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Hydrocarbon potential, source correlation, and paleoenvironmental reconstruction of the Jurassic interval in the Zey Gawra Oilfield, Kurdistan Region, Iraq

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Abstract: A comprehensive geochemical analysis for the Sargelu, Naokelekan, and Najmah formations cutting rock and crude oil samples from Z1, Z3, and Z5 wells of Hawler Block, Kurdistan Region, Iraq have been studied for source rock evaluation. Depending on the total organic carbon (TOC) content from pyrolysis analyses, the Sargelu and Naokelekan formations are regarded as very good source rocks, and fair source rock for the Najmah Formation. The organic matter in the Sargelu Formation is characterized by types II and mixed II and III kerogens. However, the Naokelekan and Najmah formations are characterized by type II kerogen. The Sargelu and Naokelekan formations' organic matters are at mature stages; hence, in the oil window, whereas Najmah Formation's organic matter is at immature stage. Pyrolysis study shows that the Sargelu Formation is oil and gas prone, while the Najmah and Naokelekan formations are oil prone. The biomarkers and bulk properties of the selected oils from Gas Chromatography (GC) and Gas Chromatography-Mass Spectroscopy (GC/MS) analysis show that they originated by the same source rocks. The geochemical characteristics indicate a carbonate source in a reducing environment for the studied formations and oils. Based on the oleanane index, tricyclic terpane indices, $C_{28}S/C_{29}S$ ratios, and gammacerane index, the relative age of the oils and cuttings of Sargelu, Naokelekan, and Najmah formations is Middle to Late Jurassic and deposited under moderate saline condition. The biomarkers parameters show evidence that molecules from the cutting rocks of the Sargelu and Naokelekan formations are related to the oils in Z1, Z3, and Z5 wells. However, they are not related to the Najmah Formation.

Keywords: Sargelu, Naokelekan, Najmah, source rock, biomarker, oil-oil correlation

INTRODUCTION

Middle and Upper Jurassic successions are considered as major and widespread source rocks in Iraq (Jassim & Al-Gailani, 2006). It is believed that the Jurassic marine shales and carbonates are the main sources for the hydrocarbons formed in the Zagros Basin and Fold Belt (Pitman *et al*., 2003). According to Aqrawi & Badics (2015), the Sargelu, Naokelekan-basinal, and Najmah formations (and their equivalents) may be the most excellent possible shale-gas and oil plays in Iraq, Kuwait, and Iran. In the Balad Oilfield, Albeyati *et al*. (2021) considered the Sargelu Formation has a fair to decent quantity of organic matter, plus fair to excellent and very high to exceptional for Naokelekan and Najmah formations, respectively.

The Sargelu Formation in northern Iraq contains an abundance of oil-prone organic matter (Al-Ameri *et al*., 2014) that belongs to types II and III kerogen (Abdula, 2010; Fatah & Mohialdeen, 2016; Saeed & Mohialdeen, 2016; Mamaseni, 2020; Sulaiman *et al*., 2022). The percentage of organic matter decreases toward the north and northeast of the area (Abdula, 2015). In the Taq Taq Oilfield, the Sargelu Formation's kerogen types are III and IV (Baban & Ahmed, 2021), while in well Atrush-2 in Duhok Governorate, the formation comprises type II and mixed-type II-III kerogen (Akram *et al*., 2021) with thermal maturity within oil generation zone (Hakimi *et al*., 2018; Al-Atroshi *et al*., 2020; Abdula, 2020). The Sargelu Formation is classified as good source rock in Ain Zalah to a very good in Baiji and excellent in Kand wells based on their total organic matter (Al-Dolaimy *et al*., 2021). In Zab-1 Well, the Sargelu Formation samples exhibit T_{max} values ranging from 422 °C to 431 °C (Abdula, 2016a). Similarly, in Shaikhan-2 Well, Shaikhan Oilfield, multiple linear regression approach for the vitrinite reflectance estimation from well logs indicated immature organic matter of the Sargelu and Naokelekan formations (Hussein & Abdula, 2018). Contrary, toward the end of the Eocene, the Sargelu Formation has entered the oil producing phase in the Kirkuk Oilfield (Beydoun, 1993).

The Naokelekan Formation in the Kirkuk-109 and Qara Chuq-1 wells, Northern Iraq has an average TOC of 4% (Al-Habba & Abdullah, 1989) that comprises of a mixed terrestrial-marine organic matter, types II and III kerogens

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(Abdula *et al*., 2020a; Damoulianou *et al*., 2020) as a main component for mature organic matter and potential for generation and expulsion of oil and/or gas (Abdula *et al*., 2020b). The organic matter of the Naokelekan Formation is mature and within the oil generation window in Sargelu Village and Miran Oilfield (Baban & Ahmed, 2014; Mohialdeen *et al*., 2018).

The amount of hydrocarbon produced from the Sargelu Formation in the Kurdistan Region, Iraq is determined to be 3.4199 × 10^{12} kg (Abdula, 2017a; Abdula *et al*., 2017; 2019; 2020c). In the same way, the amount of generated hydrocarbon from the Naokelekan Formation in the same area is estimated to be 70.5 billion bbl (Abdula, 2023).

The purpose of this study is to carry out a geochemical analysis for rock cuttings and crude oil samples from wells of Hawler Block, Kurdistan Region, Iraq (Figure 1) to determine petroleum potentiality, kerogen types, and the maturity level of organic matter of Sargelu, Naokelekan, and Najmah formations. The work also aims to study biomarkers characteristics, isotopes, and trace elements of crude oil samples and extracted organic matter for: determining the type of oils and detecting the oils' probable source rocks; determining depositional environment of crude oils' source rock; maturity level of crude oils; and crude oils' source rock relative age. The study focuses on Hawler Block which is located 17 km north east of Guwair Town in south west of Erbil Governorate in Iraqi Kurdistan close to Great Zab River and includes Z1, Z2, and Z3 wells.

METHODS

The study is based on 11 rock cuttings samples (Table 1) that were packed by Oryx Petroleum Hawler Company Limited (OPHCL) and stored at Directorate of Geological Survey, Cutting Store, Erbil, Kurdistan Region, Iraq. In the summer of 2021, three samples of crude oil were also collected from three wells in the OPHCL for organic geochemical analyses. The cuttings rock samples have been taken from subsurface (Zey Gawra-1 Well) at different depths in Hawler Block, including the Sargelu, Naokelekan, and Najmah formations. The analytical methods undertaken were: Rock-Eval analysis, Soxhlet extraction, column chromatography (SARA), Gas chromatography (GC-FID), Gas Chromatography-Mass Spectroscopy (GC/MS) analysis, and carbon stable isotope.

The cutting samples were first cleaned from contaminations to eliminate the drilling mud fluid by Benzene polar solvent. After washing, the samples were filtered, dried at the room temperature and crushed into powder and weighed to be between 90-100 mg in the Chemistry Laboratory of Soran University in Kurdistan

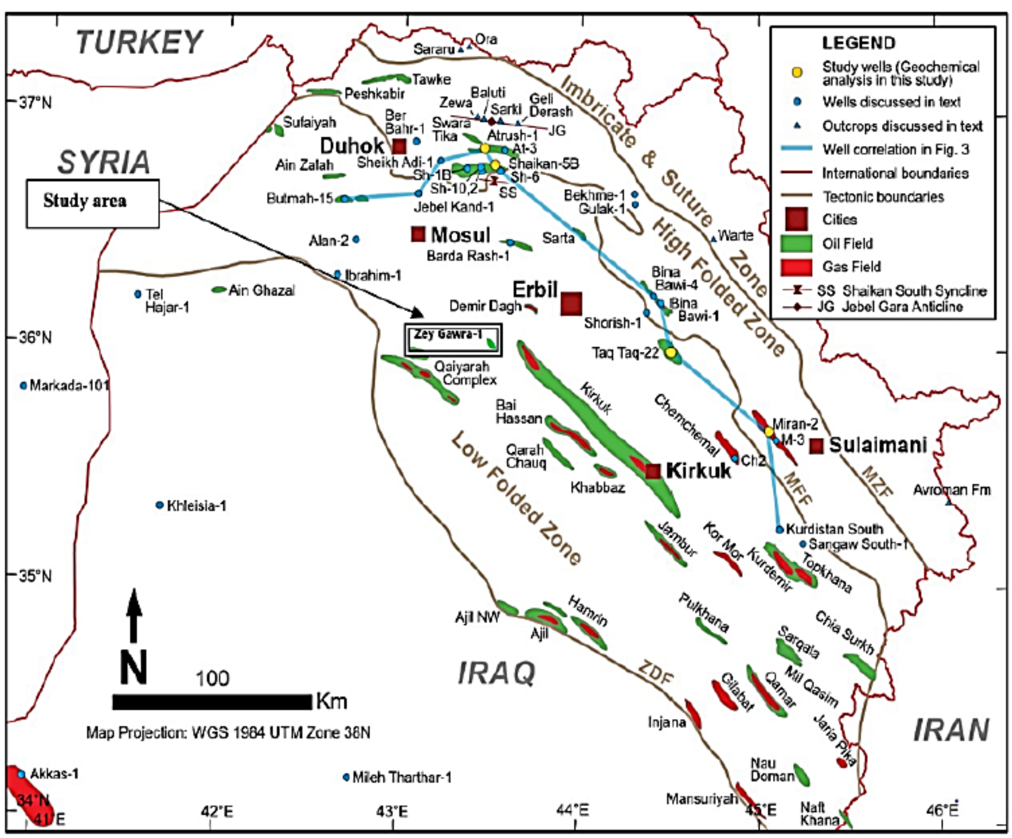

Figure 1: Map shows the locations of the main hydrocarbon accumulations within structural traps throughout northern Mesopotamian basin (Mohialdeen *et al*., 2022).

Table 1: Type of samples, well names, formation names, and the depth of samples collected from Hawler Block, Kurdistan Region, Iraq for geochemical analysis.

Sample Type	Well Name	Formation Name	Depth Interval (m)
Crude Oil	Z-1	UN	UN
Crude Oil	Z-3	UN	UN
Crude Oil	Z-5	UN	UN
Cuttings	Z-1	Najmah	2385-2390
Cuttings	Z-1	Najmah	2990-2995
Cuttings	Z-1	Naokelekan	3180-3185
Cuttings	Z-1	Sargelu	3185-3190
Cuttings	Z-1	Sargelu	3190-3195
Cuttings	Z-1	Sargelu	3195-3200
Cuttings	Z-1	Sargelu	3200-3205
Cuttings	Z-1	Sargelu	3205-3210
Cuttings	Z-1	Sargelu	3210-3215
Cuttings	Z-1	Sargelu	3215-3220
Cuttings	Z-1	Sargelu	3220-3225

Region, Iraq. The crude oil samples were kept in dry and clean glass bottles and perfectly sealed to prevent contamination and vaporizing of volatile compounds.

Rock-Eval-6 pyrolysis analysis was conducted at the Scientific Research Center of the Soran University, Kurdistan Region, Iraq. Such an analysis is performed to determine the quantity, quality, and maturity of organic matter. With no oxygen present, the Rock-Eval apparatus essentially warms samples of finely crushed rock (90-100 mg) at a predetermined temperature rate beginning at 300 °C in an inert atmosphere and increasing at a rate of about 25 °C/min, up to 850 °C (Peters, 1986; Hunt, 1996; Sykes & Snowdon, 2002).

The most three high TOC contain samples among those 11 samples have been selected for Soxhlet extraction and submitted to the FullTech Laboratory Erbil office which analyzed at the Santez Group for Laboratory Testing Services, Karaj, Alborz Province, Iran.

About 22 g of each sample was subjected to bitumen extraction, using a Soxhlet apparatus for 72 hours and using a mixture of dichloromethane and n-hexane (20:80) as extractant solvents. The solvent is heated to reflux, the solvent enters the chamber containing the solid thimble through a distillation arm and overflows it.

SARA analysis that was performed by the Santez Group for Laboratory Testing Services, Karaj, Alborz Province, Iran is used for many crude oil components, asphaltene can be soluble in pentane or heptane. Half gram of oil sample was dissolved in pentane for asphaltene precipitation. Saturates, aromatics and resins were determined by adsorption chromatography silica/ alumina. Saturates, aromatics, and resins were eluted by hexane, toluene, and methanol, respectively. Gas chromatograph model Trace GC ultra from Thermo Electron company with flame ionization detector (FID) was used for selected samples analysis by the Santez Group for Laboratory Testing Services, Karaj, Alborz Province, Iran. The conditions were as follows:

TR – 1 capillary column 30 m, 0.25 mm ID, 0.25 µm film thickness, injection port temperature 290 °C, initial oven temperature: 50 °C (1 min), final oven temperature: 300 °C (15 min), ramp temperature 10 °C /min, carrier gas: hydrogen, gas flow rate: 1 ml/min, detector temperature: 290 °C air: 250 ml/min, H_2: 25 ml/min, make up gas: N_2 (20 ml/min), sample size: 1 µlit, splitless time: 0.2 min.

A gas chromatograph model Trace GC from Thermo of Finnigan equipped with Mass spectrometer DSQ from Thermo Finnigan was used in single ion monitoring (SIM) mode for both aromatic and saturate sample analysis. The conditions for aromatics were as follows:

DB-5 fused silica capillary column 30 m, 0.25 mm ID, 0.25 µm film thickness, injection port: 280 °C, initial oven temperature: 60 °C (1 min), final oven temperature: 290 °C (30 min), ramp temperature: 5 °C/min, carrier gas: helium, gas flow rate: 1 ml/min, sample size: 1 µlit, source temperature: 230 °C, scan mode: SIM, electron energy: 70 eV, splitless time: 0.5 min.

The conditions for saturates were as follows:

DB-5 fused silica capillary column 30 m, 0.25 mm ID, 0.25 µm film thickness. Injection port: 280 °C, initial oven temperature: 120 °C (1 min), final oven temperature: 290 °C (30 min), ramp temperature: 5 °C/min, carrier gas: helium, gas flow rate: 1 ml/min, sample size: 1 µlit, source temperature: 230 °C, scan mode: SIM, electron energy: 70 eV splitless time: 0.5 min.

Gas chromatography (GC) and Gas Chromatography-Mass Spectroscopy (GC/MS) analysis were utilized to investigate the biomarkers distribution of the crude oils and bitumen extraction from the cutting rock samples. Carbon stable isotope, American Petroleum Institute (API) gravity, and the composition of the elements carbon, hydrogen, computed oxygen, nitrogen, and sulfur (C, H, O, N, S) was examined for crude oils and were done by Santez Group for Laboratory Testing Services, Karaj, Alborz Province, Iran through their representative in Erbil, Iraq.

GEOLOGICAL SETTING

The Arabian Plate has a complicated tectonic history and is strongly affected by eustatic sea-level fluctuations (Haq & Al-Qahtani, 2005). The Middle-Upper Jurassic and the Lower Cretaceous were periods of tectonic instability (Buday & Jassim, 1984). The Arabian Plate was a component of the Gondwana's extensive and broad northern passive margin, which bordered the Paleo-tethys Ocean (Beydoun, 1991). Late Precambrian suturing of various terranes of basic and plutonic materials and dense volcanic assembled the Arabian Plate together as revealed in the Arabian Shield and elsewhere (Haq & Al- Qahtani, 2005).

Iraq's stratigraphy is strongly affected by the structural of the country's location among the main geostructural units of the Middle East area, as well as by Iraq's structure itself (Al-Juboury, 2009). Tectonically, Iraq lies at the conversion between the Arabian Shelf in the southwest and the extremely distorted Taurus and Zagros Suture Zone in the north and northeast.

Tectonic evaluation of the area during the Early-Middle Jurassic Period represented by the major tectonic event was begun after the Triassic when the Gondwana split, Indian Plate started to separate, and in the Late Jurassic, it was isolated from Arabia (Grabowski & Norton, 1995). The northern portion of the Arabian Plate was affected by rifting that started in the Early Jurassic in the central Mediterranean (Haq & Al-Qahtani, 2005). A new passive margin and new accommodation space were developed along the subsiding shelf at the plate's northwest edge as a consequence of rifting that occurred in the late Early Jurassic (Sharland *et al*., 2001).

Liassic was the time of generally steadiness as represented by deposition of evaporite and carbonate units e.g., Alan, Mus, and Adaiyah, Butmah or their equivalents, Sehkaniyan and Sarki formations. Due to Toarcian rifting, a new basin formed in the Middle Jurassic. It was characterized by the deposition of the Sargelu and its equivalents throughout the region (Sadooni, 1997).

Variety in the Najmah Formation thickness as described by Dunnington (1955) reflects the basin's geometry after Bathonian onwards. Alongside the western margin of a basin, the Najmah oolites were developed, which is represented in the east-northeast by the Naokelekan in the Mountainous Zone (Sadooni, 1997; Abdula, 2016b).

The eastern margin of this basin is not known in northern Arabia since it was overthrusted during the Late Cretaceous onwards. Large portions of the basin margin were uplifted in the Khlaisiya High and in the country's southwest during the Neocomian (Sadooni, 1997). Further, Ponikarov *et al*. (1967) discovered that the adjacent northern parts of Syria are lacking of any Upper Jurassic deposits.

In the Kurdistan region, all significant hydrocarbon discoveries have actually occurred within structural traps fashioned throughout the Alpine Orogeny. During the stratigraphical development, subsidence and deposition played a significant role for generating and migration of hydrocarbon from deeper source rocks (Mina & Abdula, 2023). The generated hydrocarbons had migrated a comparatively short distance to charge the Zagros anticlines (English *et al*., 2015). Consequently, it is theorized that the regional first-order trends in the Middle and Upper Jurassic source rocks maturity thought to be closely related to the spatial variation of oil maturity in Jurassic (and Cretaceous) reservoirs (English *et al*., 2015).

Peak burial throughout the Mesopotamian Basin and the Zagros fold belt occurred during the Neogene deposition within the foredeep of the Zagros orogeny (Pitman *et al*., 2004).

The general stratigraphic descriptions of the selected formations are based on the stratigraphic column of the successions which has been redrawn based on the master log of the Z1 well (Figure 2).

The Sargelu Formation is underlaid by the Alan Formation and is overlaid by the Naokelekan Formation. The depth of the upper contact is 3186 m measured depth (MD) and the lower contact is 3222 m MD. It comprises of mainly limestone interbedded with thin shale. The thickness of the formation in this well is 36 m from the total depth which is 4400 m. The Naokelekan Formation is overlaid by the Najmah Formation. The depth of the upper contact is 3133 m MD and lower contact is 3186 m MD. It comprises of limestone interbedded with shales and claystone. The thickness of the formation in this well is 53 m. The Najmah Formation is overlaid by the Garagu Formation. The depth of the upper contact is 2275 m MD and lower contact is 3133 m MD. It comprises of mainly limestone, interbedded with thin beds of claystone and dolomites. The thickness of the formation in this well is 858 m.

RESULTS AND DISCUSSION

Source rock evaluation

In organic geochemistry, the use of Rock-Eval pyrolysis is a common and rapid technique for the petroleum source rock identification (Sykes & Snowdon, 2002). The important parameters that pyrolysis analysis reveals for each sample are: (1) S1 peak which is the free hydrocarbons that the sample releases after the initial 300 °C heating without the kerogen being cracked; (2) S2 peak which is the hydrocarbon amount that is released from the samples during the second heating stage; (3) S3 peak which relates to the amount of carbon dioxide (CO_2) released when the kerogen thermally cracks up to 390 °C; and (4) T_{max} is the temperature measured during pyrolysis at which a maximum amount of hydrocarbon can be generated (Tissot & Welte, 1984; McCarthy *et al*., 2011). The measured and calculated parameters are shown in Table 2 for the studied samples.

Total organic carbon (TOC)

Eleven cutting rock samples from Z1 Well in the Hawler Block were examined to determine their TOC wt.% content (Table 2) to evaluate the Sargelu, Naokelekan and Najmah formations quantitatively from the perspective of hydrocarbon potential.

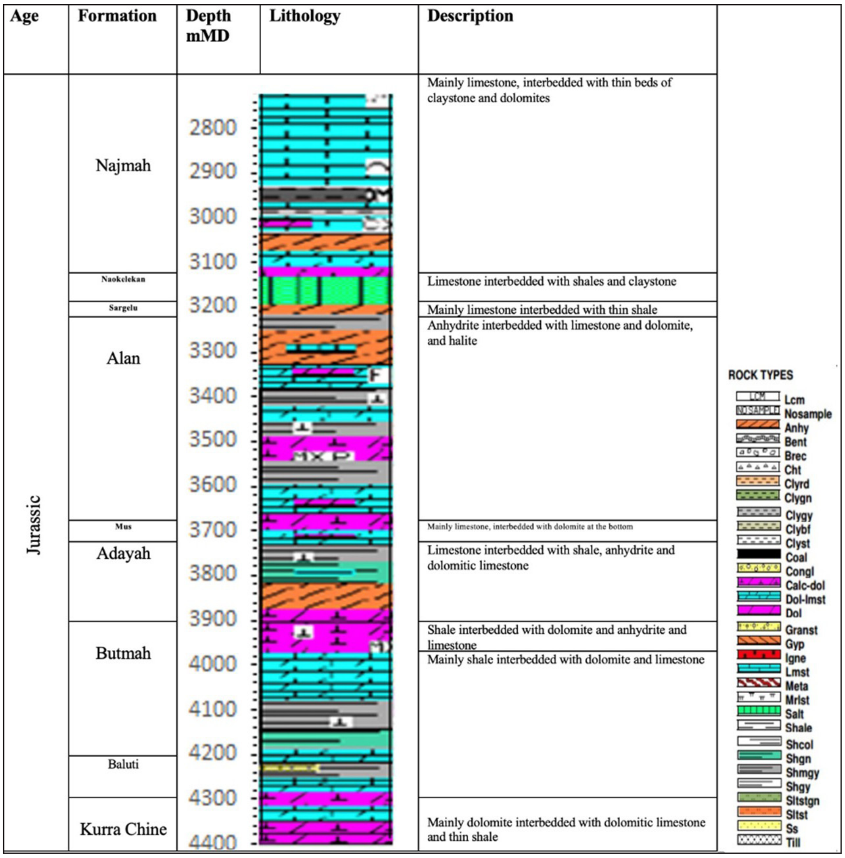

Figure 2: Stratigraphic column of Z1 Well showing the lithology of studied formations in Hawler Block, Kurdistan Region, Iraq which is redrawn from the master log of Z1 Well from OP Hawler Company.

Table 2: Rock-Eval results from the Z1 Well, Hawler Block, Kurdistan Region, Iraq.

Formation Name	Depth (m)	TOC (wt.%)	S1 (mg HC/ g rock)	S2 (mg HC/ g rock)	S3 (mg CO_2/ g rock)	T_{max} (°C)	HI (mg HC/ g TOC)	OI (mg HC/ g TOC)	GP (mg HC/ g rock)	PI	Calculated Ro%	S2/ S3
Najmah	2385-2390	0.71	0.50	3.37	0.68	420	475	96	3.87	0.13	0.40	5.00
	2990-2995	0.21	0.14	0.82	0.15	423	390	71	0.96	0.14	0.45	5.50
Naokelekan	3180-3185	4.51	1.60	18.52	1.53	439	411	34	20.12	0.08	0.74	12.10
Sargelu	3185-3190	2.28	1.04	7.81	1.58	437	343	69	8.85	0.12	0.71	4.90
	3190-3195	3.29	1.13	13.14	1.11	439	399	34	14.27	0.08	0.74	11.80
	3195-3200	3.34	1.06	13.75	1.14	438	412	34	14.81	0.07	0.72	12.10
	3200-3205	3.03	0.82	11.20	1.32	438	370	44	12.02	0.07	0.72	8.50
	3205-3210	3.21	1.07	10.63	1.69	437	331	53	11.70	0.09	0.71	6.30
	3210-3215	3.49	1.07	14.86	1.07	437	426	31	15.93	0.07	0.71	13.90
	3215-3220	2.94	0.73	7.69	1.33	434	262	45	8.42	0.09	0.65	5.80
	3220-3225	3.42	1.06	12.45	1.19	439	364	35	13.51	0.08	0.74	10.50

The TOC values show that the Sargelu Formation generally has higher TOC wt.% than the Najmah Formation. The highest TOC wt.% content was recorded in the Naokelekan Formation at 3180-3185 m from its slight thickness of the underlying Sargelu and overlying Najmah formations (Table 2). The TOC wt.% of the Sargelu Formation samples ranges between 2.28 and 3.49 wt.% and Najmah Formation samples recorded 0.21 and 0.71 wt.% (Table 2).

Hydrogen and oxygen indices

The hydrogen and oxygen indices can be acquired from the obtained pyrolysis parameters. These estimated parameters are mainly utilized to evaluate the quantity, quality, and maturity levels of organic matter. Hydrogen index (HI) is calculated as [(100 x S2)/TOC], which is obtained from the ratio of hydrogen to TOC. The oxygen index (OI) is calculated as [(100 x S3)/TOC], which is obtained from the carbon dioxide (CO_2) to TOC ratio (Tissot & Welte, 1984; Peters & Cassa, 1994; Hunt, 1996; and McCarthy *et al*., 2011).

The HI is positively proportional to the hydrogen content of the kerogen and the OI is related with the CO_2 content of the kerogen (McCarthy *et al*., 2011). Tracking kerogen types at earlier thermal maturity stages is attained by these indices: HI values >600 mg HC/g TOC and OI values <50 mg CO_2/g TOC are typically found in type I kerogen; HI values of 300-600 mg HC/g TOC and OI values of 50 mg CO_2/g TOC are usual in type II kerogen; the hydrogen index of type II and type III combination ranges from 200 to 300 mg HC/g TOC; HI values of 50-200 mg HC/g TOC and OI values of 50-100 mg CO_2/g TOC are commonly found in type III kerogen; and a typical HI result for type IV kerogen is <50 mg HC/g TOC (Tissot & Welte, 1984; Peters & Cassa, 1994). The HI of the organic materials begins decreasing once the kerogen approaches the oil window (Dembicki Jr., 2009).

From the analyzed samples it has been observed that the Najmah Formation organic matter has the highest HI (390 and 475 mg HC/g TOC), and Naokelekan Formation recorded 411 mg HC/g TOC of HI. Whereas the Sargelu Formation organic matter ranged between 262-426 mg HC/g TOC of HI, which indicates type II for the Naokelekan and Najmah formations, and type II-III kerogen for the Sargelu Formation.

Genetic potential

The genetic potential is the highest amount of hydrocarbon that a source rock with adequate maturity might yield. It can be expressed as the summation of S1 and S2 measured in mg/g of rock. As a result, it takes into consideration the amount of hydrocarbon the rock has already produced (S1) as well as those it could yet produce if maturation continues (S2) (Tissot & Welte, 1984; McCarthy *et al*., 2011; Abdula *et al*., 2020d).

The genetic potential provides a qualitative evaluation of the potential for hydrocarbon resources; however, it is not capable to determine types of kerogens (Pitman *et al*., 1987).

According to Tissot & Welte (1984) values of the genetic potential and their corresponding source rock evaluations, the genetic potential of Najmah Formation is relatively moderate, while Naokelekan and Sargelu formations have good genetic potential (Table 2).

Production index

The relation between the hydrocarbons generated in the initial and second stages of pyrolysis provides the basis for the production index or transformation ratio (McCarthy *et al*., 2011; Abdula, 2017b).

Mathematically, the Production index (PI) can be defined as [S1/(S1+S2)] which the hydrocarbon (S1) that kerogen has initially generated and the amount of entire hydrocarbon that might attained from kerogen (Tissot & Welte, 1984). A significant amount of oil generation initiates when the PI value is 0.1, and when it is 0.4, oil yielding ceases and gas generation initiates (Hunt, 1996).

The production indexes of the studied samples in the Sargelu, Naokelekan, and Najmah formations are shown in Table 2.

Kerogen classification

The insoluble sedimentary organic matter which is effective in generating petroleum and natural gas is called kerogen (Vandenbroucke, 2003; Vandenbroucke & Largeau, 2007). The relative abundances of HI and OI attained by Rock-Eval pyrolysis can be used to determine the type of kerogen (Espitalié *et al*., 1977). To avoid the oxygen effect while detecting the kerogen type, HI versus T_{max} is frequently used rather than HI and OI modified plot of van Krevelen (Hunt, 1996). The samples plot within type II with the exception of one sample of the Sargelu Formation which plots in types II and III kerogen (Figure 3).

The type of organic matter can also be identified by the plot of TOC wt.% versus S2 as shown in Figure 4. The cross plot indicates the mixture of type II and III kerogens for Sargelu organic matter and type II kerogen for Naokelekan and Najmah formations (Figure 4). The plot of TOC versus S2 can indicate the hydrocarbon prone (Langford & Blanc-Valleron, 1990) (Figure 4). Furthermore, hydrogen index and S2/S3 distinguishes the types of organic matters depending

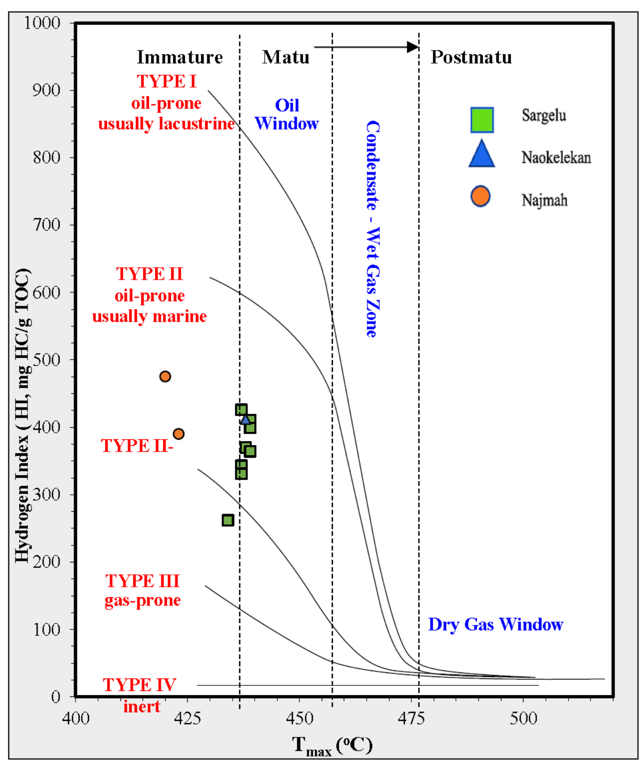

Figure 3: HI versus T_{max} diagram classified kerogen types, maturity, and hydrocarbon generation of cuttings rock samples (Espitalié *et. al.,* 1977).

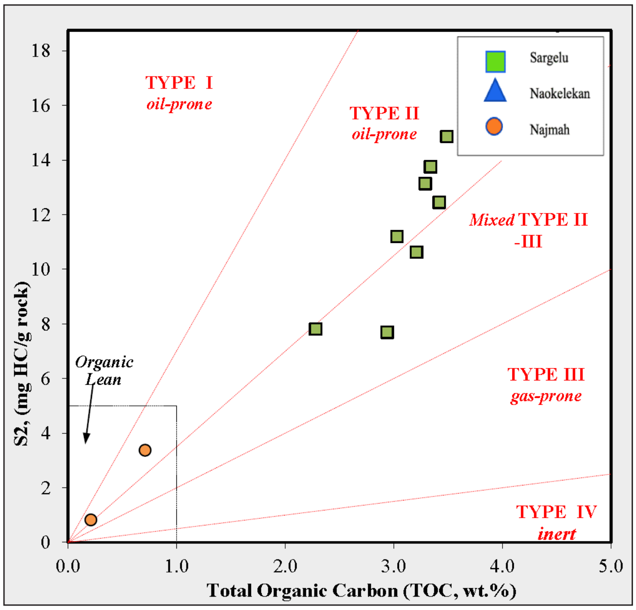

Figure 4: TOC versus S2 diagram of kerogen types for the analyzed samples. Additionally, the plot indicates the oil or gas prone of kerogen (Langford & Blanc-Valleron, 1990).

on their values: gas has a HI <150 HI mg HC/g rock, and S2/S3 ratio 0-3; gas and oil has a HI range of 150 to 300 mg HC/g rock and S2/S3 ratio 3-5; and oil has a HI more than 300 mg HC/g rock and S2/S3 ratio more than 5 (Peters, 1986). The generated hydrocarbon type is oil for all three formations except one sample of the Sargelu Formation which is oil and gas as it has HI less than 300 mg HC/g rock and S2/S3 is 5.

Thermal maturity

The degree of organic matter transformation during the heating process is referred to as source rock maturation. It can be affected by a number of factors, including the type of organic matter, the quantity of excess hydrocarbon within rock, the mineral content, depositional environment, tectonic, or the burial depth (Peters & Cassa, 1994; Atta-Peters & Garrey, 2014). Based on Rock Eval pyrolysis data, the type and maturation of organic matter from petroleum source rocks were determined. One of the measurements that is used to assess the source rocks' thermal maturity is their T_{max} values that is the maximum temperature at which pyrolysis produces its most S2 (Espitalié *et al*., 1984; Peters & Cassa, 1994). The T_{max} recorded is 434 °C to 439 °C from the Sargelu Formation; 420 °C and 423 °C from Najmah Formation; and 439 °C for Naokelekan Formation indicating that the source rocks are mature in the Sargelu and Naokelekan formations and immature in the Najmah Formation (Table 2).

The HI versus T_{max} plot can be used to identify the level of thermal maturity (Figure 3). The figure shows that the Sargelu and Naokelekan formations samples are mature and the Najmah Formation samples are immature. The thermal maturity of source rocks can be indicated by plotting T_{max} against PI as it increases by increasing both parameters. The PI values provide the kerogen conversion level of the organic matter (Peters & Cassa, 1994; Jimoh *et al*., 2020). The Sargelu and Naokelekan formations samples are plotted in the early mature area and the Najmah Formation samples in the immature area.

Calculated Vitrinite Reflectance (VR_o) is an additional supportive characteristic for estimating the maturity of the source rocks. To determine VR_o using T_{max} data, Jarvie *et al.* (2001) suggested a conversion formula. The mathematical formula for the conversion is: VR_o (calculated) = (0.018) (T_{max}) – 7.16 (Jarvie *et al*., 2001). Table 2 displays the calculated vitrinite reflectance of the studied samples that ranged between 0.40 and 0.74. The calculated vitrinite reflectance values demonstrate that the Sargelu and Naokelekan formations samples are mature, while Najmah Formation samples are immature.

In order to evaluate the characteristics and hydrocarbon potential of the examined organic matter of the investigated formations in the Z1 Well in Hawler Block, several cross-plots and diagrams are utilized to show the relationship between the parameters obtained from the pyrolysis data.

Depending on TOC wt.% values of Tissot & Welte (1984) and Alaug *et al*. (2014) classification, the Sargelu and Naokelekan formations can be considered as a very good source rock, and fair source rock for Najmah Formation as it has less than 1.0 wt.% TOC which is the lower limit to be considered as a productive source rock.

The HI versus OI classified the type II kerogen for all three formations. HI versus T_{max} diagram indicates the same kerogen type which is type II for all three formations except one sample that appears to be kerogen type II and III from the Sargelu Formation at depth 3215-3220m (Figure 3).

The HI values of samples of all three formations are between 300 and 600 mg HC/g TOC which indicate type II kerogen associated usually within open marine environment and this type of kerogen produces both oil and gas. Exception of one sample from the Sargelu Formation having HI value less than 300 mg HC/g TOC reveals mixed type II and III kerogen (Tissot & Welte, 1984; Peters & Cassa, 1994). The TOC wt.% against S2 diagram identified: type II and III for 3 samples, type II for 5 samples from the Sargelu Formation, and type II for Naokelekan and Najmah formations (Figure 4). The diagrams and calculated parameters identify that the kerogen type of the Sargelu Formation is II and mixed II and III. However, the Naokelekan and Najmah formations were detected to be kerogen type II.

By applying the guides on the T_{max} and VR_o values of the studied samples in Table 2, it appears that the organic matter of the Sargelu and Naokelekan formations are at least at mature stage, and Najmah Formation is immature stage at the investigated location (Peters & Cassa, 1994). According to Tissot *et al.* (1987), T_{max} is a strong determinant of maturity which is used in various plots as a base for interpreting the thermal maturity for source rocks, the cross plot of HI versus T_{max} implies the thermal maturity level for Sargelu and Naokelekan formations are at mature stage in the oil window and Najmah Formation is at immature stage (Figure 3).

The TOC versus S2 diagram suggested the oil and gas prone for Sargelu Formation and oil prone for Najmah and Naokelekan formations (Figure 4). The HI versus T_{max} plots identified the oil prone for all three formations except one sample from Sargelu Formation which is oil and gas prone (Figure 3).

Geochemical oil typing

Oil classification

Using the API gravity and percentages of the SARA composition (saturate, aromatic, resin, and asphaltenes) for Z1, Z3, and Z5 oils, oil types were identified for the studied oil samples. The API gravity for Z1 and Z5 crude oils are 23.88 and 28.79, respectively, while Z3 has API gravity of 33.95; hence, Z1 and Z5 are classified as medium crude oils and Z3 is classified as light crude oil. Based on the SARA compositions all three oils are classified as paraffinic-naphthenic (Figure 5; Table 3).

Oil-oil correlation

Biomarker and non-biomarker analytical results can both be used to provide accurate interpretation and differentiate of the produced related and unrelated oils. Due to their intricate chemical structures which is unaltered during early burial and sedimentation, biomarkers are more dependable since they provide more information about their genesis than other substances as the concept for oil-oil correlations predicts that oils with comparable geochemical features originate by the same source rock and depositional environment (Peters & Moldowan, 1993; Peters *et al*., 2005).

Bulk properties

The results of various bulk properties of the studied oil samples have been presented in Table 3, which are used to differentiate the group of oils. The crude oil's chemical components e.g., carbon, hydrogen, sulfur, nitrogen, and oxygen (C, H, S, N, O) are a bulk property of oils (Hunt, 1996).

Based on the variation in the CHSNs percentage composition, the oxygen content was calculated by the following equation:

$$\text{Calculated oxygen content (O)} = 100 - (C + H + S + N)$$

The crude oils would demonstrate their similarity by comparing weight percentage of N+O with percentage weight of sulfur and sulfur with American Petroleum Institute (API) gravity (Table 3). API gravity is also bulk parameter of oils which is measured by their specific gravity and is contrariwise linked to the density of the liquid petroleum

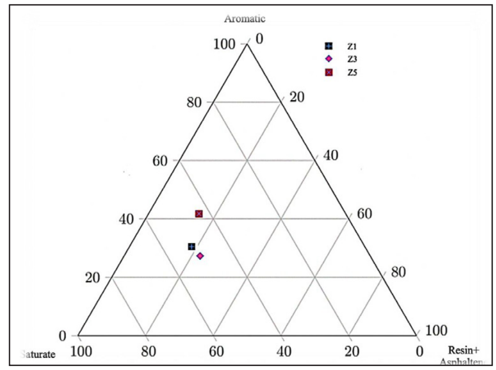

Figure 5: Ternary diagram showing the SARA composition of oils from Z1, Z3, and Z5 wells from Hawler Block, Kurdistan Region, Iraq (López & Mónaco, 2017).

(Peters *et al*., 2005). The measured API gravities for analyzed crude oils are displayed in Table 3. Accordingly, Z5 and Z1 crude oils have medium API gravities of 28.79 and 23.88, respectively with sulfur content of 3.23 and 2.21, respectively while, the Z3 has light API gravity (33.95) with sulfur content of 2.44%.

According to Sofer (1984), the $\delta^{13}C_{saturates}$ versus $\delta^{13}C_{aromatics}$ could be utilized to differentiate between different oil families and to determine whether an oil source is non-waxy (marine) or waxy (terrestrial). The comparison shows that the oils are nonwaxy. It also shows a good relationship among oils.

Biomarkers

Crude oils, rocks, and sediments are containing biomarkers or molecules originated from living organisms which show minimal or no structural variation beyond their source organic compounds in organisms (Hunt, 1996; Peters *et al*., 2005). According to Zhang *et al*. (2017), biomarkers found in sedimentary organic matter are generated from the earliest stages of life that have remained stable through the time. It is possible to detect biomarker concentrations precisely, they have low concentrations and by calculating ratios with each other assist to describe and classify oils, correlate oil-source rock, indicate maturity level, and determine depositional environment (Tissot & Welte, 1984; Peters & Moldowan, 1992; Hunt, 1996). The biomarkers are presented in Tables 4 and 5.

The used biomarker parameters from m/z 191 and m/z 85 chromatograms are: acyclic isoprenoids (pristane and phytane), C_{21} tricyclic terpane, C_{22} tricyclic terpane, C_{23} tricyclic terpane, C_{24} tricyclic terpane, C_{29}H norhopane, C_{30}H hopane, C_{31}HR homohopane, C_{35}HS extended hopane, C_{34}HS extended hopane, and GCRN gammacerane (Peters & Moldowan, 1993; Abdula, 2015; Abdula *et al*., 2018). As well as bulk properties in association with biomarkers can be used as a correlation tool such as comparing Pr/Ph with canonical variable (CV) (Sofer, 1984; Alizadeh *et al*., 2007; Abdula, 2015). The most two acyclic isoprenoids

Table 3: Bulk properties of extracts in the selected formations from the Z1 Well and oils from three different wells, Hawler Block, Kurdistan Region, Iraq.

Name of Samples	Well Name	Sample Type	Depth (m)	API	C %	H %	N %	S %	O %	Sat %	Aro %	Asph %	Resin %	Sat/ Aro	$\delta^{13}C_{Sat}$	$\delta^{13}C_{Aro}$	CV
Sargelu Extract	Z1-Well	Cutting Rock	3220 -3225					1.80		46.97	35.71	5.21	12.11	1.32	-27.97	-27.80	-2.60
Naokelekan Extract	Z1-Well	Cutting Rock	3180 -3185					1.30		48.21	39.76	3.24	8.75	1.21	-27.71	-26.90	-1.26
Najmah Extract	Z1-Well	Cutting Rock	2385 -2390					0.50		44.01	39.32	4.91	11.82	1.12	-28.35	-28.07	-2.24
Z1	Z1-Well	Crude Oil	UN	23.88	80.60	12.13	0.44	2.21	4.62	48.31	32.01	6.88	13.11	1.51	-27.18	-27.09	-3.02
Z3	Z3-Well	Crude Oil	UN	33.95	81.86	12.51	0.62	2.44	2.57	48.25	29.81	7.61	14.33	1.62	-27.2	-27.24	-3.31
Z5	Z5-Well	Crude Oil	UN	28.79	79.83	11.92	0.56	3.23	4.46	42.78	40.13	5.12	12.01	1.07	-27.18	-27.09	-3.02

API: API Gravity at 15.56°C
S%: Sulfur wt. percent
C%: Carbon wt. percent
O%: Oxygen wt. percent
H%: Hydrogen wt. percent
N%: Nitrogen wt. percent
CV: Canonical Variable = $-2.53\ \delta^{13}C_{Sat.} + 2.22\ \delta^{13}C_{Aro.} -11.65$
$\delta^{13}C_{Sat.}$: Stable carbon isotopic composition of the saturated hydrocarbons
$\delta^{13}C_{Aro.}$: Stable carbon isotopic composition of the aromatic hydrocarbons

Table 4: Geochemical characteristics of extracts in the selected formations from the Z1 Well and oils from three different wells, Hawler Block, Kurdistan Region, Iraq from GC analysis.

Name of samples	Well Name	Sample Type	Depth (m)	C_{17}	Pr	C_{18}	Ph	C_{19}	C_{20}	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}	C_{28}	C_{29}	C_{30}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	Pr/ Ph	CPI
Sargelu Extract	Z1-Well	Cutting Rock	3220-3225	7.28	2.01	9.63	3.84	6.35	7.80	6.48	5.65	5.32	5.68	5.64	4.93	4.26	3.61	3.86	2.80	1.80	1.30	0.65	0.83	0.62	0.52	1.11
Naokelekan Extract	Z1-Well	Cutting Rock	3180-3185	6.71	1.97	9.88	4.80	6.63	8.54	7.17	6.79	5.77	6.11	5.45	4.86	4.01	3.41	3.03	2.24	1.47	1.01	0.84	0.65	0.27	0.41	1.08
Najmah Extract	Z1-Well	Cutting Rock	2385-2390	2.64	0.67	4.74	3.33	3.00	4.60	3.10	4.35	5.67	7.50	9.55	9.32	8.16	6.96	5.99	4.49	3.52	2.84	1.74	1.60	1.30	0.20	1.11
Z1	Z1-Well	Crude Oil	UN	1.19	7.75	2.00	7.10	5.86	4.42	3.49	2.91	2.61	2.02	1.71	1.22	1.01	0.95	0.74	0.47	0.34	0.20	0.22	0.14	0.08	1.09	1.14
Z3	Z3-Well	Crude Oil	UN	8.39	0.71	6.11	1.37	4.77	3.66	3.28	2.59	2.34	2.11	1.65	1.48	1.18	1.03	0.90	0.59	0.41	0.31	0.20	0.21	0.13	0.52	1.05
Z5	Z5-Well	Crude Oil	UN	10.44	9.32	4.66	6.42	5.24	6.48	4.37	3.21	2.51	2.44	2.11	1.68	1.73	1.65	1.45	1.43	1.20	0.86	0.68	0.42	0.45	1.45	1.14

15: normal alkane series relative percent; e.g., n-C_{17}
Pr: Pristane relative percent
Ph: Phytane relative percent
Pr/Ph: Pristane to phytane ratio
CPI: Carbon Preference Index

Table 5: Geochemical characteristics of extracts of the selected formations from the Z1 Well and oils from three different wells, Hawler Block, Kurdistan Region, Iraq from GC/MS analysis.

Name of Samples	Well Name	Sample Type	Depth (m)	C_{21}TT	C_{22}TT	C_{23}TT	C_{24}TT	C_{25}TT	C_{26}TT	C_{29}H	C_{30}H	C_{31}HR	C_{34}HS	C_{35}HS	GCRN	GCRNI	C_{27}S	C_{28}S	C_{29}S	C_{28}S /C_{29}S
Sargelu Extract	Z1-Well	Cutting Rock	3220-3225	0.75	0.76	3.05	0.89	0.91	0.26	21.70	11.90	4.91	2.53	1.93	3.76	0.32	26.44	24.44	49.12	0.50
Naokelekan Extract	Z1-Well	Cutting Rock	3180-3185	1.23	1.41	4.66	1.64	1.70	0.65	14.60	14.00	6.73	1.90	1.64	1.84	0.13	40.30	15.96	43.75	0.36
Najmah Extract	Z1-Well	Cutting Rock	2385-2390	0.24	0.33	1.93	0.64	0.62	0.20	16.10	18.40	5.55	2.55	2.95	4.72	0.26	34.48	22.11	43.41	0.51
Z1	Z1-Well	Crude Oil	UN	1.53	1.52	3.93	1.20	1.11	0.33	18.40	12.90	4.72	1.79	1.90	3.24	0.25	36.40	22.60	41.10	0.55
Z3	Z3-Well	Crude Oil	UN	1.69	1.56	4.22	1.47	1.22	0.23	20.60	12.20	4.36	1.80	1.74	2.61	0.21	31.47	27.33	41.19	0.66
Z5	Z5-Well	Crude Oil	UN	1.11	0.77	3.71	1.11	1.35	0.21	18.60	14.00	5.24	2.21	2.09	3.08	0.22	35.73	24.04	40.23	0.60

C_{21} TT: C_{21} tricyclic terpane
C_{22} TT: C_{22} tricyclic terpane
C_{23} TT: C_{23} tricyclic terpane
C_{24} TT: C_{24} tricyclic terpane
C_{25} TT: C_{25} tricyclic terpane
C_{26} TT: C_{26} tricyclic terpane
C_{29} H: C_{29}H norhopane
C_{30} H: C_{30}H hopane
C_{31} HR: C_{31}HR homohopane
C_{34}HS: C_{34}HS extended hopane
C_{35}HS: C_{35}HS extended hopane
GCRN: gammacerane
GCRNI: gammacerane index
C_{27} S: ($C_{27}\alpha\beta\beta$20R+$C_{27}\alpha\beta\beta$20S)
C_{28}S: ($C_{28}\alpha\beta\beta$20R+$C_{28}\alpha\beta\beta$20S)
C_{29}S: ($C_{29}\alpha\beta\beta$20R+ $C_{29}\alpha\beta\beta$20S)

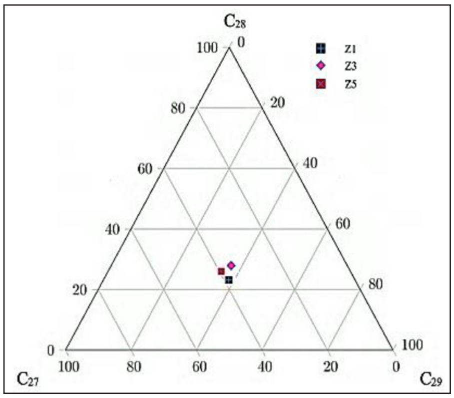

Figure 6: Ternary diagram shows the distribution of C_{27} ($C_{27}\alpha\beta\beta20R+C_{27}\alpha\beta\beta20S$), C_{28} ($C_{28}\alpha\beta\beta20R+C_{28}\alpha\beta\beta20S$), and C_{29} ($C_{29}\alpha\beta\beta20R+C_{29}\alpha\beta\beta20S$) steranes for oils from: Z1, Z3, and Z5 wells. The plot displays a good relationship among Z1, Z3, and Z5 oils (modified from Riva *et al*., 1986).

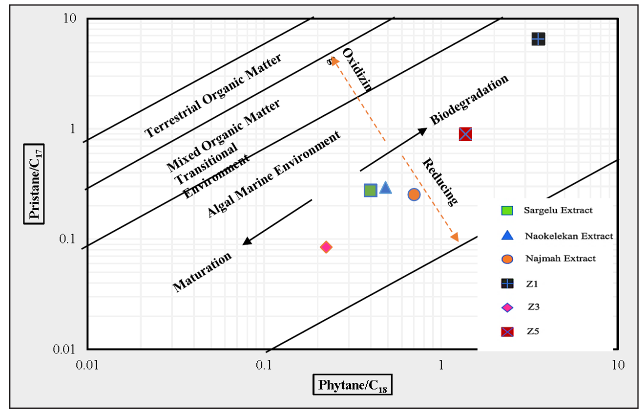

Figure 7: Pristane/n-C_{17} versus phytane/n-C_{18} of crude oils from Z1, Z3, and Z5 wells, and cuttings extracts from Z1 Well. The plot shows the marine source organic matter accumulation deposited under reducing conditions (Ten Haven *et al*., 1987).

which are formed from the phytol side chain of chlorophyll are typically Pr and Ph. The normal alkanes C_{17} and C_{18} are frequently linked to Pr and Ph as they contain C_{19} and C_{20} (Powell & McKirdy, 1973). The CV is mathematically obtained from saturated and aromatic of stable carbon isotopic composition's measurements:

$$CV= -2.53\ \delta^{13}C_{sat.} + 2.22\ \delta^{13}C_{aro.} - 11.65 \text{ (Sofer, 1984)}$$

The crude oils of Z1, Z3, and Z5 have Pr/Ph ratio less than 2 (1.09, 0.52, and 1.45). The Pr/Ph ratios have been compared with CV for the analyzed samples (Tables 3 and 4) which displays marine source under reducing condition.

Steranes distributions of C_{27}, C_{28}, and C_{29} are displayed in a ternary diagram which utilized from m/z 217-218 chromatograms for oil samples (Figure 6). The ternary diagram demonstrates the good correlation among all three crude oils (Riva *et al*., 1986; Hunt, 1996).

Depositional environment

According to Meyers (2003), a crucial technique for separating marine from terrestrial depositional settings is the stable carbon isotopic composition of organic material. A $\delta^{13}C$ values of saturates and aromatics plotting against each other are frequently used to distinguish nonwaxy marine and waxy terrestrial origins for oils and extracts (Sofer, 1984). The variation between saturates and aromatics in hydrocarbons are contingent on the source of hydrocarbons, the source rocks' depositional environment, and the maturity level of the hydrocarbon (Sofer, 1984; Zein El-Din & Shaltout, 1987; Younes & Philp, 2006).

The waxy terrestrial crude oils and extracts have the CV values greater than 0.47, while nonwaxy marine crude oils and extracts have the CV values less than 0.47 (Sofer, 1984). The stable carbon isotope values and calculated CV ratios for the analyzed crude oils and extracts from Hawler Block, Kurdistan Region, Iraq are shown in Table 3.

All the samples have CV values between -3.31 to -1.26 that signifies a nonwaxy marine source. Moreover, the $\delta^{13}C_{sat.}$ to $\delta^{13}C_{aro.}$ ratios show the nonwaxy marine source for the examined samples.

A number of researchers claim that a crude oils' Pr/Ph ratio of less than 0.8 suggests anoxic organic-rich carbonate source rock during deposition, Pr/Ph between 0.8 and 3 suggests redox- suboxic condition, and more than 3 suggest an oxic terrigenous organic matter in deposition (Didyk *et al*., 1978; Peters & Moldowan, 1993; Hughes *et al*., 1995). The Pr/Ph ratios for Z1 and Z5 are 1.09 and 1.45, respectively while for Z3 crude oil is 0.52 suggesting anoxic to suboxic condition for all three oils.

Aside from Pr and Ph are associated with n-alkanes C_{17} and C_{18}, correspondingly which is shown in a cross plot of Pr/C_{17} versus Ph/C_{18} (Figure 7). The plot demonstrates the marine source organic matter accumulation was deposited under reducing conditions.

The ternary diagram of $C_{27}S\%$, $C_{28}S\%$, and $C_{29}S\%$ steranes was widely used for figuring out the source of the original organic matter. The analyzed samples are characterized by the relative abundance of C_{29}. The analyzed samples were mainly deposited within a marine environment (Peters *et al*., 2005; Rabbani & Kamali, 2005) (Figure 8).

The results and calculated biomarkers are presented in Table 5. The ratio of $C_{29}H/C_{30}H$ for Z1, Z3, Z5 crude oils of the Sargelu, Naokelekan, and Najmah formations extracted rock cuttings are: 1.82, 1.04, 0.88, 1.43, 1.69, and 1.33; and the ratio of $C_{35}HS/C_{34}HS$ are: 0.76, 0.86, 1.16, 1.06, 0.97, and 0.95, respectively. The $C_{29}H/C_{30}H$ ratios >0.6 when coupled with the $C_{35}HS/C_{34}HS$ ratios >0.8 imply marine carbonate under anoxic conditions (Peters & Moldowan, 1991). Also, high $C_{22}TT/C_{21}TT$ ratios for Z1, Z3, Z5 crude oils of the Sargelu, Naokelekan, and Najmah formations extracted rock cuttings are: 1.00, 1.15, 1.38, 0.99, 0.92, and 0.69; with low $C_{24}TT/C_{23}TT$ ratios: 0.29, 0.35, 0.33, 0.31, 0.35, and 0.30, respectively supports the

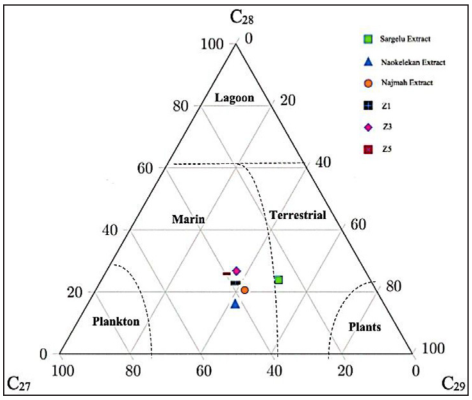

Figure 8: Steranes ternary diagram of C_{27}%, C_{28}% and C_{29}% concerning the crude oils from Z1, Z3, and Z5 wells, and cuttings extracts from Z1 Well, showing that the samples were deposited under marine environment (after Rabbani & Kamali, 2005).

marine carbonate sources under reducing conditions (Peters *et al*., 2005; Abdula, 2015; Abdula, 2017c). The occurrence of gammacerane is indicating a high salinity depositional under reducing condition. Thus, the oils from Z1, Z3, Z5 wells and extracts from the Sargelu, Naokelekan, and Najmah extracted rock cuttings were deposited under reducing condition associated with moderate salinity depending on GCRNI (gammacerane/hopane) ratio: 0.32, 0.13, 0.26, 0.25, 0.21, 0.22, respectively (Table 5) (Hunt, 1996; Peters *et al*., 2005; Mohialdeen *et al*., 2024).

Thermal maturity proxies

Thermal maturity is an indicator of thermal alteration during petroleum expulsion, chemical modification, and thermal breakdown of organic matter into hydrocarbons during burial (Osuji & Antia, 2005). Depending on this alteration compared with new produced chemical structures, thermal maturity can be indicated by biomarker and bulk parameters.

Immature source rocks frequently have high CPI values of >1.5, while CPI values for mature source rocks range from 0.8 to 1.2 (Moldowan *et al*., 1985). The calculated CPI values for all analyzed samples are ranging between 1.05 and 1.14 indicating that they are in the mature stage (Table 4). The ratios of $C_{31}HS/(C_{31}HS+C_{31}HR)$ homohopane and $C_{32}HS/(C_{32}HS+C_{32}HR)$ homohopane is a maturity parameter that were used in assessing the thermal maturity (Seifert & Moldowan, 1986). Equilibrium phase occurs between 0.57 and 0.62, while 0.50-0.54 suggest early oil window maturity (Osuji & Antia, 2005). Therefore, the studied crude oil samples are at least at early oil window maturation stage (Table 6). A cross plot of pristane/n-C_{17} versus phytane/n-C_{18} (Figure 7) suggest the same indication.

Age related proxies

Angiosperms and higher plants, which did not emerge until the end of the Cretaceous and into the Early Tertiary, are known to be the source of 18 (H)-Oleanane. Therefore, the biomarker 18 (H)-Oleanane has been used as a proxy for oils that originated from rocks that are Late Cretaceous or younger (Ekweozor & Udo, 1988). Oleanane Index (OI) is expressed as Oleanane Index=Oleanane/C_{30}Hopane. Whereas a lack or trace proportion of oleanane is compatible with a Jurassic or earlier source, and an oleanane ratio more than 0.2 indicates Tertiary source rocks (Peters *et al.*, 2005). All the samples have an OI less than 0.2, indicating a pre-Cretaceous age for their source rock (Table 6).

Extended tricyclic terpane ratios (ETR) is also the age-related proxy obtained by utilizing mass/charge 191 chromatograms for oil and extracts samples to discriminate between Triassic and Jurassic samples. Mathematically the ETR ratio is stated as ETR= $(C_{28}TT+C_{29}TT)/Ts$. The ETR ratios separate the Triassic samples ≥2.0 from the Jurassic samples ≤2.0 (Peters *et al*., 2005). Depending on their study which was based on geochemical and geological data, a

Table 6: The $C_{31}HS/(C_{31}HS+C_{31}HR)$ homohopane and $C_{32}HS/(C_{32}HS+C_{32}HR)$ homohopane ratios for thermal maturity indication, and used age proxy parameters of extracts in the selected formations from the Z1 Well and crude oils from three different wells.

Name of samples	Depth (m)	OLE	$C_{30}H$	$C_{28}TT$	$C_{29}TT$	Ts	OI	ETR	$C_{31}HS$	$C_{31}HR$	$C_{32}HS$	$C_{32}HR$	$C_{31}HS/(C_{31}HS + C_{31}HR)$	$C_{32}HS/(C_{32}HS + C_{32}HR)$
Sargelu Extract	3220 - 3225	0.42	11.90	0.42	1.02	3.45	0.03	0.42						
Naokelekan Extract	3180 - 3185	0.21	14.00	1.50	0.94	3.22	0.01	0.76						
Najmah Extract	2385 - 2390	0.44	18.40	0.22	0.37	0.83	0.02	0.71						
Z1 Crude Oil	UN	0.45	12.90	0.44	0.80	2.16	0.03	0.57	5.82	4.78	2.80	2.52	0.55	0.53
Z3 Crude Oil	UN	0.18	12.20	0.46	0.87	2.29	0.01	0.58	5.19	4.36	2.75	1.99	0.54	0.58
Z5 Crude Oil	UN	0.90	14.00	0.47	0.72	1.96	0.06	0.61	6.32	5.24	3.67	2.75	0.55	0.57

OLE: Oleanane; $C_{30}H$: C_{30}Hopane; $C_{28}TT$: C_{28}Tricyclic terpane; OI: OLE/$C_{30}H$
ETR: $(C_{28}TT+C_{29}TT)/Ts$; $C_{29}TT$: C_{29}Tricyclic terpane; Ts: C_{27} 18α-Trisnorneohopane

collection of crude oil samples throughout the world with Triassic and Jurassic source rocks were analyzed, hence documented that ETR was often less than 1.2 in Middle or Late Jurassic oil samples, and was almost always less than 2.0. The analyzed crude oil and extract samples have less than 1.2 which gives the evidence that their relative age is Middle to Late Jurassic (Table 6).

Oil-source rock correlation

Based on similarities in their compositions, hydrocarbons and source rocks can be geochemically correlated if they have a genetic relationship with each other. Gas chromatography/mass spectrometry of biomarkers is significantly utilized in geochemical correlations (Peters *et al*., 2005). The biomarkers that is suitable for oil-source rock correlation should contain sufficient distinctive chemical distributions between the source rocks and crude oils that assist for the separation of different source rocks and crude oils, and also have resistance to biodegradation (Tissot & Welte, 1984).

The Z1, Z3, and Z5 oils are related to extracts of Sargelu and Naokelekan formations rock cuttings; however, they are not related to the Najmah Formation extract from Z1 Well from Hawler Block according to C_{26}TT/C_{25}TT versus C_{31}HR/C_{30}H, and C_{29}H /C_{30}H versus C_{31}HR/C_{30}H (Figures 9 and 10).

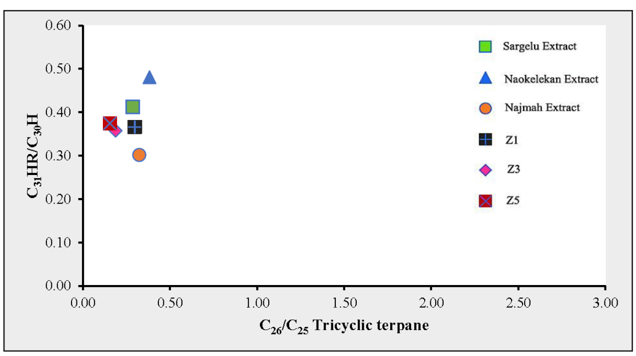

Figure 9: Plot of C_{26}/C_{25} tricyclic terpane versus C_{31}HR homohopane (22R)/C_{30}H hopane for crude oils from Z1, Z3, and Z5 wells, and cutting extracts from Z1 Well. The plot shows the relation of the oils with the extracted rock cuttings of the Sargelu, Naokelekan, and Najmah formations.

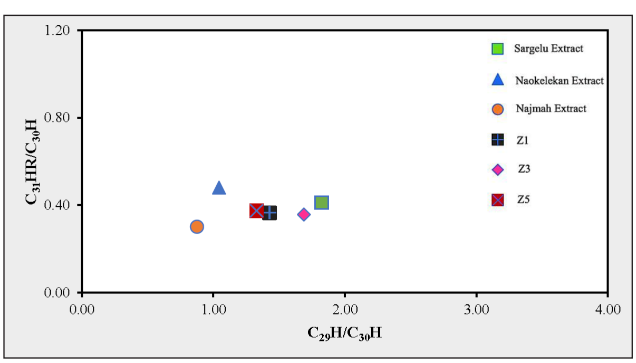

Figure 10: Plot of C_{29} norhopane/C_{30} hopane versus C_{31}HR homohopane (22R)/C_{30}H hopane for crude oils from Z1, Z3, and Z5 wells, and cutting extracts from Z1 Well. The plot displays a relation between extracted cutting rock of the Sargelu, Naokelekan, and Najmah formations with the oils that is produced in the same field.

The SARA compositions of oils classified them as paraffinic-naphthenic (Figure 5). Based on the API gravity, Z1 and Z5 are classified as medium crude oils and Z3 is classified as light crude oil. Z1 and Z5 were influenced by biodegradation; therefore, they are different in API and sulfur (Table 3).

The biomarkers and bulk properties have been used in form of different plots and indexes in order to evaluate the relation of their genetic source for the selected oils of the three wells. According to pristane/n-C_{17} versus phytane/n-C_{18}, steranes distributions of C_{27}, C_{28}, and C_{29} in the ternary diagram (Figures 7 and 8) considerably show good relationships among all three oils.

The selected oils appear to be originated by the same source rocks depending on the created plots and diagrams which indicate the similar genetic characterization for them, while having different separation and grouping between them in different biomarkers plotting which are due to their biodegradation.

The saturates and aromatics carbon isotope values signify a nonwaxy marine source for Z1, Z3, Z5, and rock cuttings extracted. The Ph/n-C_{18} versus Pr/n-C_{17} (Figure 7), and Pr/Ph ratio versus canonical variable (CV) (Tables 3 and 4) indicate the marine carbonate source rocks deposited under anoxic environment. In addition to acyclic isoprenoids, the other biomarker ratios such as: C_{29}H/C_{30}H, C_{35}HS/C_{34}HS, C_{22}TT/ C_{21}TT, and C_{24}TT/C_{23}TT indicate anoxic marine carbonate source rocks origin for the analyzed oils and rock cuttings extracted.

The ternary diagram of C_{27}%, C_{28}%, and C_{29}% steranes indicated that the studied samples were deposited within a marine environment (Figure 8). Based on gammacerane concentration of the oils from Z1, Z3, Z5 wells and extracts from Sargelu, Naokelekan, and Najmah rock cuttings, they were deposited in a moderate saline reducing condition.

The Sargelu, Naokelekan, and Najmah formations were suggested by earlier researches to be carbonate dominant sediments that were deposited under anoxic conditions (e.g., Abdula *et al*., 2015; Sharezwri *et al*., 2020; Albeyati *et al*., 2021).

The ratios of C_{31}HS/(C_{31}HS+C_{31}HR) homohopane and C_{32}HS/(C_{32}HS+C_{32}HR) homohopanes reveal that the analyzed crude oil samples are at least at early oil window maturity stage. The cross plot of pristane/n-C_{17} versus phytane/n-C_{18} (Figure 7) supports the similar thermal maturity state for oils. The maturity of Z3 is similar to Z1 and Z5, although it has higher API which could be due to migration of oil.

The relative age of the oils and cutting extracted samples is suggested to be Middle to Late Jurassic based on the oleanane and extended tricyclic terpane indexes. The findings of the oils from the Z1, Z3, and Z5 wells corroborate the theory that the accumulating oil in Iraq's major reservoir is produced mostly by Jurassic source rocks (Pitman *et al*., 2004).

The biomarker ratios plots and diagrams C_{26}TT/C_{25}TT versus C_{31}HR/C_{30}H (Figure 9), and C_{29}H/C_{30}H versus C_{31}HR/C_{30}H (Figure 10), indicate that the oils of Z1, Z3, and Z5 correlate with the rock cuttings extracted from the Sargelu and Naokelekan formations; however, it is not related to Najmah Formation because it is an immature source rock. As the Z1, Z3, and Z5 oils appear to be generated from marine reducing carbonate source rocks, as well as the cutting rock extract of the Sargelu and Naokelekan formations based on the depositional indices which suggested in this study are deposited under the same condition. Therefore, the oils are seemed to be related to the extracted cutting rocks of Sargelu and Naokelekan formations.

CONCLUSIONS

In order to reduce risk in petroleum exploration, this study determined the geochemical characterization of source rocks and crude oils. The interpretation from this study plays a significant role in recognizing the main Jurassic source rocks and their linkage to crude oils.

The Sargelu and Naokelekan formations are considered as a very good source rocks, and fair source rock for the Najmah Formation based on their TOC content. According to the obtained values from the pyrolysis analysis of the studied samples; the existed organic matter in the Sargelu Formation is kerogen types II and mixed II and III. However, the Naokelekan and Najmah formations are identified to be kerogen type II. The thermal maturity level for Sargelu and Naokelekan formations are at least at mature stage and Najmah Formation is at immature stage. Oil and gas prone for Sargelu Formation and oil prone for Najmah and Naokelekan formations were revealed from the pyrolysis analysis.

Z1 and Z5 oils are categorized as medium crude oils according to the API gravity, whereas Z3 is categorized as light crude oil. All three oils were classed as paraffinic-naphthenic based on the SARA analysis. Biomarkers characteristics show that the oils share a comparable genetic characteristic, which appear to have originated by the same source rock. However, the varied separation between them in different biomarkers plotting is caused by the biodegradation. A marine depositional setting was confirmed by carbon isotope ratios. Additionally, a carbonate source for oils and the Sargelu, Naokelekan, and Najmah formations rock cuttings extract in a reducing environment is indicated by the geochemical characteristics. Based on the gammacerane concentration of the oils from Z1, Z3, Z5 wells and extracts from Sargelu, Naokelekan, and Najmah rock cuttings, they were deposited in a moderate saline under reducing condition. Biomarkers sensitive to maturity indicated that the analyzed oil samples are at early oil window. Based on the oleanane and extended tricyclic terpane indices, cooperatively with the presence of gammacerane and C_{28}S/C_{29}S ratios, it is suggested that the relative age of the oils and cuttings extracted samples of the Sargelu, Naokelekan, and Najmah formations is pre-Cretaceous. The biomarker parameters provide evidence that molecules from the extracted rock cuttings of the Sargelu and Naokelekan formations are related to the Z1, Z3, and Z5 oils. However, they are not related to immature Najmah Formation cutting rock.

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AUTHORS CONTRIBUTION

CTM performed analysis and conducted geochemical result interpretation and wrote the whole manuscript. RAA contributed to critically reviewing the manuscript and contributing ideas to improve the paper.

CONFLICT OF INTEREST

The authors declare there is no conflict of interest.

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