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ORGANIC GEOCHEMISTRY AND THERMAL HISTORY MODELING OF THE UPPER PART OF KURRA CHINE FORMATION (UPPER TRIASSIC) FROM BUTMAH-15 WELL, NORTHWESTERN IRAQ

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Abstract

The potentiality of the upper part of the Kurra Chine Formation (Late Triassic) for hydrocarbon generation in northern Iraq was assessed using data from the Butmah-15 well. Total organic carbon (TOC) and Rock-Eval pyrolysis analyses were conducted on nine rock samples; biomarker analysis was carried out for two samples, after extraction of the bitumen, to determine the paleodepositional environment conditions. The examined interval has low TOC values (< 0.5 wt.%) and limited potential for hydrocarbon generation. Thermal history modeling results suggest that the high TOC intervals in the lower part started oil generation from the Middle Jurassic (~170 Ma) to the end of the Early Cretaceous (~ 100 Ma), and reached the end of the oil window at the end of the Miocene. Maturity parameter values (biomarkers and Tmax) indicate early to mid-mature organic matter. Normal alkane distribution shows the dominance of short chains over long chains and suggests that the organic matter is mainly of marine origin. $C_{35}S/C_{34}S$ and Pr/Ph ratios suggest that the examined interval was deposited under low oxygen conditions (suboxic-anoxic).

Keywords: Kurra Chine; Butmah; Biomarkers; Thermal history; Source rocks.

1. Introduction

The Late Triassic Kurra Chine Formation is composed mainly of limestone, with some intervals of dolomite and fissile shales (Jassim & Goff, 2006). The formation contains some gypsum lenses at the outcrop near the Sirwan area, and salt, anhydrite, and sandstone beds were recorded in the Mileh Tharthar-1 well (Jassim & Goff, 2006). Toward central Iraq, the

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lower part of the formation becomes increasingly clastic (Sadooni, 1995). In northern Iraq, the Kurra Chine Formation regressive facies (tidal facies) were deposited during the Early Carnian on an epeiric platform (Sadooni & Alsharhan, 2004).

Although Jurassic and Cretaceous petroleum systems are the most important petroleum systems, where the Sargelu Formation is the most important source rock for Cretaceous oils (e.g., (Abdula, 2015; Alkhafaji et al., 2023); (Al-Essa & Alkhafaji, 2024a; (Al-Essa & Alkhafaji, 2024b), and oil seepage in northern Iraq (Alkhafaji et al., 2020), the Triassic is an important system in northwestern Iraq, with the Kurra Chine Formation providing the source, reservoir, and seal. Potential source rocks are represented by the mudstone rocks interbedded with evaporites (Aqrawi et al., 2010). Kurra Chine Formation is the oil reservoir in the Alan, Butmah, and Sufaiya oilfields in northwestern Iraq, and in Rumailan, Tishreen, Souedie, and Jebbissa in Syria (Sadooni, 1995). In northern Iraq, it is also the oil reservoir in the Shaikan oilfield (Baban & Ahmed, 2021), and is one of the main targets for future hydrocarbon exploration (Edilbi et al., 2019). Previous studies of the hydrocarbon potential of the formation in northwestern Iraq (Al-Ameri et al., 2009; Al-Dolaimy et al., 2021) recorded poor to good potential for hydrocarbon generation and contains type II and III kerogen. Awdal et al. (2016) studied the Kurra Chine Formation based on the outcrop samples in northern Iraq, and they found a high fracture in the dolomite rocks with secondary porosity. Edilbi et al. (2019) studied the source rock of the Kurra Chine Formation and found thermally mature organic matter. In central Iraq, (Al-Dolaimy et al., 2021b) report marine algal and bacterial organic matter (OM) deposited under anoxic conditions within the Kurra Chine Formation. In the Kurdistan Region of northern Iraq, shale beds contain poor to good potentiality for oil generation, with mature type III and II/III kerogen (Edilbi et al., 2019). In the Butmah oilfield, the composition of the oil reservoir in the upper part of the Kurra Chine Formation, which is suggested to be generated from the Kurra Chine Formation, differs from that of the Cretaceous reservoirs (Dunnington, 1958). In Syria, the Kurrachine Formation is considered a source rock for Mesozoic reservoirs in the northeast Palmyrides oilfields (Abboud et al., 2005). The average TOC values of shale beds is 1.0 wt.%, and the organic matter is mature (Barrier et al., 2014).

This study aims to investigate the depositional environmental conditions, type of OM, their thermal maturity level, and source rock potential of the upper part of the Kurra Chine Formation, recorded in the Butmah-15 well (Figure 1), using a range of organic geochemical analyses; in addition to simulating the thermal history of the basin.

2. Geological Setting

The rifting of the Arabian Plate's passive margin during the Triassic time led to the formation of an intra-shelf basin in Mesopotamia (Numan, 1997). This rifting is followed by subsidence during the Late Triassic-Early Jurassic time. In western Iraq, the Rutba uplift, a narrow ridge, was developed during the early-mid Triassic. About 2 Km of Late Triassic carbonate and evaporites were deposited on an extended platform in northern Iraq. Three main facies were deposited on that platform during the Late Triassic: clastic and carbonates (Zor Horan and

Mullusa formations) in the Stable Shelf, carbonate-evaporites in the Low Folded Zone, and restricted lagoonal facies represented by Baluti and Kurra Chine formations in the High Folded Zone (Jassim & Goff, 2006); it is also considered as a part of the Low Folded Thrust Zone by (Lawa et al., 2013).

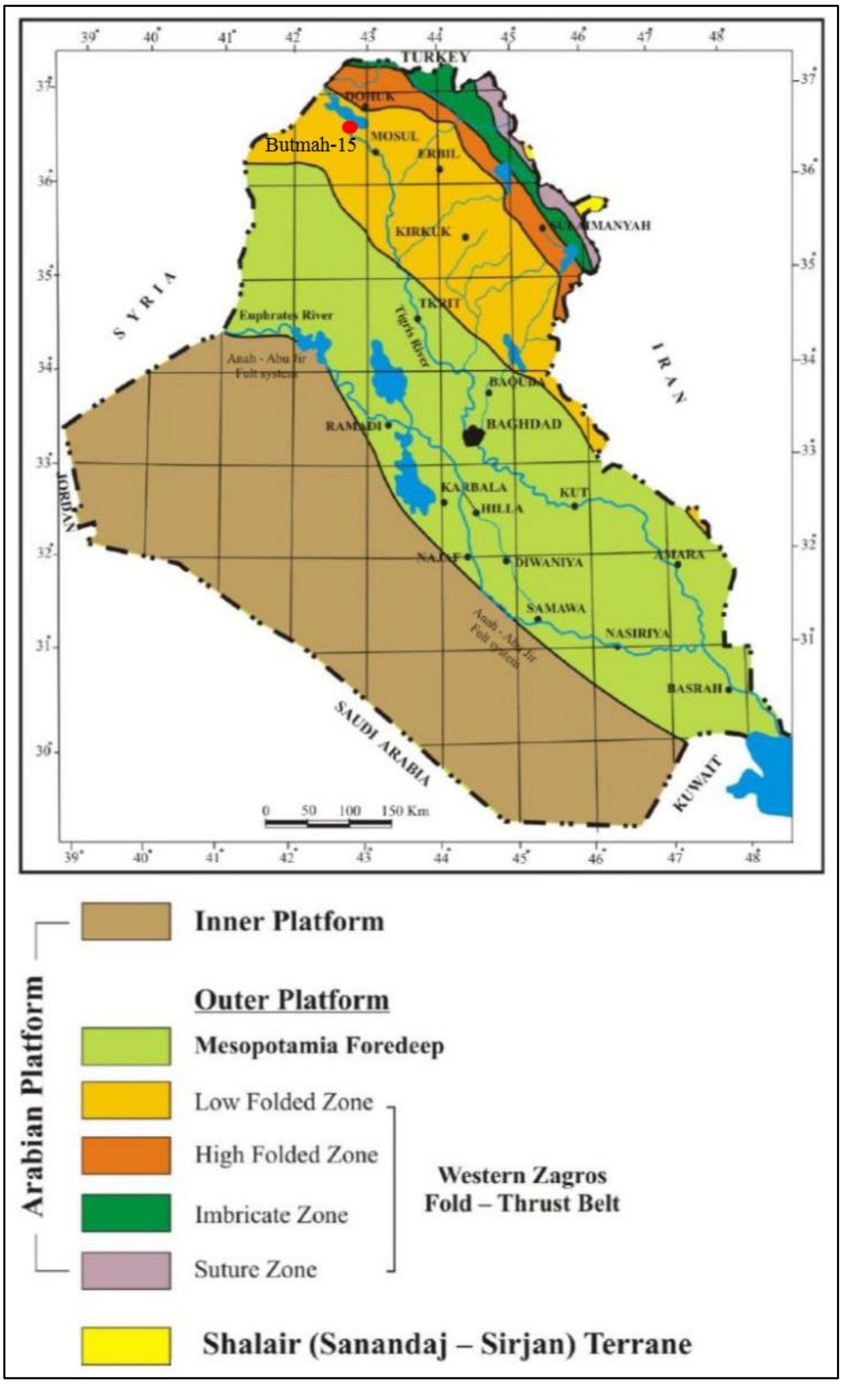

Figure 1. Tectonic map of Iraq (after Fouad, 2015) showing the well location (Butmah)

This Foothill Zone, in which the Butmah oilfield is located (Figure 1), contains thick Mesozoic-Cenozoic sequences (up to 1500 m). The internment uplift of this Zone during the Jurassic and Cretaceous led to the formation of ridges (submerged or exposed) (Jassim &

Goff, 2006). In the Paleogene, it became a foredeep basin, and during the late Neogene time the trough that filled by molasse sediments. This Zone contains northwest-southeast trending long anticlines and broad and deep synclines. The Foothill Zone can be divided into three transversal blocks: Kirkuk, Sinjar, and Mosul. The study area lies in the Mosul block (Jassim & Goff, 2006).

Kurra Chine Formation underlies the Baluti Formation and overlies the Galikhana Formation. The lower contact of the Kurra Chine Formation is unconformable, whereas its upper contact is conformable (Jassim & Goff, 2006). Al-Hamdani et al. (2021) studied the microfacies of Kurra Chine and found different depositional environments. Balaky et al. (2023) described shale as heterogeneous in the Kurra Chine Formation. In northern Iraq, subsurface drilled wells reached the Kurra Chine Formation, which can be found in Tawke Field, Swaratika Field, and Sarta Field. It shows limestone, dolomite, dolomitic limestone, shale, and gypsum.

3. Materials and Methods

Nine rock samples of the upper part of the Kurra Chine Formation from the Butmah-15 Well were collected from the North Oil Company (Kirkuk). Rock-Eval pyrolysis and TOC measurements were conducted for all samples, and two samples (K3 and K6) were selected for biomarker analysis. All these analyses were carried out at GeoMark Ltd, USA.

Samples for TOC analysis were decarbonated, filtered, and then placed into a LECO crucible. Then TOC measurements were undertaken using a LECO C230 instrument.

Rock-Eval pyrolysis was used for determining the free hydrocarbons already present (S1), the remaining petroleum potential of the kerogen (S2), the temperature of peak hydrocarbon generation during the S2 measurement (Tmax), and CO_2 gas (S3).

Bitumen was extracted from 5 g of powdered sample using dichloromethane as a solvent. Asphaltenes precipitated by pentane; then the extracts were fractionated into three fractions: resin (NSO compounds), aromatic hydrocarbons, and saturated hydrocarbons by liquid chromatography. Gas chromatography and Gas chromatography-mass spectrometry (GC-MS) were used to determine the biomarker ratios of the saturated and aromatic hydrocarbons monitoring ions 191, 217, 218, 221, 231 and 259 (saturated hydrocarbons) and 170, 178, 184, 188, 192, 198, 231, 239, 245, and 253 (aromatics).

4. Results and Discussion

4.1. Organic Richness

The total organic carbon (TOC) values of the analyzed samples are generally low, ranging between 0.18-0.41 wt.%, with the average at 0.28 wt.%. S2 values are also low; they are in the range of 0.27-0.85 (Table 1). According to ranges suggested by Peters & Cassa (1994), the present samples of the upper part of the Kurra Chine Formation from Butmah-15 would not be classified as petroleum source rocks.

Table 1. Rock-Eval pyrolysis, carbonate, and TOC data of the upper part of Kurra Chine Formation from Butmah-15.

No.	Depth (m)	TOC wt.%	CaCO3 wt.%	S1	S2	S3	Tmax ºC	HI	OI	PI
K1	2970	0.21	71.48	0.18	0.27	0.39	441	128	185	0.40
K2	2980	0.33	69.96	0.18	0.44	0.45	438	135	138	0.29
K3	3000	0.30	89.28	0.14	0.48	0.32	442	159	106	0.23
K4	3020	0.18	68.00	0.19	0.27	0.59	436	147	321	0.41
K5	3050	0.30	76.92	0.21	0.75	0.41	435	248	135	0.22
K6	3080	0.41	77.27	0.17	0.85	0.38	434	208	93	0.17
K7	3100	0.30	90.33	0.17	0.44	0.41	438	145	135	0.28
K8	3130	0.24	71.13	0.17	0.51	0.42	435	211	174	0.25
K9	3168	0.26	72.83	0.19	0.43	0.27	436	165	104	0.31
Average		0.28	76.36	0.18	0.49	0.40	437	171.86	154.60	0.28

Reported TOC values of the interval 3222 – 4337 m in the same well are between 0.03 – 3.04 wt.%, with an average of 0.9 wt.%. Al-Ameri et al. (2009). Seven samples in that published dataset have TOC between 0.03 – 0.6, and the other three samples have values between 1.99 and 3.04 wt.%. TOC values are > 2.0 and 2.7 wt.% in Ain Zala 29 (AZ-29) and Kand-1 (Kd-1), respectively(Al-Ameri et al., 2009). On the other hand, (Al-Dolaimy, et al., 2021a) recorded low TOC values in Ain Zala 29 and Kand-1 wells between 0.09 – 0.30 and 0.18 – 0.66 wt%, respectively. Generally, high TOC values are associated with shale intervals, while low TOC values are associated with limestone ones (Al-Ameri et al., 2009). In the Tawke oilfield, which is not far away from the Butmsh oilfield, the TOC values of the upper part of the Kurra Chine Formation (3870 – 4530 m) are in the range of 0.13 – 1.52, with an average of 0.55 wt.%. Aswad et al. (2023). The studied samples between 2970 and 3168 m are extremely rich in carbonate with an average of 76%. This is consistent with the very low values of TOC.

In the Kurdistan Region of northern Iraq, the shale beds are considered poor to good source rocks, with TOC values between 0.45 – 1.72 wt.%; hydrogen index values range between 184 – 600; and they contain mature mixed II/III and type III (Edilbi et al., 2019). Generally, the recorded TOC values of the shale intervals are higher than those of the limestone ones. These values indicate that most of the formation is poor source rocks and has low potentiality for hydrocarbon generation; whereas the good source rocks are restricted to the shale intervals within the Kurra Chine Formation, as previously recorded by Aqrawi et al. (2010).

4.2. Thermal Maturity

Tmax and production index (PI) values are between 434 – 442 ºC (with an average of 437 ºC); and 0.17–0.41, respectively (Table 1); indicating mature organic matter (early mature to peak oil window). Hopane and sterane biomarker ratios support this maturity level. The low C_{30} moretane/hopane ratio is 0.06 for the two samples. The ratio between

$$\frac{[\mathrm{C32S}\,\{17\alpha, 21\beta - \mathrm{bishomohopane}\ (22\mathrm{S})\}]}{[\mathrm{C32}S\,\{17\alpha, 21\beta - \mathrm{bishomohopane}\ (22\mathrm{R})\}\ + \mathrm{C32R}\,\{17\alpha, 21\beta - \mathrm{bishomohopane}\ (22\mathrm{R})\}]}$$

Was used to estimate the thermal maturity. The ratio in the range of 0.57 – 0.62 indicates the equilibrium phase (Peters et al., 2005). The value of the present study samples is (0.61 – 0.62) (Table 2). Moreover, the 20S/(20R + 20S) and ββ/(ββ + αα) of the C_{29} steranes ratios are 0.38 – 0.41 and 0.53 – 0.55, respectively (Table 2). These values suggest the organic matter has not yet reached the peak of the oil window, where they have not yet reached the equilibrium values (Peters et al., 2005). However, sterane isomerization measurement by GC-MS is generally less accurate than by GC-MS/MS. This maturity level of the organic matter deduced from biomarker ratios is consistent with the Tmax value and PI values. With the maturity level of the present study samples, other more robust maturity parameters, such as Ts/Tm and cracking ratio of the triaromatic steroids, are not useful because they are not sensitive at low thermal maturity levels (Peters & Moldowan, 2017).

Table 2. Bitumen fractions and GC parameters of the Kurra Chine samples.

Samp.	**Depth (m)**	**Satu.**	**Aro.**	**Resi.**	**Asph.**	**CPI**	**TAR**	**Pr/Ph**	**Pr/nC$_{17}$**	**Ph/nC$_{18}$**
K3	3000	36.67	23.33	40.00	0.00	0.97	0.16	0.76	0.31	0.48
K6	3050	20.41	18.37	57.14	4.08	0.90	0.09	0.91	0.34	0.50

The Tmax values of the examined samples for this study are similar to those of the Kurra Chine Formation recorded from other oilfields near Butmah (Al-Ameri et al., 2009), and they are slightly lower than those in the Kurdistan Region of north Iraq (Tmax between 429 – 450 ^{o}C; Edilbi et al., 2019). The Kurra Chine Formation is mature with Ro > 0.55% in Kand-1 Well (Abdula, 2017). This indicates that the thermal maturity level of the upper part of the Kurra Chine Formation of the present study is slightly lower than that at the Iraqi Kurdistan region, and could indicate that burial depth at the Iraqi Kurdistan Region is higher than that of the northwestern Iraq (present study area). Based on the thermal history modeling, the Kurra Chine Formation in northern Iraq reached the peak of oil generation and expulsion during the Middle Miocene (Edilbi et al., 2019). While the Kurra Chine Formation entered the oil generation window at Guwair-2 and Shaikhan-2 at 64 Ma and 46 Ma, respectively (Abdula, 2020).

4.3. Source of Organic Matter

Rock-eval pyrolysis parameters are widely used for assessing the kerogen type. The examined samples have low S2 values (0.27 – 0.85), low HI (128 – 248), and relatively high OI (93 – 321) (Table 1). From the pseudo and modified van Krevelen diagrams (Figure 2), it is evident that OM of Kurra Chine Formation is a mixed type II/III and III kerogen, suggesting mixed terrestrial and marine origin. This finding is similar to that suggested by Al-Ameri et al.s (2009) for the deeper interval (3222 – 4337 m) in the same well. Therefore, based on pyrolysis parameters, the organic matter of the shale intervals is mainly of terrigenous origin in northern and northwestern Iraq (Edilbi et al., 2019). On the contrary, molecular geochemistry results of K3 and K6 samples are inconsistent with the kerogen typing based on Rock-Eval pyrolysis parameters. Normal alkane, terpane, and sterane distributions (Figures 3 – 5) suggest that the OM of the examined samples is mainly of marine origin (see below).

Therefore, the general low HI and relatively high OI values of the examined samples may be due to poor preservation of the marine organic matter caused by deposition under oxic-suboxic conditions, which led to oxidation of the organic matter and/or microbial degradation due to temporary or permanent oxygenated bottom conditions (Omarini et al., 2020; Jirman et al., 2019). The second interpretation for the low HI values in the studied samples is the low productivity in the surface water. The presence of marine OM in the Kurra Chine Formation in other wells near Bm-15, such as Kand-1 well (Figure 1; (Al-Ameri et al., 2009) and in central Iraq (Al-Dolaimy et al., 2021b), supports the former assumption. Al-Ameri et al. (2009) noted that the depositional environment is characterized by oscillation of terrestrial and marine deposition.

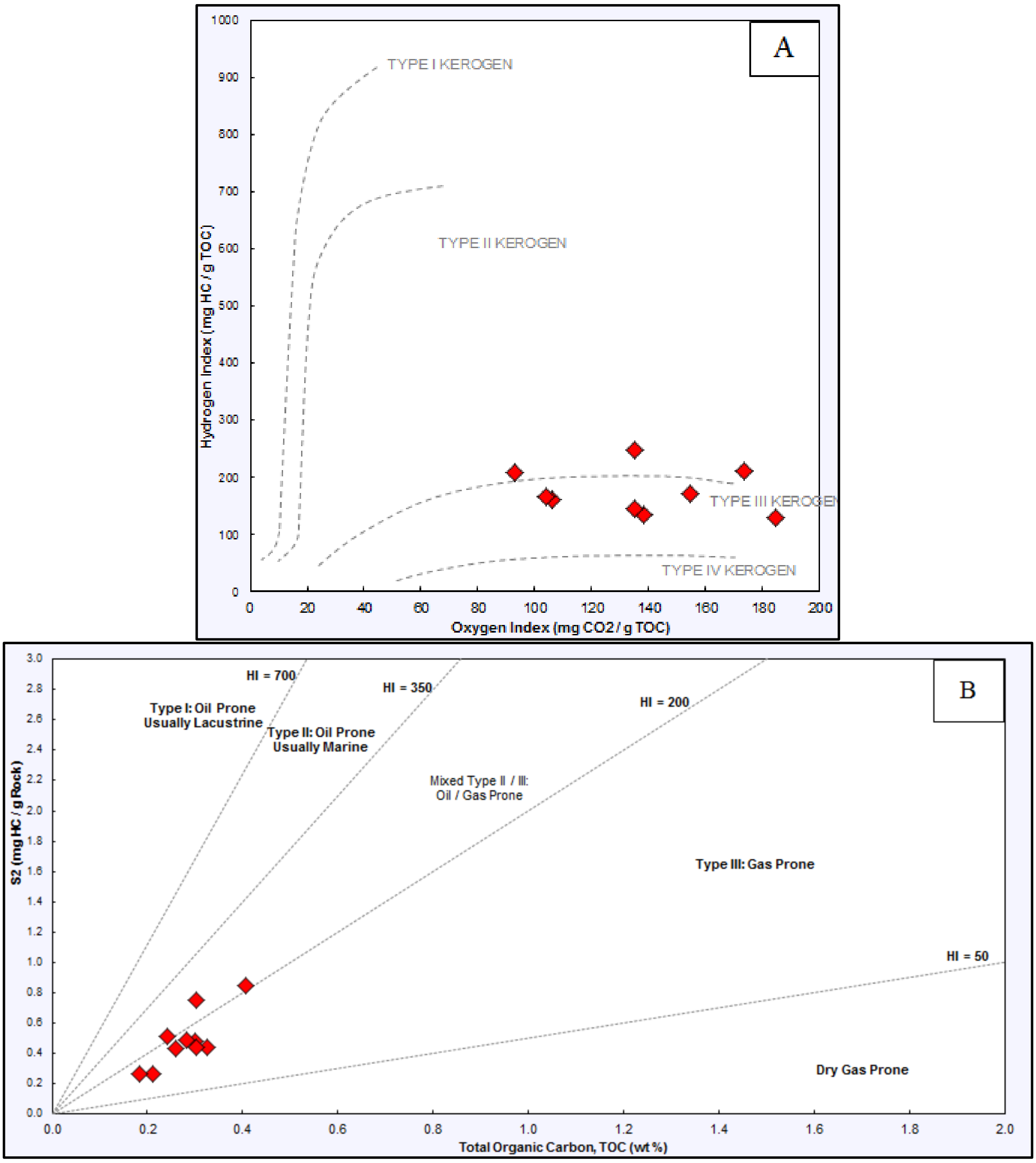

Figure 2. Kerogen typing based on (A) HI vs. OI and (B) S2 vs. TOC.

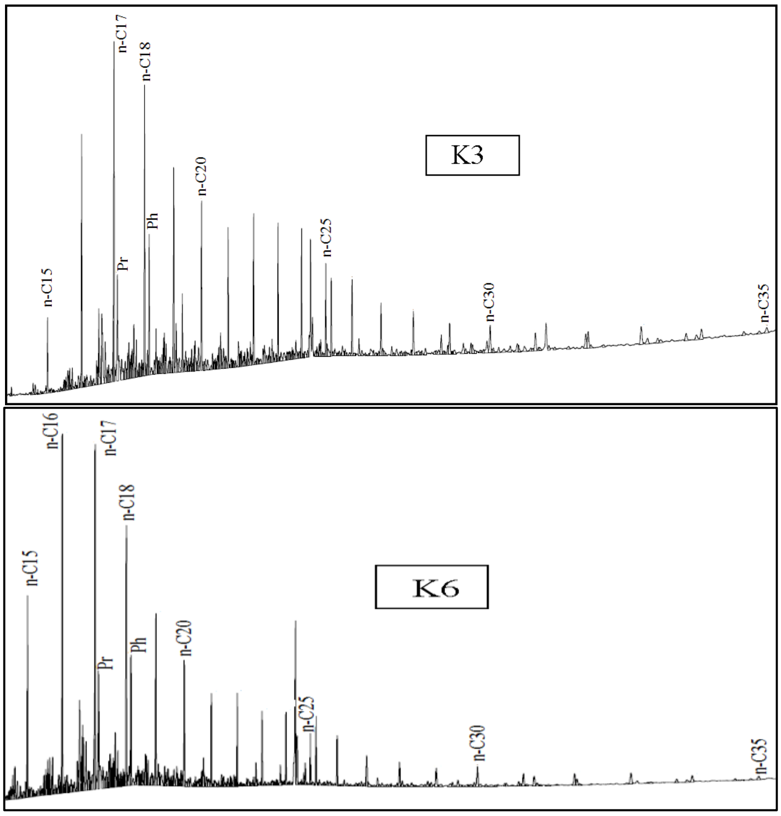

Figure 3. GC-FID of the whole extracts of K3 and K6 samples.

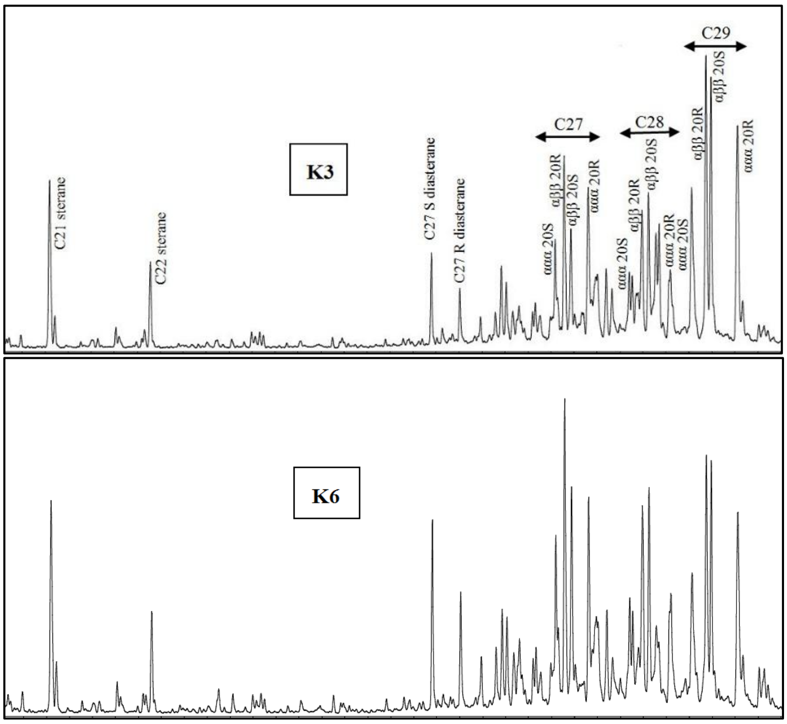

Figure 4. Sterane distributions of K3 and K6 samples.

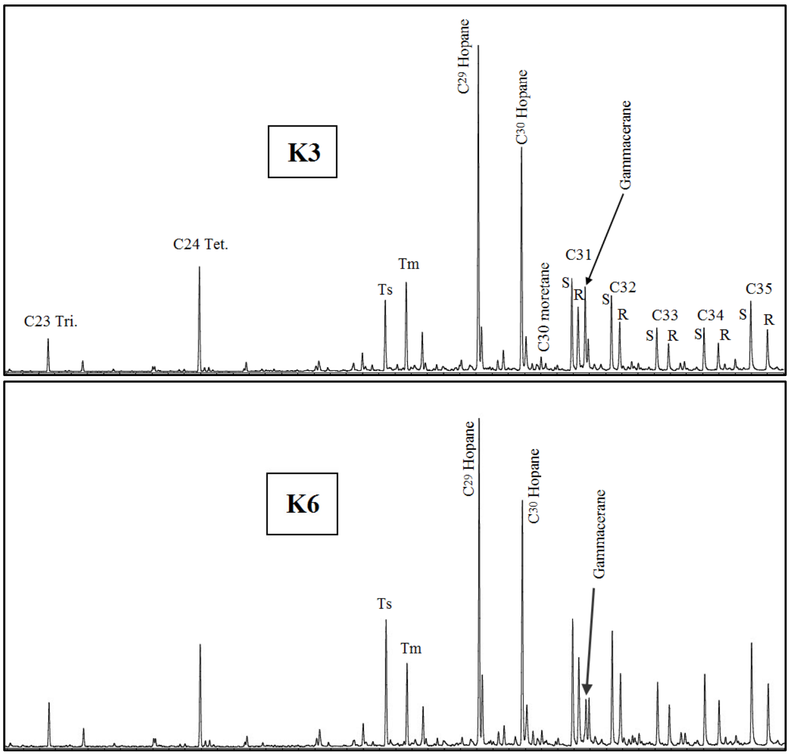

Figure 5. Terpanes distributions of K3 and K6 samples.

Normal alkane distributions reflect the origin of organic matter. In the immature source rocks, short-chain normal alkanes are produced from marine algae, and long-chain is derived from land plants (Peters et al., 2005). The normal alkane distribution of the two examined samples is unimodal and characterized by high proportions of $C_{15} – C_{20}$, maximizing at $C_{15} – C_{18}$. The abundance of the normal alkanes decreases with increasing carbon number (Figure 3). This normal alkane distribution, which shows a high abundance of short chains (especially *n*-C_{17}), is typical for marine algal organic matter (Romero et al., 2018), however, a minor contribution from terrigenous organic matter is not excluded. The marine organic matter predominance of Kurra Chine Formation is also supported by low carbon preference index values (CPI) (0.90 – 0.97), low terrigenous/ aquatic ratio (TAR) (0.09 – 0.16), low Pr/n-C_{17} (0.31 – 0.34) and Ph/n-C_{18} (0.48 – 0.50) values (Table 3).

Table 3. Calculated source and maturity-related biomarkers of the Kurra Chine samples.

No.	C_{29}/ H	S/H	C_{27} %	C_{28} %	C_{29} %	Dia./ Reg.	GA/ H	GA/ C_{31}R	C_{35}S/ C_{34}S	DBT/P	M/H	C_{32} 22S/ (22S+22R)	C_{29} (ββ/ββ+αα)	C_{19}/C_{23} Tricyclic	C_{22}/C_{21} Tricyclic	C_{24}/C_{23} Tricyclic	C_{24}Tet/C_{23} Tricyclic
K3	1.46	0.17	19.36	27.53	53.11	0.63	0.36	1.30	1.62	0.62	0.06	0.61	0.55	0.03	1.16	0.32	3.20
K6	1.34	0.23	31.02	31.85	37.13	0.93	0.17	0.49	1.43	0.34	0.06	0.62	0.53	0.10	0.87	0.41	2.34

Regular sterane distributions also indicate the origin of organic matter. Previously, most organic geochemists attributed C_{29} steranes to land plants and C_{27} steranes to be produced from algae (Volkman, 1986). More recent data suggest that C_{29} steranes can also originate from green and brown algae (Kodner et al., 2008). Sterane distribution of the two Kurra Chine samples shows equal proportions of C_{27}, C_{28}, and C_{29} in the K6, and dominance of C_{29} over C_{27} in K3 (Table 2, Figure 4). The normal alkane distribution suggests that terrigenous organic matter input to the Kurra Chine Formation is very low. Therefore, brown and green algae may be the source of C_{29} steranes in the Kurra Chine Formation. The different regular sterane distributions may suggest a slight difference in the type of organic matter. This assumption is supported by different sterane/hopane ratios, which are 0.17 and 0.23 in K3 and K6, respectively (Table 2). The low values of the former ratio indicate a high bacterial contribution to the organic matter (Peters et al., 2005). This difference in organic matter type may be due to a relative difference in environmental conditions (see below), as reflected by the bulk composition of the bitumen extracts. The K3 sample has higher saturate and aromatic content and lower NSO and asphaltenes compared to K6 (Table 3).

4.4. Depositional Environment

Biomarker and non-biomarker, such as pristine/phytane (Pr/Ph) ratios commonly used for determining the redox condition of the depositional environment. High Pr/Ph ratios (> 1.0) indicate the availability of oxygen, and low values (< 1.0) reflect low oxygen conditions (suoxic-anoxic) (Didyk et al., 1978). The Pr/Ph values of K3 and K6 are 0.76 and 0.91, respectively (Table 3). Gammacerane/C_{30} hopane (GA/C_{30} H), and $C_{35}S/C_{34}S$ ratios are opposite to Pr/Ph values, they are high in the K3 and low in K6 (Table 2). These values suggest a suboxic-anoxic depositional environment. Marine anoxic conditions are reinforced by Pr/n-C_{17} and Ph/n-C_{18} values (Figure 6; Table 3). Moreover, these criteria may indicate that the depositional environment of K3 (depth 3000 m) was more anoxic than that of K6 (3080 m), indicating oscillation in the conditions of the depositional environment. In addition, the amount of gammacerane is much higher in the K3 sample; therefore, the higher value of GA/C_{30}H which is used as stratification of water column proxy (Sinninghe Damsté et al., 1995; Jiang & George, 2020), for K3 compared to K6 may indicate deposition of K3 sample under stratified water column (may be due to salinity); whereas K6 sample was deposited under normal salinity seawater. The presence of evaporite layers in the middle part of the formation in the studied well (Butmah-15) and some parts of the Low Folded Zone (Jassim & Goff, 2006) and in northern Iraq (Sadooni & Alsharhan, 2004) supports this interpretation. On the other hand, the TOC values, which are strongly indicative of redox conditions, are low. This may indicate productivity of the organic matter in the surface water was low. The low surface productivity is supported by the low dibenzothiophene/ phenanthrene ratio (DBT/P) (<0.63; Table 2) (Hughes et al., 1995). This low value may indicate that there was insufficient sulfate reduction to allow much sulfur incorporation into organic matter due to oxygen availability. Another interpretation for the low TOC values is the dilution effect caused by a high sedimentation rate. The thickness of the Kurra Chine Formation in northwestern Iraq is very high (up to 1784 m in Mityaha-1 Well and 1150 m in Jabal Kand-1; (Jassim & Goff, 2006). This high thickness of sediments was deposited over about 20 million years, which is a very high sedimentation rate.

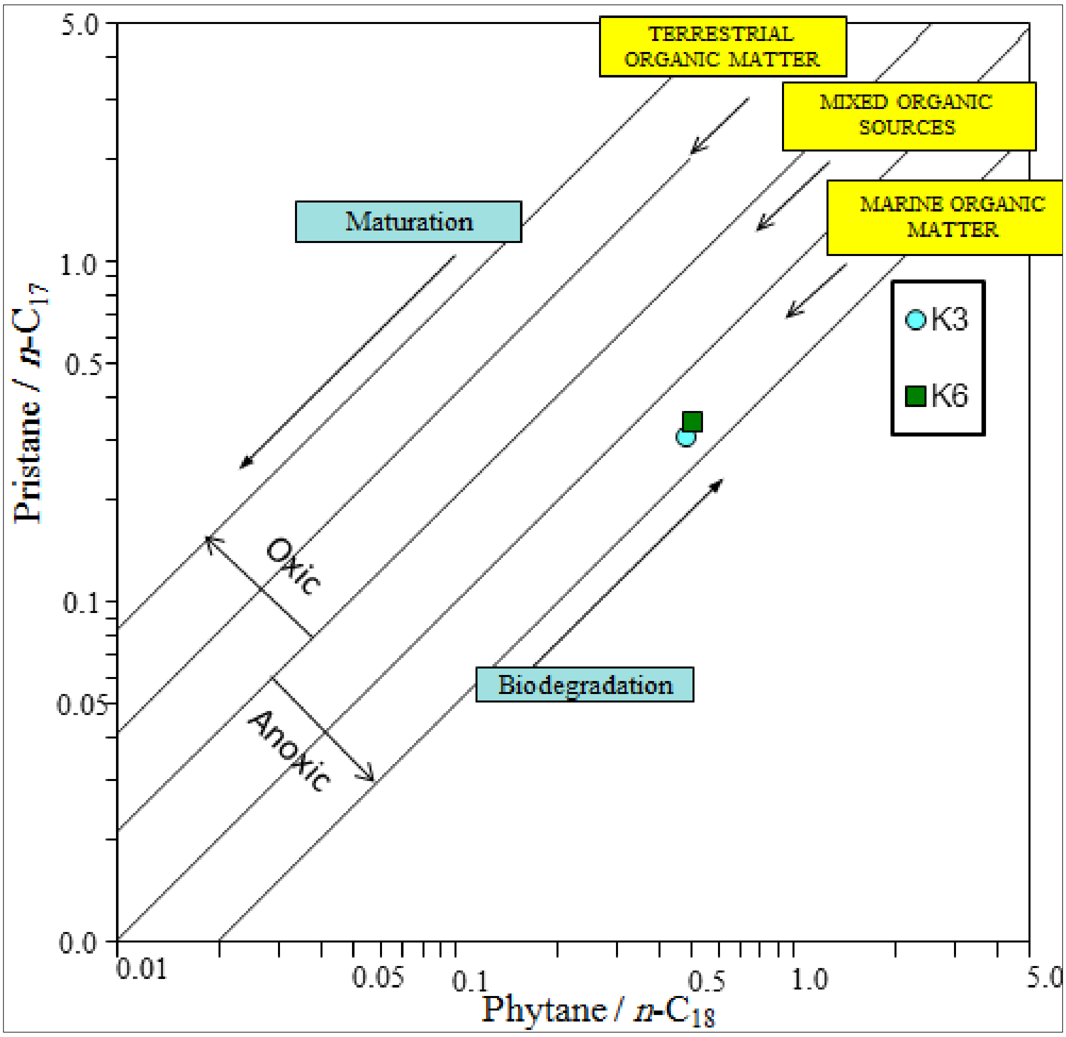

Figure 6. Redox conditions and type of organic matter based on Pr/n-C_{17} vs. Ph/n-C_{18} for the K3 and K6.

Based on Figure 7, it is observed that carbonate content (CC) versus TOC changes with the depositional environment along the studied interval. Generally, the high CC suggests marine or lacustrine influence (Sachse et al., 2012). The shift in CC may indicate the position of most proximal (relatively low CC) and distal (relatively high CC) sediments along the studied interval, suggesting fluctuation of the sea level. In comparison with samples K3 and K7, the other seven samples show lower CC and higher clastic content, which may indicate dilution of carbonate by a relatively high clastic input; but the CC is still high along the examined interval, suggesting that carbonate production still prevailed, and the clastic input was not high enough to completely stop the carbonate factory; and it only dilute the carbonate sediments. In addition, in spite of the fluctuation of the carbonate content, TOC values are nearly constant, suggesting that OM within the Kurra Chine Formation is mainly of marine origin.

The different CC are reflected in the saturated and aromatic biomarker ratios. Therefore, due to the different carbonate content of the K3 and K6 samples; which is 77% and 89%, respectively; the K3 sample has higher values of $C_{22}T/C_{21}T$ (Peters et al., 2005), C_{24} TT/$C_{23}T$, norhopane/hopane (C_{29}/C_{30}) (Peters et al., 2005), and lower values of $C_{24}T/C_{23}T$, Ts/Tm, diasterane/regular sterane, dibenzothiophene/phenanthrene relative to K6 sample (Table 2).

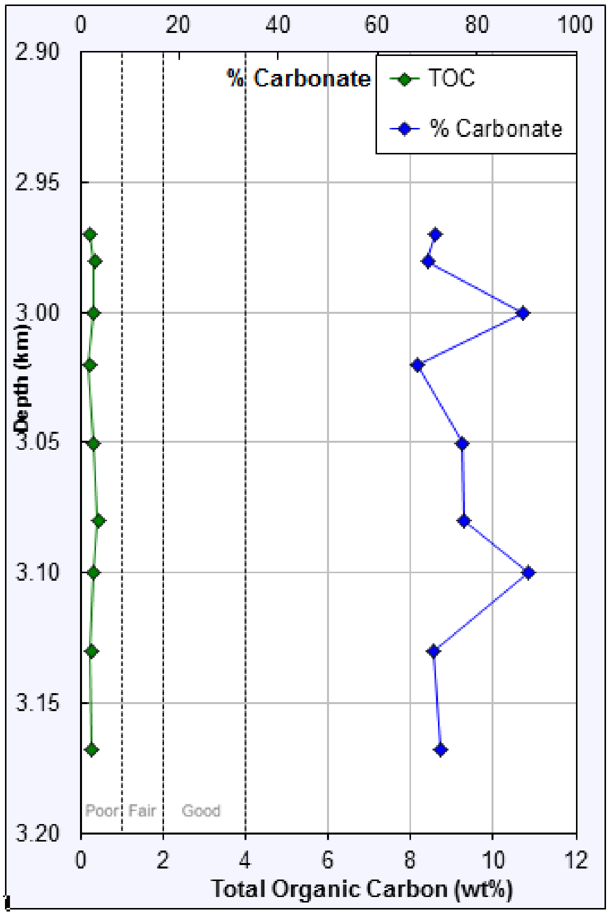

Figure 7. Variation of TOC and carbonate content of the Kurra Chine samples.

4.5. Basin Modeling

The one-dimensional (1-D) model was built to model the burial history of the Kurra Chine Formation at the Butmah-15 Well, to simulate the maturity of the source rock, thermal histories, and hydrocarbon generation, as well as migration. Top, base, thickness, age, and lithologies of the penetrated formations, erosion age, well temperatures, petroleum system elements, TOC, and initial HI potential are among the input data for well-15 of the Butmah oilfield (Table 4). These were used to build the burial and thermal histories model (Figures 8 – 10).

Table 4. Burial history data in Butmah-15 well

Formation	Top (m)	Base (m)	Thickness (m)	Age		Erosion Age (My)		Lithology	Petroleum system element	TOC%	Initial HI mgH/g TOC
				From	To	From	To				
Euphrates	0	160	60	23	15	23	35	Lst/ Maryl Lst			
Avana/Jaddala	160	226	66	38	35			Lst			
Jaddala	226	601	375	45	38			Marly Lst			
Aliji/Sinjar	601	800	199	50	45			Marly Lst/ Lst			
Aliji	800	1100	300	60	50	60	67	Marly Lst	Source		
Shiranish	1100	1677	577	75	67	75	80	Marly Lst	Reservoir		
Mushora	1677	1727	50	86	80	86	100	Lst	reservoir		
Qamchuqa	1727	1867	140	110	100			Lst	Reservoir		
Sarmord	1867	1898	31	120	110	120	163	Lst			
Sargelu	1898	2050	154	183	163			Lst/Shale	Source		420
Alan	2050	2072	20	185	183			Anhydrite			
Mus	2072	2093	21	188	185			Lst			
Adaiya	2093	1203	110	190	188			Anhydrite			
Butmah	1203	2602	399	201	190			Lst/Anhydrite			
Baluti	2602	2724	122	205	201			Shale			
Kurra Chine	2724	3709	985	225	205	242	225	Lst	Source	0.4-5.0	171
Gelikhana	3709	4305	596	274	242			Lst			

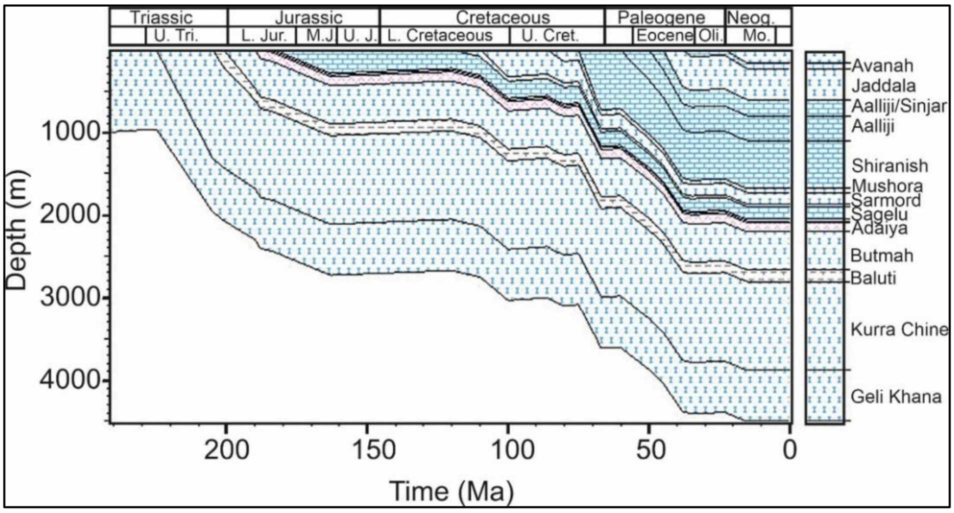

Figure 8. Burial history of the penetrated geological formations in the Butmah-15 Well.

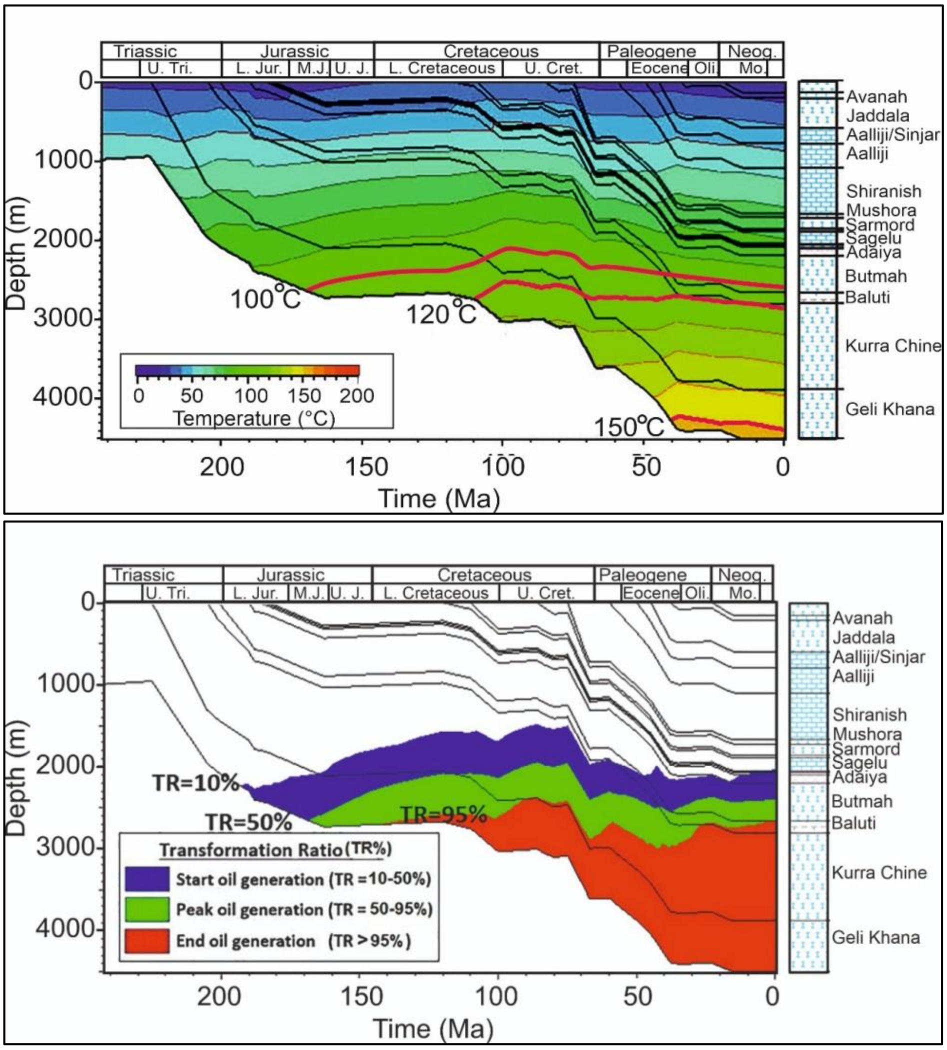

Figure 9. Thermal history (Upper) and the transformation ratios (Lower) of the geological formations in the Butmah-15 well.

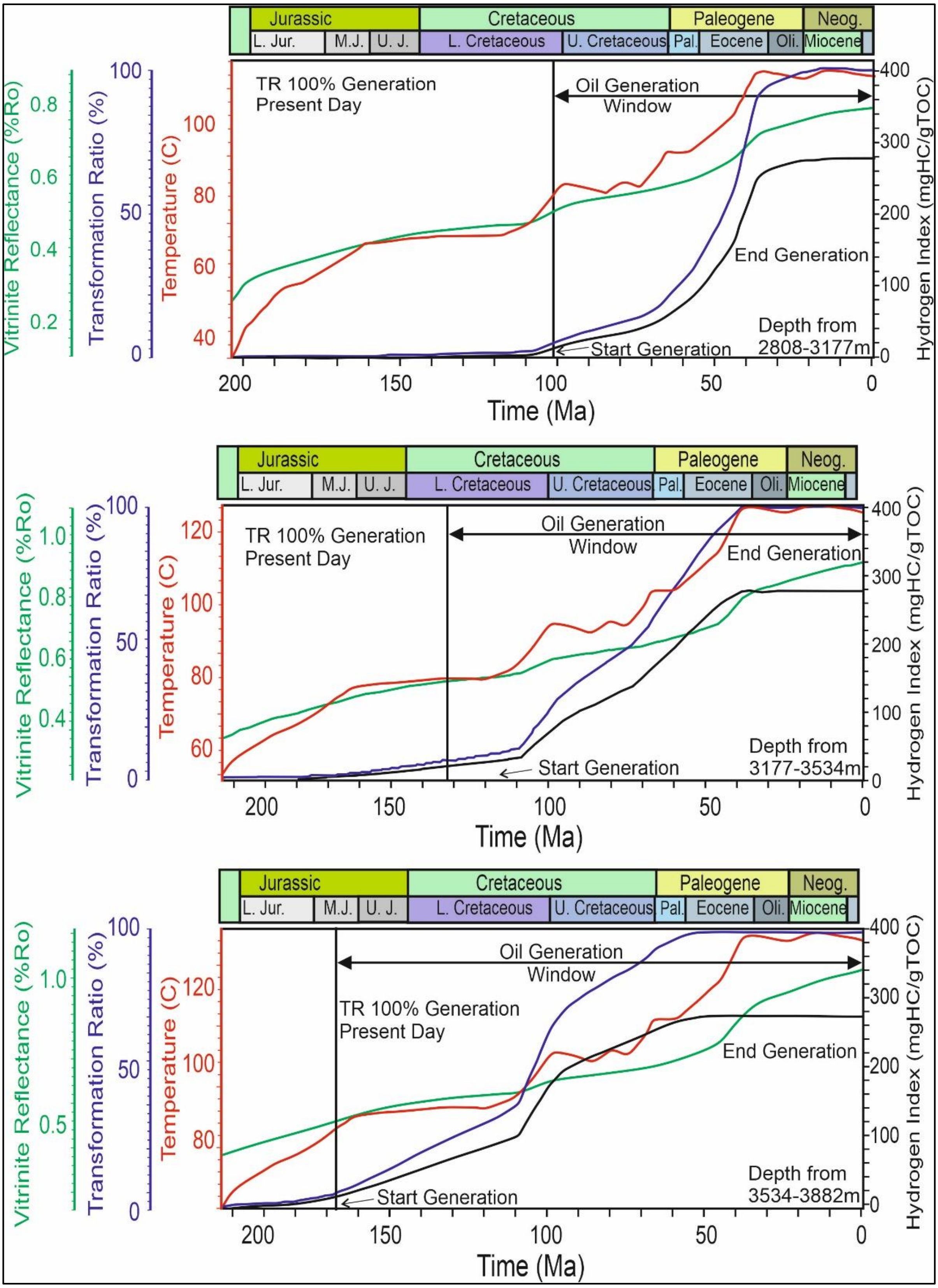

Figure 10. Timing of hydrocarbon generation of the Kurra Chine Formation in the Butmah-15 well.

4.5.1. Burial History

The burial history reconstruction model for the Butamah-15 well, illustrated in Figure 8, includes gaps in the stratigraphic depositional column due to a hiatus in deposition or erosion. The drilled well penetrated a geological formation from the Triassic (Geli Khana) to the Miocene (Euphrates). A modest rate of subsidence is recorded in the Late Triassic and early Jurassic Period (225 – 188 Ma.) during the sedimentation of the Kurra Chine, Butmah, and Baluti formations (Figure 8), which may have been influenced by the impact of the Neo-Tethys Extension. The rapid subsidence rate from 75 to 67 Ma during the deposition of the Shiranish Formation deposition, reflects dynamic rifting during the Zagros Orogeny (Numan, 1997).

The location was subject to uplift after the deposition of Middle Jurassic successions (Sargelu Formation) (Dunnington, 1958). In subsurface sections, north and west of Mosul, considerable amounts of the Middle Jurassic succession, including the Sargelu Formation and the entire sequence of the Late Jurassic and Berriasian rock succession, are absent (Abdula, 2015). In this area, the Sargelu Formation is overlain by the Aptian Sarmord Formation and appears to be eroded. The total number of eroded beds is different throughout the area. A second uplift occurred during the Miocene as a result of the collision between the Arabian Plate and the Iranian and Turkish plates (Numan, 1997). As shown in Figure 9, only the Triassic and Early Jurassic formations are thermally mature at the present day; whereas Cretaceous and Tertiary formations can be considered immature because of the small thickness of the overburdened rocks.

The thermal history model (Figure 9) shows how rapid burial affected source-rock temperatures. The current burial temperatures of Kurra Chine rocks in the Butmah oilfield are from 120 ^{o}C to 140 ^{o}C, at a depth of approximately from 2724 to 3700 m, respectively, in the Late Miocene. As illustrated in Figure 9, the Paleocene to Miocene period records the highest temperature associated with deep burial and represents the late petroleum generation and trap filling.

4.5.2. Timing of Oil Generation

The thermal history curves (Figure 10) for the high TOC units of the upper part (2808 – 3177 m) of the Kurra Chine Formation (if present) suggest oil generation began at the end of the Early Cretaceous (about 100 Ma ago), corresponding to transformation ratio (TRs) of 0.1, the middle part (3177 – 3534 m) at the beginning of the Early Cretaceous (~130 Ma), and the lower part (3524 – 3882 m) at the middle Jurassic time (~166 Ma). These units reached their peak oil generation at the end of the Eocene (about 38 Ma), and the end of the oil window was reached at the end of the Miocene, which corresponds to TRs of 0.95 (Figure 10).

5. Conclusions

Samples analyzed from the upper part of the Triassic Kurra Chine Formation, within the depth range of 2970 – 3168 m in the Butmah-15 well, have low TOC and HI values. This interval is interpreted to be a poor source rock and has no potential for hydrocarbon generation. From the Rock-Eval pyrolysis data (HI and OI), it is evident that the organic matter of the studied interval of the Kurra Chine Formation is of mixed origin type II/III (marine and terrigeneous OM) and type III kerogen (terrigeneous OM). Molecular geochemistry results (hopane and sterane ratios) suggest predominantly marine OM within the upper part of the formation. This may indicate that the original marine organic matter was influenced by early microbial degradation, which led to the decomposition of this organic matter and reduced its HI values. Rock-Eval pyrolysis Tmax and biomarker ratios (moretane/ hopane, C_{32} hopane isomerization, and C_{29} sterane isomerization) suggest early- to mid-mature organic matter. The variable carbonate content of the samples indicates variable position in the depositional basin; and led to variable biomarker ratios in K3 and K6 samples. From the thermal history modeling results, the onset of oil generation from lower and upper parts of the Kurra Chine Formation was in the beginning about ~166 Ma (Middle Jurassic) and 100 Ma ago latest Cretaceous, and ended in the Miocene.

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References

Abboud, M., Philp, R. P., & Allen, J. (2005). Geochemical correlation of oils and source rocks from Central and NE Syria. *Journal of Petroleum Geology*, *28*(2), 203–216. https://doi.org/10.1111/j.1747-5457.2005.tb00080.x

Abdula, R. A. (2015). Hydrocarbon potential of Sargelu Formation and oil-source correlation, Iraqi Kurdistan. *Arabian Journal of Geosciences*, *8*(8), 5845–5868. https://doi.org/10.1007/s12517-014-1651-0

Abdula, R. A. (2017). Petroleum System Modeling of Jabal Kand Oil Field, Northern Iraq. *ZANCO Journal of Pure and Applied Sciences*, *29*(2), 88–95. https://doi.org/10.21271/zjpas.29.2.9

Abdula, R. A. (2020). Oil And Gas Generation History Based On Burial History Reconstruction And Thermal Maturity Modeling Of Petroleum Systems In Northern Iraq. *Journal of Petroleum Research and Studies*, *10*(4), 95–120. https://doi.org/10.52716/jprs.v10i4.370

Al-Ameri, T. K., Al-dolaimy, Q. H., & Al-Khafaji, A. J. (2009). *Palynofacies and hydrocarbon generation potential of the upper Triassic Kurrachine Formation and lower part of the Baluti Formation, Mosul Block, Northwestern Iraq*. *Arabian Journal of Geosciences 2*, 237–283. https://doi.org/10.1007/s12517-009-0041-5

Al-Dolaimy, A. M. S., Al-Beyati, F. M., & Al-Mallah, A. Y. (2021). Distribution of Steranes and Triterpanes Biomarkers as Indication of Depositional Environment and Maturity of Sargelu and Kurrachine Formations in Different Wells Northern Iraq. *Iraqi Geological Journal*, *54* (1C), 87–100. https://doi.org/10.46717/igj.54.1C.7Ms-2021-03-27

Al-Dolaimy, A. M. S., Al-Mallah, A. Y., Abdel-Fattah, M. I., & Al-Beyati, F. M. (2021). Source Rock Characteristic of Sargelu and Kurrachine Formations from the Source Rock Characteristic of Sargelu and Kurrachine Formations from the Selected Wells in Northern Iraq. *Iraqi Geological Journal*, *54(2A)*, 60–74. https://doi.org/10.46717/igj.54.2A.5Ms-2021-07-26

Al-Essa, A. K., & Alkhafaji, M. W. (2024a). Organic Matter Characteristics and Hydrocarbon Potential of Jurassic Sargelu Formation in X Well, Northern Iraq. *Iraqi Geological Journal*, *57*(2), 52–64. https://doi.org/10.46717/igj.57.2D.4ms-2024-10-14

Al-Essa, A. K., & Alkhafaji, M. W. (2024b). Source Rock Characteristics of Sargelu Formation in X Well, Northern Mesopotamian Zone, Iraq. *Iraqi Geological Journal*, *57*(1F), 33–46. https://doi.org/10.46717/igj.57.2D.2ms-2024-10-12

Al-Hamdani, A. M., Ali, M. S., & Dabagh, M. M. Al. (2021). *Microfacies Evaluation of Kurra Chine Formation (Late Triassic) and Scenario of Depositional Basin Development in Northern and North Western Iraq*. *Journal of Petroleum Research and Studies* 33, 1-19. DO http://doi.org/ 10.52716/jprs.v11i4.566

Alkhafaji, M. W., Aljubouri, M. A., Al-Miamary, F. A., & Connan, J. (2020). Biodegradation and the origin of surface bitumens in the Palaeocene Kolosh Formation, Northern Iraq. *Arabian Journal of Geosciences*, *13*(13), 1–20. https://doi.org/10.1007/s12517-020-05579-1

Alkhafaji, M. W., Peters, K. E., & Moldowan, J. M. (2023). Biomarker geochemistry of Qaiyarah, Butmah and Ain Zala crude oils, northern Iraq: Implications for the Jurassic source rocks. *Geoenergy Science and Engineering*, *221*, 211382. https://doi.org/10.1016/j.geoen.2022.211382

Aqrawi, A. A. M., Goff, G. C., Horbury, A. D., & Sadooni, F. N. (2010). *Petroleum Geology of Iraq*. Scientific Press Ltd. 590 p.

Aswad, M. K., Naqshabandi, S. F., & Omer, M. F. (2023). Kurra Chine Formation: Evaluation of Source Rock, Based on Rock-Eval Pyrolysis Analysis Integrated by Selected Wells and Outcrop Samples in Iraq's Kurdistan Region. *Iraqi Geological Journal*, *56*(2), 37–50. https://doi.org/10.46717/igj.56.2B.3ms-2023-8-12

Awdal, A., Healy, D., & Alsop, G. I. (2016). Fracture patterns and petrophysical properties of carbonates undergoing regional folding : A case study from Kurdistan, N Iraq. *Marine and Petroleum Geology*, *71*, 149–167. https://doi.org/10.1016/j.marpetgeo.2015.12.017

Baban, D. H., & Ahmed, M. M. (2021). Characterization of the Carbonate Reservoir Unit A of the Upper Triassic Kurra Chine Formation in the well SH-4, Shaikan Oilfield, Iraqi Kurdistan Region, Using Wireline Log Data. *Tikrit Journal of Pure Science*, *26*(2), 71–87.

Balaky, S. M., Al-Dabagh, M. M., Asaad, I. S., Tamar-Agha, M., Ali, M. S., & Radwan, A. E. (2023). Sedimentological and petrophysical heterogeneities controls on reservoir characterization of the Upper Triassic shallow marine carbonate Kurra Chine Formation, Northern Iraq: Integration of outcrop and subsurface data. *Marine and Petroleum Geology*, *149*, 106085. https://doi.org/10.1016/j.marpetgeo.2022.106085

Barrier, E., Machhour, L., & Blaizot, M. (2014). *Petroleum Systems of Syria. In L. Marlow, C. Kendall and L. Yose, eds., Petroleum systems of the Tethyan region: AAPG Memoir 106, p. 335–378*. https://doi.org/10.1036/13431862M1063612

Didyk, B., Simoneit, B., Brassell, S., & Eglinton, G. (1978). *Organic geochemical indicators of paleoenvironmental conditions of sedimentation*. *Nature 272*, 216-222. https://doi.org/10.1038/272216a0

Dunnington, H. V. (1958). Generation, migration, accumulation, and dissipation of oil in Northern Iraq. In: Weeks, G.L. (Ed.), Habitat of Oil. AAPG, Tulsa, Oklahoma, pp. 1194–1251. https://doi.org/10.2113/geoarabia100239

Edilbi, A. N. F., Kolo, K., Muhammed, N. R., Yasin, S. R., & Mamaseni, W. J. (2019). *Source rock evaluation of shale intervals of the Kurra Chine Formation, Kurdistan Region-Iraq : An organic geochemical and basin modeling approach*. *Egyptian Journal of Petroleum 28*, 315–321. *https://doi.org/10.1016/j.ejpe.2019.06.003.*

Fouad, S. F. A. (2015). *TECTONIC MAP OF IRAQ, SCALE 1 : 1000 000* ,. *11*(1), 1–8.

Hughes, W. B., Holba, A. G., & Dzou, L. I. P. (1995). The ratios of dibenzothiophene to phenanthrene and pristane to phytane as indicators of depositional environment and lithology of petroleum source rocks. *Geochimica et Cosmochimica Acta*, *59*(17), 3581–3598. https://doi.org/10.1016/0016-7037(95)00225-O

Jassim, S. Z., & Goff, J. C. (2006). *Geology of Iraq. Dolin, Prague, and Moravian Museum*. 341p.

Jiang, L., & George, S. C. (2020). Geochemical comparison of three oil families from the Gippsland Basin, SE Australia. *Marine and Petroleum Geology*, *121*, 104575. https://doi.org/10.1016/j.marpetgeo.2020.104575

Jirman, P., Ger, E., Bubík, M., Sachsenhofer, R. F., & Bechtel, A. (2019). *Depositional environment and hydrocarbon potential of the Oligocene Menilite Formation in the Western Carpathians : A case study from the Lou č ka section (Czech Republic). 107*, 334–350. https://doi.org/10.1016/j.marpetgeo.2019.05.034

Kodner, R. B., Pearson, A., Summons, R. E., & Knoll, A. H. (2008). *Sterols in red and green algae : quantification, phylogeny, and relevance for the interpretation of geologic steranes*. *Geobiology 6*, 411–420. https://doi.org/10.1111/j.1472-4669.2008.00167.x

Lawa, F. A., Koyi, H., & Ibrahim, A. (2013). Tectono-stratigraphic evolution of the NW segment of the Zagros fold-thrust belt, Kurdistan, NE Iraq. *Journal of Petroleum Geology*, *36*(1), 75–96. https://doi.org/10.1111/jpg.12543

Numan, N. M. S. (1997). A PLATE TECTONIC SCENARIO FOR THE PHANEROZOIC SUCCESSION IN

IRAQ. *Iraqi Geological Journal*, *30*, 85–119. https://doi.org/10.1016/j.gr.2015.08.003

Omarini, J., Lescano, M., Odino-barreto, A. L., Campetella, D., Tunik, M., Garbán, G., Brea, F., Erra, G., & Aguirre-urreta, B. (2020). Palaeoenvironmental conditions for the preservation of organic matter during the late Hauterivian in the Neuquén Basin (Western Argentina). *Marine and Petroleum Geology*, *120*(May), 104469. https://doi.org/10.1016/j.marpetgeo.2020.104469

Peters, K. E., & Cassa, M. R. (1994). *Applied Source Rock Geochemistry*. In Magoon, L. B, and W. G. Dow, eds. The petroleum system—from source to trap: AAPG Memoir 60, 93-120.

Peters, K. E., & Michael Moldowan, J. (2017). Biomarker: Assessment of thermal maturity. *Encyclopedia of Earth Sciences Series*, 116–123. https://doi.org/10.1007/1-4020-4496-8_28

Peters, K. E., Walters, C. C., & Moldowan, J. M. (2005). The Biomarker Guide. Second edition. Cambridge University Press. 1155 p. https://doi.org/10.1017/cbo9781107326040

Romero, A. A. M., Nguyen, T., & Philp, R. P. (2018). *Organic geochemistry of the Eagle Ford Group in Texas*. *AAPG Bulletin 102 (7)*, 1379-1412. https://doi.org/10.1306/0828171614717055

Sachse, V. F., Delvaux, D., & Littke, R. (2012). *Petrological and geochemical investigations of potential source rocks of the central Congo Basin, Democratic Republic of Congo*. *AAPG Bulletin* 96(2), 245–275. https://doi.org/10.1306/07121111028

Sadooni, F. N. (1995). Petroleum Prospects of Upper Triassic Carbonates in Northern Iraq. *Journal of Petroleum Geology*, *18*(2), 171–190. https://doi.org/10.1111/j.1747-5457.1995.tb00896.x

Sadooni, F. N., & Alsharhan, A. S. (2004). *Stratigraphy, lithofacies distribution, and petroleum potential of the Triassic strata of the northern Arabian plate*. AAPG Bulletin 88(4), 515-538. https://doi.org/10.1306/12030303067

Sinninghe Damsté, J. S., Kenig, F., Koopmans, M. P., Köster, J., Schouten, S., Hayes, J. M., & de Leeuw, J. W. (1995). Evidence for gammacerane as an indicator of water column stratification. *Geochimica et Cosmochimica Acta*, *59*(9), 1895–1900. https://doi.org/10.1016/0016-7037(95)00073-9

Volkman, J. K. (1986). *A review of sterol markers for marine and terrigenous organic matter*. Organic Geochemistry *9*(2), 83-99.

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