSIONS

Based on the history of the burial for oil production in the region, the Jurassic–Lower Cretaceous formations, such as the Chia Gara (%Ro=0.84), Naokelekan (%Ro=0.87), and Sargelu (%Ro=0.90) formations, are considered to be mature because of their %Ro values >0.55%. Other formations, such as the Geli Khana and other Triassic formations have a high maturity, with %Ro values of ≥1.3%, and are in the wet and dry gases windows. The older formations are in an area where hydrocarbons or fully dry gases are produced and depleted after the oil is expelled and carried over to the rock traps in the sedimentation structure.

ACKNOWLEDGMENTS

The authors would like to thank Dr Ayad N. F. Edilbi for helping with the presentation of the enclosed figures.

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