



Hydrocarbon generation potential and thermal maturity of Middle Jurassic Sargelu Formation in Miran Field, Sulaimani Area, Kurdistan Region, NE Iraq

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Abstract

The total 61 unwashed cutting rock samples of Sargelu Formation from both Miran-3 (M-3) and Miran-4 (M-4) wells have been investigated in this study. The area of interest is Miran Field; which locates in the High Folded Zone, about 30 Km Northwest of Sulaimani City, Kurdistan region, NE of Iraq. The samples have been tested by Rock-Eval Pyrolysis and Vitrinite reflectance in order to determine organic richness, hydrocarbon potentiality, types of organic matter, and thermal maturity level of the Sargelu Formation in Miran Field.

The Total Organic Carbon content (TOC wt. %) for the Sargelu Formation ranged from 0.99-6.56 wt. %, average 2.23 wt. % for M-3 well, and between 0.86-6.41 wt. %, average 2.74 wt. % for M-4 well. It considered as a very good source rock based on TOC wt. % content. The data reveals that this formation in both wells has low amounts of Hydrogen Index (HI) (average 58, and 68 mg HC/g TOC for M-3 and M-4 wells, respectively), low amounts of S₂ (average 1.28, and 1.44 mg HC/g Rock for M-3 and M-4, respectively), as well as low amounts of Pyrolysable carbon (PC wt. %). While, the samples have high value of Residual Carbon (RC wt. %). Thus, the Sargelu Formation has low potentiality and it is classified as a poor to fair source rock for releasing hydrocarbons. According to the interpretation of the Rock-Eval data, the kerogen types of Sargelu Formation are mostly admixture between type II and type III kerogen. This result is also supported by microscopical approach, which indicating that the dominant organic matter populations within the samples are solid bitumen. However, the ability of Sargelu Formation is only remain for gas generation in the studied field.

The analyzed samples reveal high values of thermal maturity based on the values of equivalent vitrinite reflectance (eq.VRo %). The value of eq.VRo% is between 1.5%-1.55% for M-3 well and between 1.4%-1.45% for M-4 well, which indicate postmature; i.e. gas generation zone. Whereas, peak mature is assigned based on the production index (PI) parameter (average of PI is 0.33 and 0.27 for M-3 and M-4 wells, respectively). Maturity assessment bases on Tmax is not applicable in this study, because of the effects of mud additives, therefore this parameter is not depending for the maturity assessment of the studied formation.

Introduction

Source rock evaluation is considered as a significant task during oil exploration. It could also be used to source rock assessment, such as determining the levels of maturity, the types of organic matter content of a rock, and to define paleoenvironmental conditions (Hunt, 1996). Through which, the potentiality of particular formation can be defined. Evaluation of source rock accompanied with the various aspects of geology; such as sedimentology, petroleum geology, stratigraphy, geophysics, etc. would be used as a vital tool during preliminary investigations for oil and gas exploration (Tissot and Welte, 1984).

Middle Jurassic successions, as mentioned by Jassim and Al-Gailani (2006) are very important and extensive source rocks throughout south, northeast and north of Iraq. The rocks which were precipitated in this time span are characterized by preserving more total organic carbon (TOC%) content in a relatively mature condition (Beydoun, 1986). Also, Pitman et al., (2004) revealed that the most of Iraq's oils were derived from Jurassic source rocks. Moreover, one of the most favorable time span, in global scale, for accumulating organic matter was Jurassic Period, as mentioned by Peters et al., (2005). Sargelu Formation is marked by the development of relatively deep water and euxinic environment during the Middle Jurassic time (Jassim and Buday, 2006b). The climatic condition created a good environment for deposition and preservation of an adequate amount of organic matter which makes Sargelu Formation the most obvious source rock. Moreover, the Jurassic time is recognized by a transgression period that covered all Iraq except Rutba uplift (Ibid). Therefore, Sargelu Formation was deposited in a wide basin that needs further study in different localities to evaluate it.

All those phenomena we mentioned, encouraged us to select the Sargelu Formation in this research. Therefore, the main objectives in this research are to characterize the Sargelu Formation in order to determine: organic richness (TOC % content), hydrocarbon potentiality, type of organic matter content (Kerogen types), and types of expelled hydrocarbon based on maturity level.

Geologic setting

The study area, Miran Field, is located about 30 Km Northwest of Sulaimani City, NE Iraq (Figure 1). Miran Field is belonged to the Miran Block; it occupies about 70 Km length by 15 Km width, elongated in the Northwest-Southeast direction.

Sargelu Formation was first recognized and described by Wetzel and Morton (1950 in Bellen et al., 1959) from Surdash Anticline of the High Folded Zone of the northern Iraq. Based on the master log of M-3 and M-4 wells, which were created by Heritage Oil Company, the Middle Jurassic Sargelu Formation is underlain by Alan Formation instead of Sehkanian Formation, and overlain by Naokelekan Formation with conformable gradational contact (Figure 2). The thickness of the Sargelu Formation in M-3 well is 188.2 m, at the depth interval between 2418 m to 2606.2 m. while in M-4 well the formation begins from depth of 2882.4m to 2994.5 m, thus the thickness is 112.1m.

Tectonically, Miran Field situates in the High Folded Zone according to the tectonic map of Iraq (Figure 1). This zone consists of harmonic folds with Mesozoic limestone in their cores and Palaeogene and Neogene limestone and clastic on their flanks (Jassim and Buday, 2006a). Field mapping and seismic data indicate that there is a large anticlinorium in the Miran block which is formed by two sub-parallel anticlines known as Miran East and Miran West Anticlines (Heritage report, 2012). Jassim and Buday, (2006a) mentioned that the effect of block movements in the High Folded Zone was intermittently uplifted this area during Cretaceous and Palaeogene, also strongly deformed in the Late Tertiary. One of the anticlines in this area which were subjected to this deformation is Miran anticline; which was subjected to thick-skinned deformation before two million years ago (Kubli, 2013). This deformation causes little shortening, steep reverse faults and tightening of pre-existing anticlines as well as causing uplift of several anticlines in this area. Al-Hakari (2011) mentioned that the Miran structures (East and West) have slight expressions on the surface. The structures are capped by Sinjar Formation as it is mostly eroded by weathering processes.

The Sargelu Formation belongs to a basin which known as "Gotnia Basin" as mentioned by Aqrawi et al. (2010). Deposition in this basin occurred in a restricted, relatively deep water environment during Middle Jurassic, and the basin became evaporitic from Late Kimmeridgian to Early Tithonian. The margin of Gotnia

basin is not well known because of subsequent erosion (Ibid). The Depositional environment of Sargelu Formation was assigned as a basinal euxinic marine environment (Buday, 1980; Jassim and Buday, 2006b).

During Mid Jurassic time, the sea level rise and probably reached to the maximum flooding surface (MFS). This phenomenon was lead to the development of deep water and then the Posidonia-bearing shale of lower part of Sargelu Formation has been precipitated (Sharland et al., 2001). According to the assumptions of Jassim and Buday (2006b), the rock units of Mid - Late Jurassic Megasequence were deposited during the time of isolation of a main intra-shelf basin of Mesopotamia from the Neo-Tethys Ocean probably due to the regenerated rifting along the northeastern margin of the Arabian Plate.

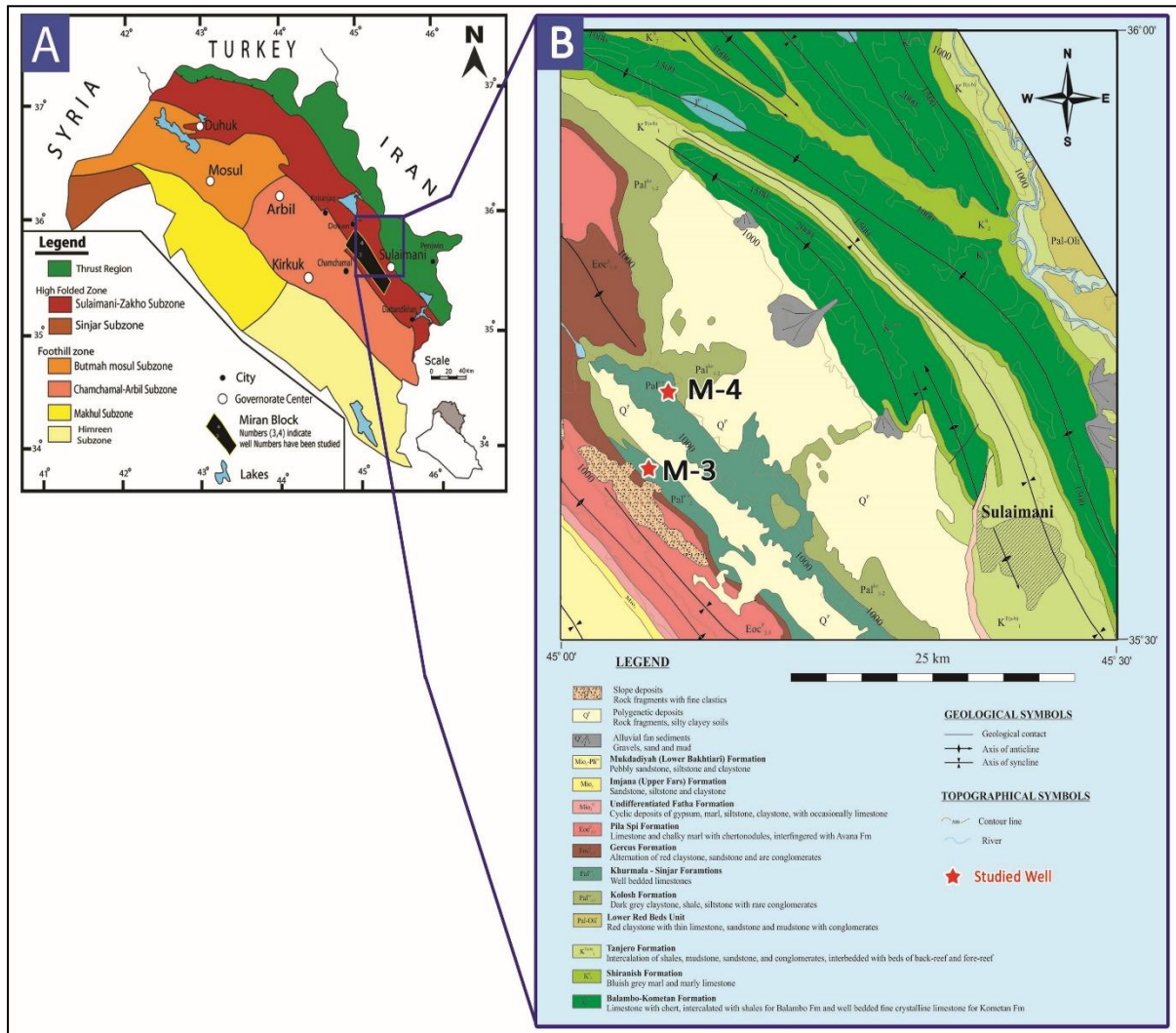


Figure 1: Location map of the study area. A: simplified Tectonic Map of northern Iraq with an indication of Miran Block, B: Geological map of studied area (after GEOSURV-IRAQ, 1996).

Many researchers (Buday, 1980; Balaky, 2004; Pitman et al., 2004; Jassim and Al-Gailani, 2006; Sherwani and Balaky, 2006; Abdula, 2010; Al-Ahmed, 2011; Al-Ameri and Zumberge, 2012; Al-Ahmed, 2012; Al-Badry, 2012; Hussein et al., 2013; Summons et al., 2013; Al-Ameri et al., 2013; Abdula, 2014) have been tried to describe Sargelu Formation in different localities as well as in different aspects of geology to characterize this rock unit.

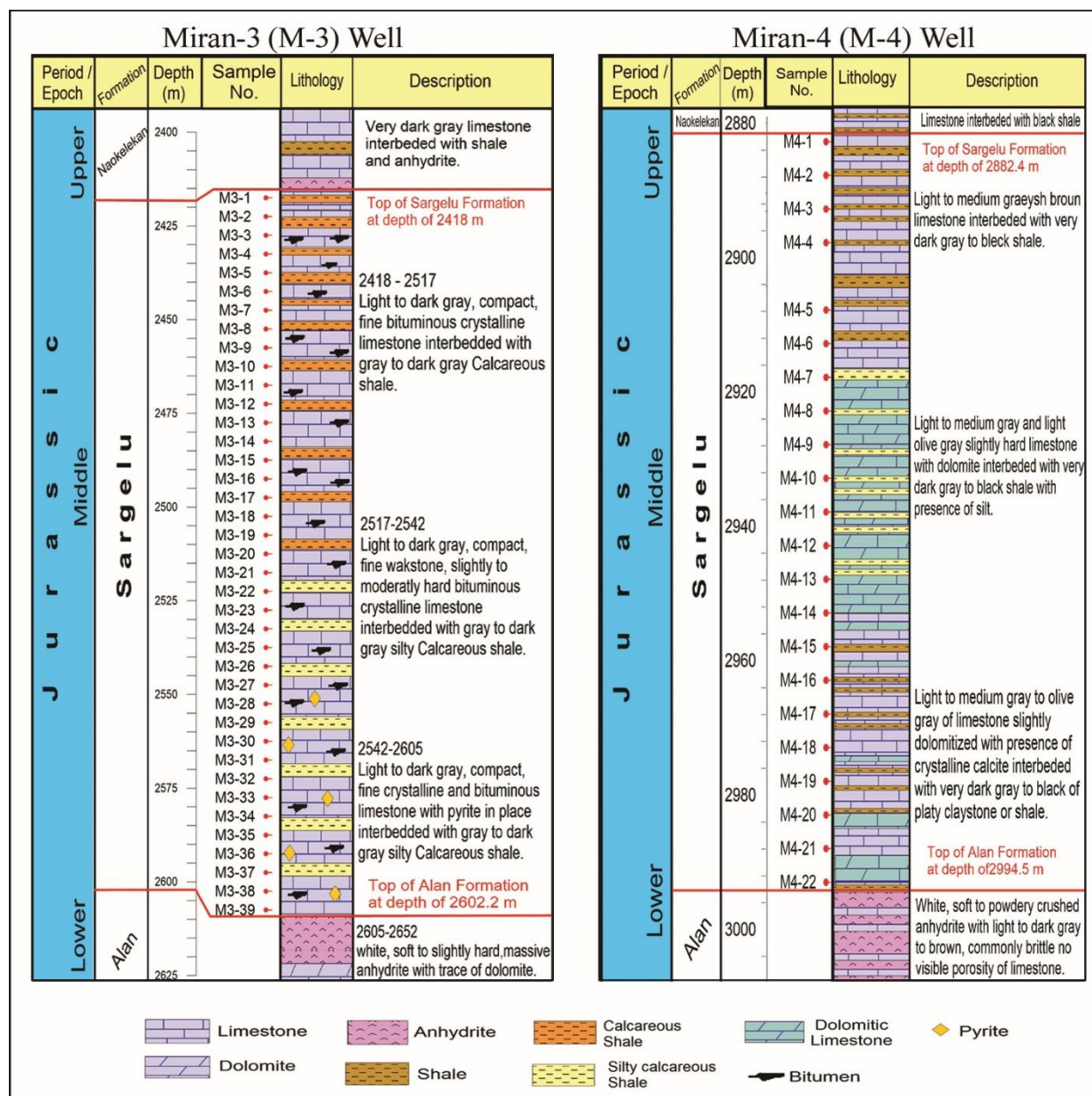


Figure 2: Stratigraphic column of M-3 and M-4 wells, with indication of sample numbers. Compiled from Jassim and Buday (2006b), and master log of both wells that were created by Heritage Oil Company (2012).

Materials and Methods

The total 61 unwashed cutting rock samples of Sargelu Formation (39 samples from M-3, and 22 samples from M-4) have been taken from the store house of the Ministry of Natural Resources in Erbil Governorate (Figure 2). The samples have been tested in CSTGF Center (Laboratory of TOTAL Oil Company) in Pau City, France. All the samples have been analyzed by Rock-Eval pyrolysis. Three samples from M-3 and 2 samples from M-4 wells have been used in order to determine vitrinite reflectance measurement.

A. Rock-Eval Pyrolysis

This test is performed to all the selected samples. The samples have been crushed, pulverized, homogenized and then analyzed by Rock-Eval 6 apparatus. The process involves a continuous heating of a small amount of pulverized rock sample (70-100 mg) in an inert atmosphere (Helium or Nitrogen gas) under programmed temperature ranging from 100°C – 850 °C. Heating of the sample started from 100 °C then held in 300 °C for several minutes followed by programmed heating at 25 °C per minute to maximum temperature about 850 °C. The more details about this technique and its parameters can be provided in

(Tissote and Welte (1984), Espitalie et al. (1985), Peters (1986), Peters and Cassa (1994), Lafargue et al., (1998), and Behar et al., (2001). The Four main parameters have been provided by this method: **S1**; represents thermo-vaporized free and adsorbed hydrocarbons released about 300 °C, **S2**; corresponds to the thermal degradation of kerogen at a temperature between 300-650 °C, **S3**; provides CO and/or CO₂ that is released from organic compounds containing Oxygen element, and **T_{max}**, which represents the Rock-Eval pyrolysis temperature (°C) at maximum S₂ peak generation. These parameters are used to calculate some other parameters such as: Total Organic Carbon (**TOC** wt. %); Hydrogen Index (**HI**=S₂/TOC×100, in mg HC/g TOC); Oxygen Index (**OI**= S₃/TOC×100, in mg CO₂/g TOC); Genetic Potential (**GP**=S₁+S₂.) and Production Index (**PI**=S₁/S₁+S₂). Additionally, two other parameters (Pyrolysable Carbon (PC %) and Residual Carbon (RC %)) have been calculated. The former one belongs to all of the organic compounds decomposed during vaporizing and cracking, while later one corresponds to the all of inert organic compounds which generate neither oils nor gases. Results are tabulated in Tables 1 and 2.

B. Vitrinite Reflectance

Microscopical examination applied in this study for both Kerogen-containing rock and isolated kerogen in 6 samples (Five samples from Sargelu Formation. And One sample from Alan Formation) depending on richness in organic carbon content. The kerogen isolated from the matrix (using HCl and HF to remove most of the minerals) and embedded in an epoxy resin, grinded with carborundum and diamond grit, and then polished. While, all rock samples crushed and embedded in resin, grinded, and then polished. In this study, the maturity evaluation was performed by optical observation (vitrinite reflectometry and UV fluorescence intensity). The analysis were carried out on both; polished concentrates of organic matter obtained by densimetric techniques, and on polished sections of rock grains. Due to the richness of the samples by organic particles and the variety of organic populations, up to 100 readings per slides were recorded. Reflectance measurements were performed with natural white light (random reflectance R_o %), no polarized light measurement (R_m %) was done in this study. The lack of vitrinite macerals in the selected samples prevent us to take direct vitrinite reflectance measurement, therefore, the solid bitumen reflectance (BRo%) used instead of real vitrinite reflectance (VRo%), then the value of BRo% converted to the equivalent vitrinite reflectance (eq. VRo%) by using Jacob's equation:

$$(VRo = 0.618 * BRo + 0.40)..... \text{Jacob's equation (Jacob, 1989).}$$

Results and discussion

A. Source Rock richness and Potentiality

The TOC wt%, Rock-Eval parameters, and Vitrinite reflectance measurement results for the selected samples are listed in Tables 1, and 2. Total organic carbon values for the rock samples showed wide ranges from 0.99 – 6.56 wt% and 0.86-6.41 wt% (average of 2.23 and 2.74 wt%) for M-3 and M-4 wells respectively. These values are indicative to a very good potential source rock (Peters, 1986; and Peters and Cassa, 1994). While, based on the GP parameter, as described by Tissot and Welte (1978), Sargelu Formation is considered as a poor and a moderate source rock in M-3 and M-4 wells, respectively (Tables 1 & 2). The disagreement between TOC% and GP parameters might be related to the fact that not all organic rich sediments are a good generator for hydrocarbon (Peters, 1986). Moreover, the majority of TOC% in the studied samples represents the inert organic material (RC%) which also support low potentiality.

The cross plot of GP versus TOC% content (Figure 3;A) revealed that the Sargelu Formation in both wells showed an acceptable range of TOC% content to be a good source rock. Approximately, all the samples have more than 1% of TOC content. While, all of them showed poor to fair genetic potential, except of the three samples in M-3 well that they showed a good genetic potentiality in depths 2417.5, 2422.5, and 2447.5m. Despite the fact that a good source rock should have relatively high TOC% contents, but TOC% by itself is not a good indicator to determine how much hydrocarbon might be generated by the rock (Dembicki, 2009).

The cross plot of S₂ versus TOC % (Figure 3; B) showed that there are a little potentiality remained for Sargelu Formation in both wells, which nearly all of the samples have poor potentiality. The Sargelu Formation in these two wells might be expelled its hydrocarbons in past geologic time. Therefore, by depending on this diagram, this rock unit showed poor potentiality to generate hydrocarbon. It should be taken into consideration that this plot shows the ability of Sargelu Formation for generating hydrocarbon

nowadays. Therefore at the present time, the capacity of this rock unit for hydrocarbon generation is restricted only for gas generation (without oil), but the story of hydrocarbon generation in past might be different because of different situation in thermal history.

Table 1: Rock-Eval Pyrolysis and equivalent vitrinite reflectance measurement data for the selected samples of Sargelu Formations in M-3 well, Kurdistan Region, Northern Iraq.

Formation	Depth (m)	Sample	TOC	S1	S2	S3	S2/S3	HI	OI	GP	PI	Tmax	PC	RC	eq. VRo%
Sargelu	2417.5	M3-7	4.98	2.73	3.22	2.17	1.48	65	44	6.0	0.5	476			
Sargelu	2422.5	M3-8	6.56	2.16	3.11	1.28	2.43	47	20	5.3	0.4	489	0.5	6.06	1.54
Sargelu	2427.5	M3-9	5.14	1.44	2.22	1.86	1.19	43	36	3.7	0.4	494			
Sargelu	2432.5	M3-10	2.76	0.99	1.48	0.84	1.76	54	30	2.5	0.4	579	0.24	2.52	
Sargelu	2437.5	M3-11	2.07	1.09	1.39	1.49	0.93	67	72	2.5	0.4	441			
Sargelu	2442.5	M3-12	3.13	1.18	1.79	0.84	2.13	57	27	3.0	0.4	569	0.28	2.85	
Sargelu	2447.5	M3-13	4.52	1.52	3.19	1.28	2.49	71	28	4.7	0.3	487			
Sargelu	2452.5	M3-14	3.54	0.93	1.99	0.71	2.80	56	20	2.9	0.3	481	0.27	3.27	
Sargelu	2457.5	M3-15	2.79	0.75	1.59	0.75	2.12	57	27	2.3	0.3	443	0.23	2.56	
Sargelu	2462.5	M3-16	2.44	0.74	1.49	1.23	1.21	61	50	2.2	0.3	437			
Sargelu	2467.5	M3-17	2.21	0.60	1.15	0.86	1.34	52	39	1.8	0.3	435	0.18	2.03	
Sargelu	2472.5	M3-18	2.05	1.36	1.76	1.89	0.93	86	92	3.1	0.4	430			
Sargelu	2477.5	M3-19	2.20	0.48	1.10	0.68	1.62	50	31	1.6	0.3	438	0.16	2.04	1.52
Sargelu	2482.5	M3-20	2.06	0.49	1.14	0.60	1.90	55	29	1.6	0.3	435	0.16	1.9	
Sargelu	2487.5	M3-21	1.82	0.63	1.20	1.31	0.92	66	72	1.8	0.3	421			
Sargelu	2492.5	M3-22	1.77	0.49	1.01	0.60	1.68	57	34	1.5	0.3	434	0.15	1.62	
Sargelu	2497.5	M3-23	1.40	0.53	1.01	1.01	1.00	72	72	1.5	0.3	425			
Sargelu	2502.5	M3-24	1.56	0.20	0.73	0.39	1.87	47	25	0.9	0.2	440	0.09	1.47	
Sargelu	2507.5	M3-25	2.12	0.30	1.09	0.40	2.73	51	19	1.4	0.2	440	0.13	1.99	
Sargelu	2512.5	M3-26	1.45	0.20	0.73	0.80	0.91	50	55	0.9	0.2	436			
Sargelu	2517.5	M3-27	0.99	0.32	0.65	1.15	0.57	66	116	1.0	0.3	430			
Sargelu	2522.5	M3-28	1.60	0.35	0.88	0.60	1.47	55	38	1.2	0.3	435	0.13	1.47	
Sargelu	2527.5	M3-29	1.84	0.39	0.84	0.73	1.15	46	40	1.2	0.3	433	0.13	1.71	
Sargelu	2532.5	M3-30	1.67	0.67	1.23	1.14	1.08	74	68	1.9	0.4	428			
Sargelu	2537.5	M3-31	1.74	0.30	0.81	0.45	1.80	47	26	1.1	0.3	434	0.11	1.63	
Sargelu	2542.5	M3-32	1.42	0.38	0.91	0.65	1.40	64	46	1.3	0.3	432	0.13	1.29	
Sargelu	2547.5	M3-33	1.75	0.56	0.96	0.80	1.20	55	46	1.5	0.4	427			
Sargelu	2552.5	M3-34	1.40	0.26	0.72	0.52	1.38	51	37	1.0	0.3	434	0.1	1.3	
Sargelu	2557.5	M3-35	1.36	0.27	0.73	0.55	1.33	54	40	1.0	0.3	429	0.11	1.25	
Sargelu	2562.5	M3-36	1.96	1.30	2.06	1.50	1.37	105	77	3.4	0.4	427			
Sargelu	2567.5	M3-37	1.38	0.33	0.80	0.67	1.19	58	49	1.1	0.3	427	0.12	1.26	
Sargelu	2572.5	M3-38	1.43	0.55	0.96	0.80	1.20	67	56	1.5	0.4	423			
Sargelu	2577.5	M3-39	1.82	0.66	1.18	0.63	1.87	65	35	1.8	0.4	429	0.18	1.64	
Sargelu	2582.5	M3-40	1.64	0.28	0.75	0.58	1.29	46	35	1.0	0.3	424	0.11	1.53	
Sargelu	2587.5	M3-41	1.70	0.85	1.49	1.38	1.08	88	81	2.3	0.4	423			
Sargelu	2592.5	M3-42	1.84	0.17	0.47	0.50	0.94	26	27	0.6	0.3	565	0.08	1.76	1.94
Sargelu	2597.5	M3-43	1.79	0.18	0.32	0.60	0.53	18	34	0.5	0.4	577	0.07	1.72	
Sargelu	2602.5	M3-44	1.44	0.71	0.97	1.19	0.82	67	83	1.7	0.4	420			
Sargelu	2607.5	M3-45	1.49	0.25	0.70	0.45	1.56	47	30	1.0	0.3	425	0.1	1.39	
	Min		0.99	0.17	0.32	0.39	0.53	18	19	0.50	0.21		0.1	1.3	
	Max		6.56	2.73	3.22	2.17	2.80	105	116	5.95	0.46		0.5	6.1	
	Average		2.23	0.71	1.28	0.92	1.45	58	46	1.98	0.33		0.2	2.0	

S1: Volatile hydrocarbon (HC) content, mg HC/g rock.
 S2: Remaining HC generative potential, mg HC/g rock.
 S3: Carbon dioxide yield, mg CO₂/g rock.
 HI: Hydrogen Index = S₂/TOC x100, mg HC/g TOC.
 OI: Oxygen Index = S₃/TOC x100, mg CO₂/g TOC.
 Tmax: Temperature at maximum of S₂ peak.

PI: Production Index = S₁/ (S₁ + S₂).
 GP: Genetic Potential = S₁ + S₂.
 TOC: Total Organic Carbon, wt. %.
 PC: Pyrolysable Carbon wt. %.
 RC: Residual Carbon wt. %.
 eq. VRo: equivalent Vitrinite Reflectance %.

Table 2: Rock-Eval Pyrolysis and equivalent vitrinite reflectance measurement data for the selected samples of Sargelu Formations in M-4 well, Kurdistan Region, Northern Iraq.

Formation	depth (m)	Samples	TOC	S1	S2	S3	S2/S3	HI	OI	GP	PI	Tmax	PC	RC	eq. VRo%
Sargelu	2882.5	M4-1	3.41	0.7	1.78	2.25	0.79	52	66	2.5	0.3	568			
Sargelu	2887.5	M4-2	6.41	0.5	2.19	1.52	1.44	34	24	2.7	0.2	595	0.29	6.12	
Sargelu	2892.5	M4-3	4.92	0.3	1.68	1.07	1.57	34	22	2.0	0.2	580	0.21	4.71	1.43
Sargelu	2897.5	M4-4	3.10	0.4	1.27	1.59	0.80	41	51	1.7	0.3	565			
Sargelu	2907.5	M4-5	3.16	0.7	1.69	2.10	0.80	53	66	2.4	0.3	416			
Sargelu	2912.5	M4-6	3.98	0.4	1.57	1.48	1.06	39	37	2.0	0.2	417	0.23	3.75	
Sargelu	2917.5	M4-7	1.68	0.9	1.83	3.79	0.48	109	226	2.7	0.3	429			
Sargelu	2922.5	M4-8	0.86	0.1	0.36	1.25	0.29	42	145	0.5	0.3	409	0.09	0.77	
Sargelu	2927.5	M4-9	2.69	0.5	1.65	2.79	0.59	61	104	2.2	0.3	427			
Sargelu	2932.5	M4-10	3.58	0.3	1.46	1.28	1.14	41	36	1.8	0.2	426	0.2	3.38	
Sargelu	2937.5	M4-11	3.18	0.3	1.24	1.24	1.00	39	39	1.6	0.2	421	0.18	3	
Sargelu	2942.5	M4-12	1.87	1.1	1.72	3.80	0.45	92	203	2.8	0.4	422			
Sargelu	2947.5	M4-13	4.05	0.5	1.57	1.51	1.04	39	37	2.0	0.2	417	0.23	3.82	1.39
Sargelu	2952.5	M4-14	2.02	1.1	1.65	3.85	0.43	82	191	2.7	0.4	417			
Sargelu	2957.5	M4-15	1.91	0.8	1.38	2.80	0.49	72	147	2.2	0.4	419			
Sargelu	2962.5	M4-16	1.98	0.3	1.14	1.7	0.67	58	86	1.4	0.2	423	0.19	1.79	
Sargelu	2967.5	M4-17	1.93	0.4	0.91	1.39	0.65	47	72	1.3	0.3	407	0.16	1.77	
Sargelu	2972.5	M4-18	1.26	1.0	1.77	3.98	0.44	140	316	2.8	0.4	422			
Sargelu	2977.5	M4-19	2.44	0.4	1.62	1.92	0.84	66	79	2.0	0.2	426	0.25	2.19	
Sargelu	2982.5	M4-20	2.97	0.5	1.48	1.04	1.42	50	35	2.0	0.3	466			
Sargelu	2987.5	M4-21	1.56	0.3	0.66	1.4	0.47	42	90	0.9	0.3	383	0.14	1.42	
Sargelu	2992.5	M4-22	1.26	0.9	1.14	2.81	0.41	90	223	2.0	0.4	409			
Alan	3012.5	M4-23													1.94
Min			0.86	0.13	0.36	1.04	0.29	34	22	0.49	0.16		0.09	0.77	
Max			6.41	1.08	2.19	3.98	1.57	140	316	2.80	0.44		0.29	6.12	
Average			2.74	0.56	1.44	2.12	0.79	60	104	2.01	0.27		0.20	2.97	

S1: Volatile hydrocarbon (HC) content, mg HC/g rock.
 S2: Remaining HC generative potential, mg HC/g rock.
 S3: Carbon dioxide yield, mg CO₂/g rock.
 HI: Hydrogen Index = S₂/TOC x100, mg HC/g TOC.
 OI: Oxygen Index = S₃/TOC x100, mg CO₂/g TOC.
 Tmax: Temperature at maximum of S₂ peak.

PI: Production Index = S₁ / (S₁ + S₂).
 GP: Genetic Potential = S₁ + S₂.
 TOC: Total Organic Carbon, wt. %.
 PC: Pyrolysable Carbon wt. %.
 RC: Residual Carbon wt. %.
 eq. VRo: equivalent Vitrinite Reflectance %.

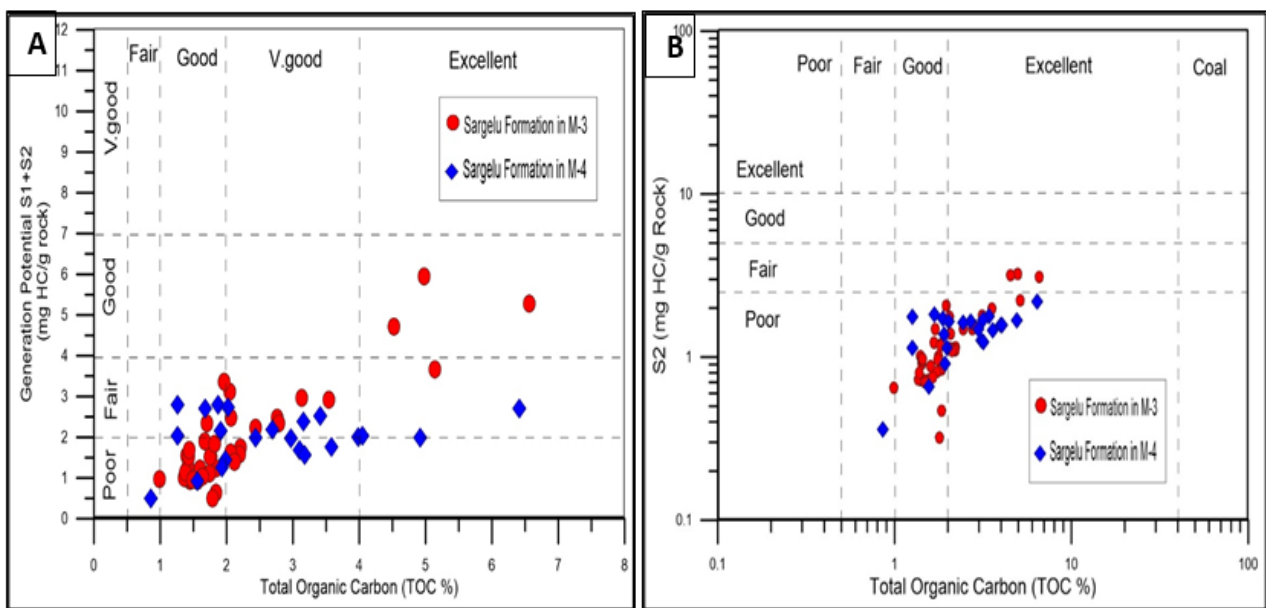


Figure 3: (A): Cross plot of TOC% content versus Genetic Potential (after Alaug et al., 2013). (B): relation between TOC% content versus S₂ (from Dembicki, 2009), for analyzed samples of Sargelu Formation in M-3 and M-4 wells.

The diagram between residual carbon (RC %) and TOC% of English et al., (2004) supports the previous conclusion about the source rock richness and potentiality of the studied formation (Figure 4). From this plot we concluded that, there is a little potentiality left behind the samples. The values of TOC% are very close to the RC% values in the majority of the samples, That is reveals the fact that, Sargelu Formation in these two wells has low potentiality to generate petroleum in the present time. It is considered as a spent source rock according to the terms that are described by Peters and Cassa (1994), but far away in a previous time, might be a good oil generator.

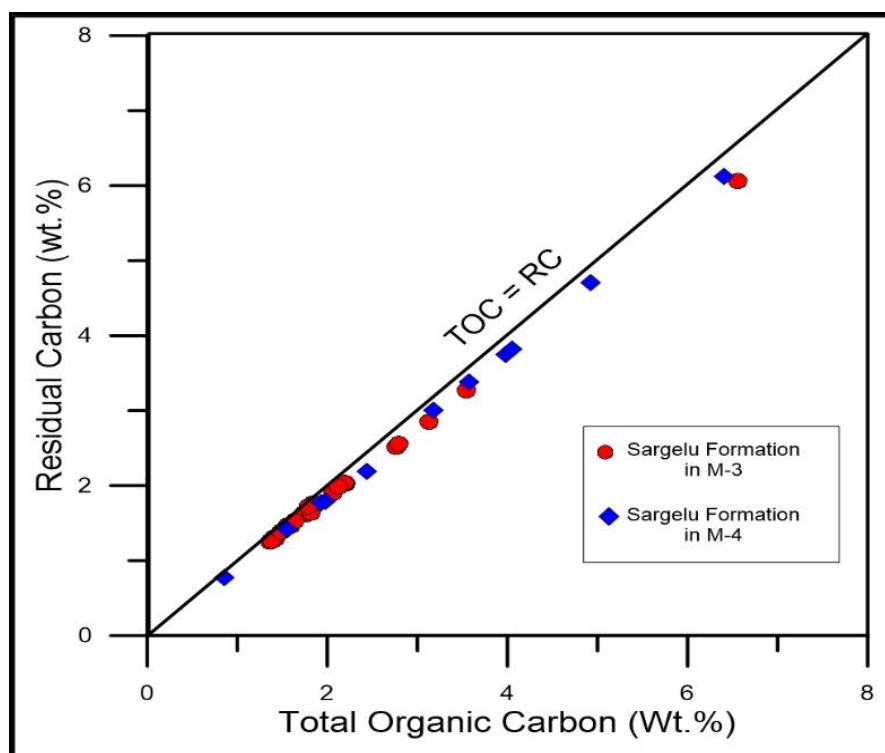


Figure 4: Cross plot of TOC% versus RC% of English et al. (2004), for the selected samples in Sargelu Formation from M-3 and M-4 wells. Solid line is an indication of TOC% value is equal to RC% value.

B. Kerogen Types and Types of Expelled Hydrocarbon

Determining of various types of kerogen in a source rock is considered as an essential work, because different types of organic matters have different potentiality to generate hydrocarbons (Tissot and Welte, 1978 and 1984). The relation between OI versus HI demonstrates the distribution of all the Sargelu samples analyzed (Figure 5). Accordingly, all the samples of M-3 well, as well as most of the samples of M-4 well are considered to have containing type III and type IV kerogen, but this result is inconsistent with the microscopical examination of the samples. All of the observed samples are free from reliable vitrinite macerals, which are the essential precursors for kerogen type III (Tissot and Welte, 1984; Hunt, 1996; Killips and Killips, 2005; Peters et al., 2005), but they are predominantly contain pyro bitumen (solid bitumen) which is indication for type II or mixed type II and type III kerogen.

The S2/S3 ratio is an indication of kerogen type variety (Alsharhan and Abd El-Gawad, 2008; Mohialdeen et al., 2013). The average of S2/S3 and HI values are of 1.45, 0.79 and 58, 60 mg HC/g TOC for the samples of M-3 and M-4 wells, respectively (Tables 1 and 2). These values indicate that the main expelled hydrocarbon for Sargelu Formation, at present time, is remain only for gas generation based on the guidelines proposed by Peters (1986) and Peters and Cassa (1994).

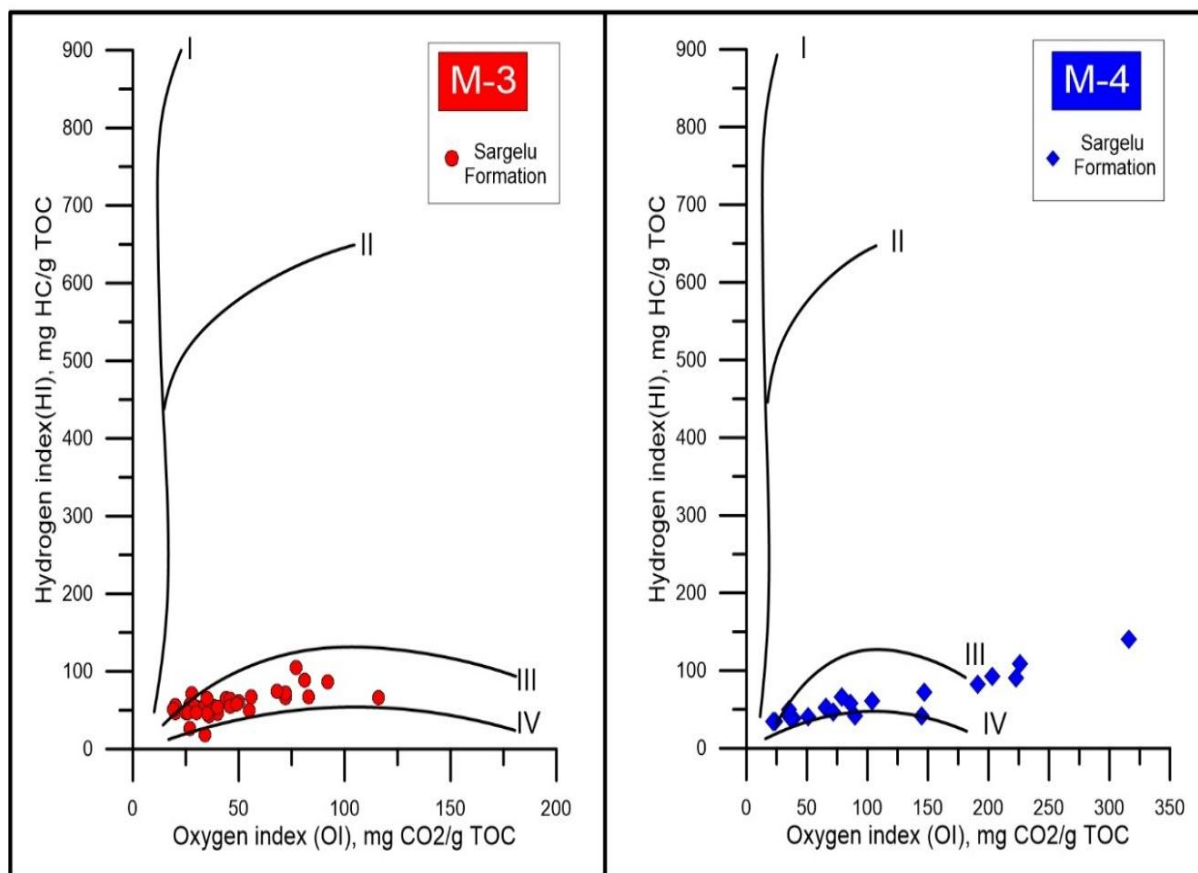


Figure 5: Analyzed samples of Sargelu Formation in both M-3 and M-4 wells plotted on the OI versus HI diagram. (The diagram from Hunt, 1996).

However, the abundant population of organic matter within the samples is solid bitumen, but very high level of maturity limits the optical determination of organic matter. The existence of abundant solid bitumen is a good indicator for past generation and expulsion of oil (Jacob, 1989; Landis and Castano, 1995). Presence of abundant solid bitumen, reveals that the organic matter content of Sargelu Formation might be oil prone type II or a mixture of type II and type III kerogen. The absence of reliable vitrinite (small quantity is present but not enough for measurement) in the examined samples is not surprising, giving the fact that the organic matters of Sargelu Formation formed type II kerogen or might be mixed type II-III. Tissot and Welte (1984) stated that the vitrinite macerals are commonly scarce in type II kerogen. Moreover, the Sargelu Formation was described by several authors (Balaky, 2004; Abdula, 2010; Al-Ameri et al., 2013) to be deposited in marine carbonate depositional environment. This type of environment is commonly lacks or contains less terrestrially-derived organic matter (Vitrinite macerals). It is also noticeable that all of the analysed samples has low Hydrogen Index (HI) values. This situation is related to the high level of thermal maturity which are discussed in the next section.

C. Maturity assessment

Rock-Eval parameters like; T_{max} , and PI are used for determining the maturity level of source rocks but partly depend on the types of organic matters (Peters and Cassa, 1994). The value of T_{max} is considered as a maturity indicator nearly between 420-460 °C and 400-600 °C for kerogen type II and terrestrial derived type III kerogen, respectively (Tissot and Welte, 1984). On the other hand, Peters (1986) and Peters and Cassa (1994) classified maturity levels of source rock which depend on T_{max} , Ro, and PI. They mentioned that the beginning and ending of oil window are about 0.1-0.4, 435-470 °C and 0.6% - 1.35% for PI, T_{max} and VRo, respectively. This classification is also used in the present study.

The cross plot of HI versus T_{max} is used for determining the kerogen quality and maturity assessment more than HI versus OI in order to eliminate the effects of OI value (Hunt, 1996). Graphical presentation of HI versus T_{max} (Figure 6) indicates a wide range of T_{max} from immature to postmature range. The distribution of the samples, bases on T_{max} values, nearly the same in M-3 and M-4 wells. In both wells, the samples are located either in immature zone (Green bounded circle group) or in postmature zone (blue bounded circle group). The low value of T_{max} is mostly related to the presence of recent organic matter (Texto-Ulminie) as generally named as mud additives, which clearly seen under the microscope (Figure 7). Such compounds are affected on the reliability of T_{max} and causing lowering down of the T_{max} values. Regarding to the high values of T_{max} are probably reflecting either residual contamination or possibly the presence of recycled organic matters, which are dominated by inertinite macerals (Akinlua et al., 2005). These are represented as Residual Carbon (RC%), which are cracked in a high temperature level.

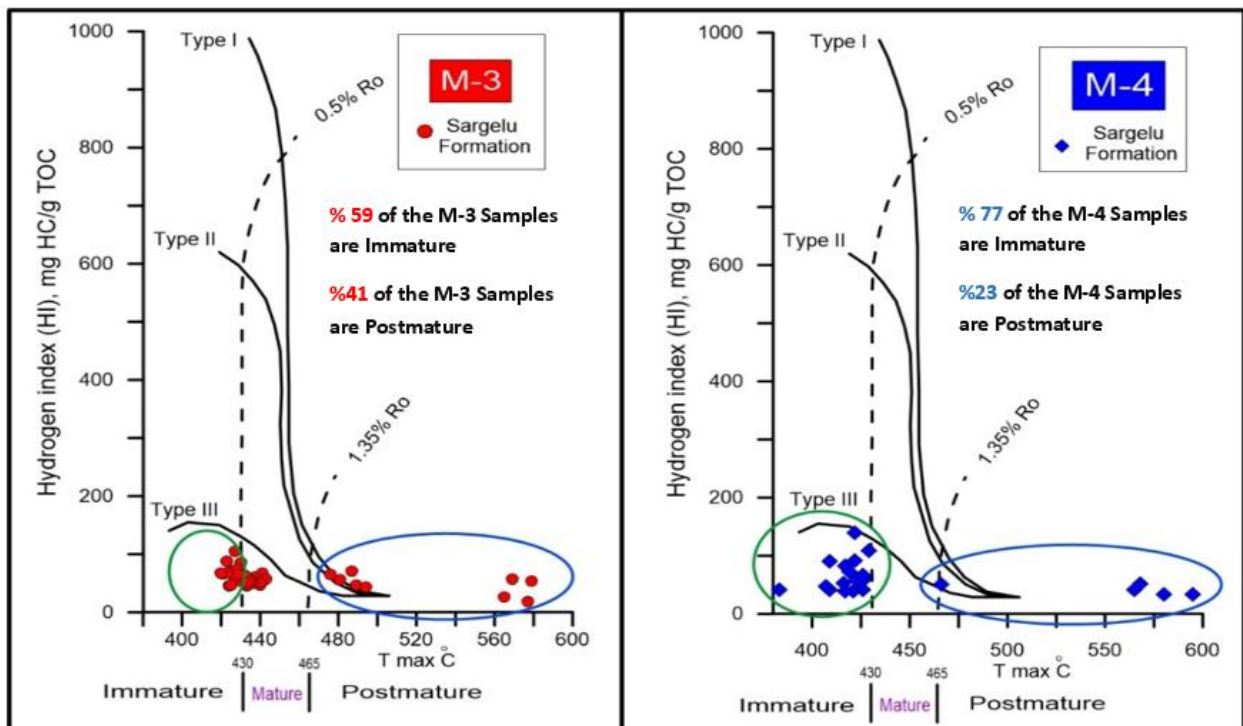


Figure 6: The cross plot of HI versus T_{max} of Hunt (1996), showing the examined samples of Sargelu Formation in M-3 and M-4 wells. Green bounded circle group indication for immature samples, while blue bounded circle group is indication of postmature samples.

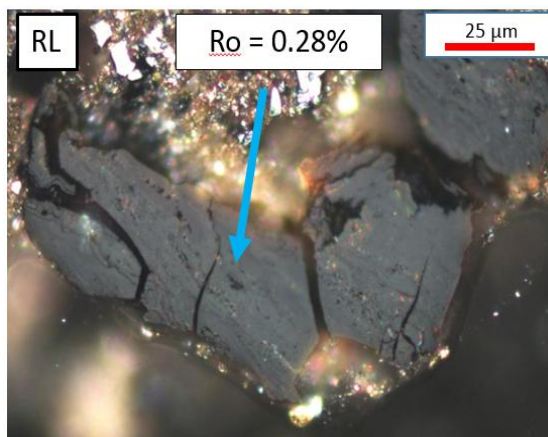


Figure 7: Photomicrograph of the selected samples of Sargelu Formation in M-3 Well. RL: Reflected light. The thick blue arrow indication for Huminite maceral (Texto-Ulminie), this maceral group some time expressing as Lignite (mud additives) as a descriptive word for low stage of maturity.

The values of both PI and T_{max} are changed with depth as a function of increasing maturity with depth (Figure 8). The general trend of T_{max} for Sargelu Formation in these diagrams is appeared more or less around 435 °C for M-3 well and 420 °C for M-4 well, except for the upper part of the formation in both wells where some samples have high T_{max} values which are more than 475 °C. It is clearly noticeable that the value of T_{max} is also inconsistency with the PI values (Figure 8), on the other hand the bimodal S2 peak also been noticed during pyrolysis (Figure 9). In such cases, the T_{max} value cannot be used for maturity assessment, because it does not represent the real cracking products of kerogen (Hunt, 1996). Therefore, T_{max} values are eliminated for maturity assessment in this study. Regarding the values of Production Index (PI), the results showed nearly all of the samples within the mature zone (oil window) for both wells. Some samples are shifted toward more mature direction (PI>0.4) especially in the upper part of M-3 well.

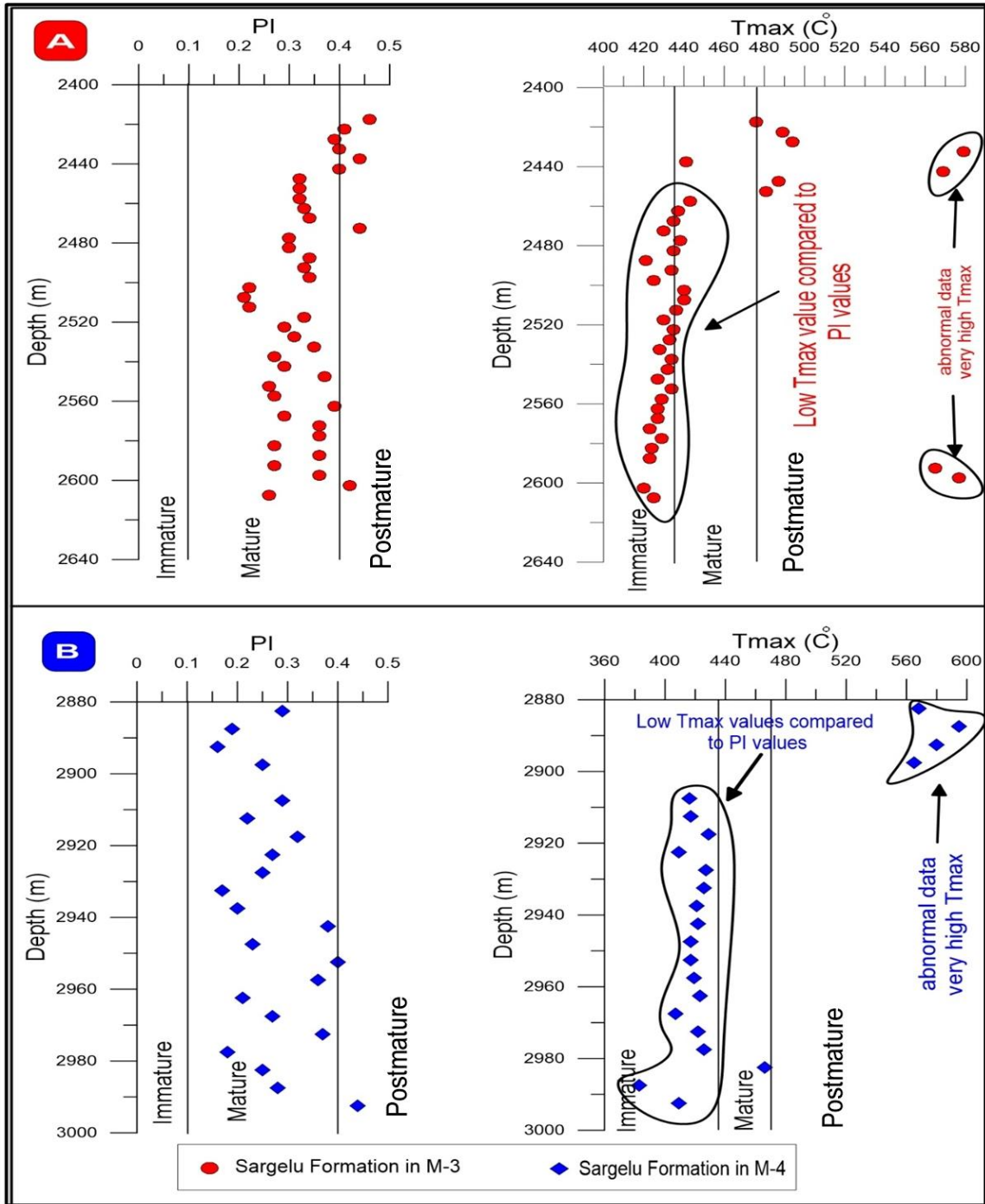


Figure 8: T_{max} and PI log showing maturity levels of the selected samples of Sargelu Formation in (A): M-3 well and (B): M-4 well.

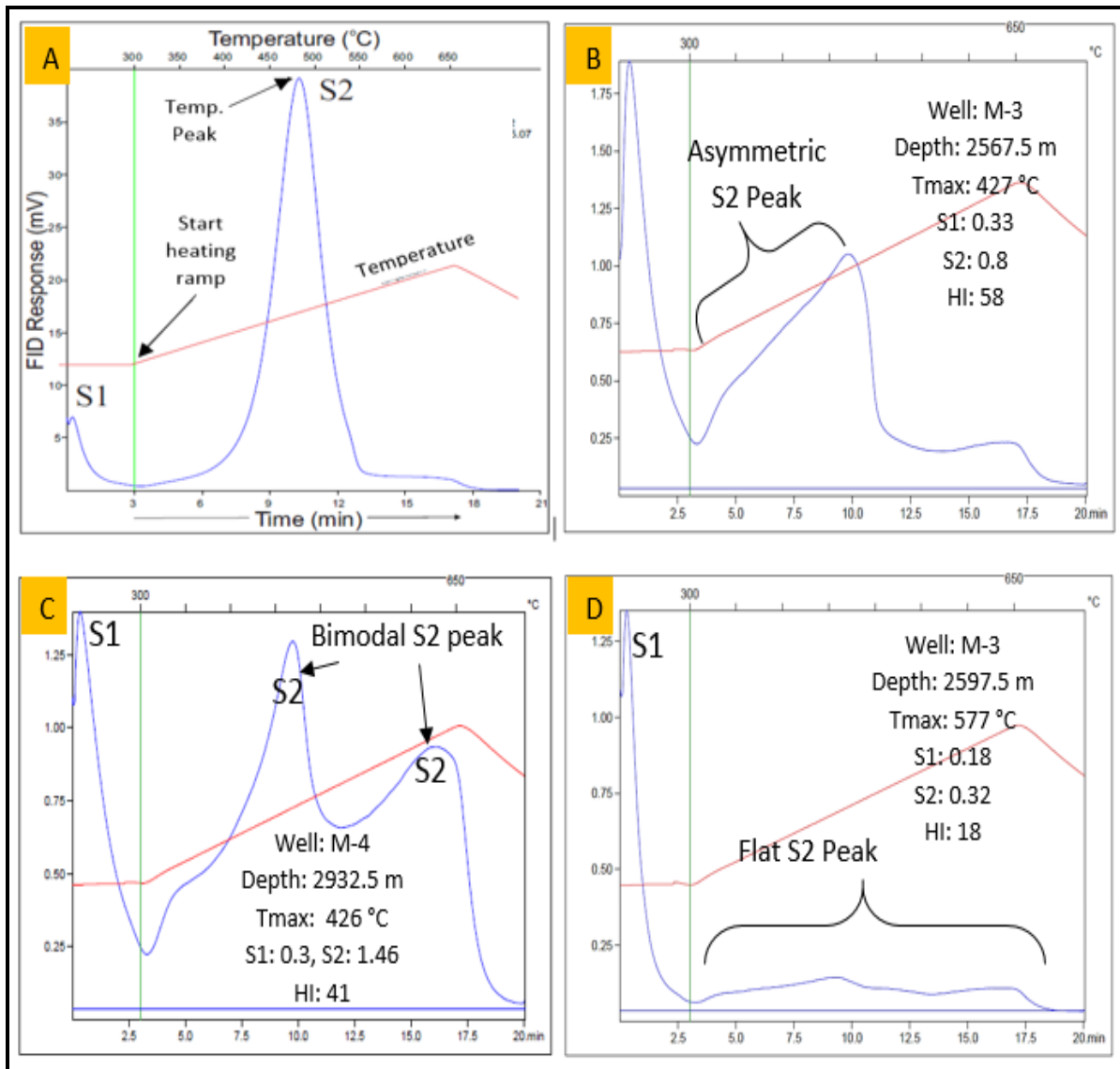


Figure 9: The effects of the shape of S2 peak on the T_{max} value. (A): typical S2 peak with more reliable T_{max} . (Issler et al., 2012), (B): asymmetrical S2 peak. (C): Bimodal S2 peak. (D): Flat S2 peak. The S2 peak in B, and C diagram causing of lowering T_{max} value, while in D causing of increase in T_{max} . The data are from analyzed samples by Rock-Eval pyrolysis for Sargelu Formation in M-3 and M-4 wells.

As previously mentioned, maturity based T_{max} is not dependable in this study. Therefore, petrographic study to confirm real maturity as well as to precise decision about kerogen types believed to be necessary. Maturity of the Sargelu Formation, basis on VRo%, in both wells is relatively high with values of around 1.5-1.55% eq. VRo for M-3 well and around 1.4-1.45% eq. VRo for M-4 well (Tables 1 and 2, Figure 10). The increasing in maturity with depth depending on the solid bitumen reflectance is not regular along the two wells. The important break (or rapid increase) is noticed at the base of the Sargelu Formation in M-3 well (1.94% against 1.5-1.55% eq. VRo) and between the Sargelu and Alan Formations in M-4 well (1.94% against 1.4-1.45 % eq. VRo). It is noticeable that this high maturity is the same for the two wells (1.94 % eq. VRo). According to Alsharhan and Abd El-Gawad (2008), the VRo around 1.45% is an indication of gas generation window. The examined samples of Sargelu Formation in the selected wells have showed high maturity level, which is located in the postmature zone. This result is more consistent with the finding of Pitman et al. (2004), they concluded that the majority of Jurassic source rocks in Iraq have reached or exceeded peak of oil generation, and most of them completed oil generation and expulsion. Accordingly, the majority of the source rocks in this region have been depleted potentiality. They also mentioned that, at

present time, the source rocks in the fold belt have expelled most of their oil (>90%) except for some local areas in the northern part which still remain more than 50% of their petroleum.

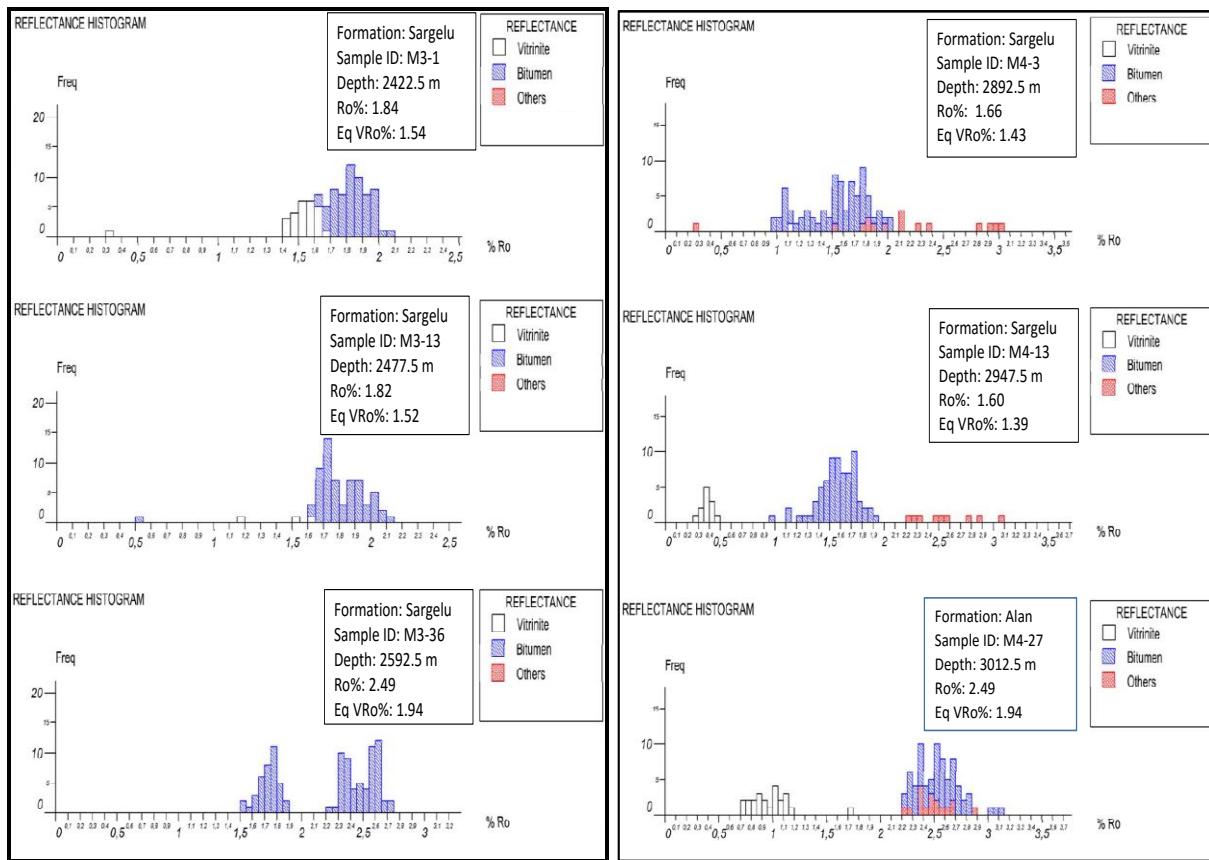


Figure 10: Vitrinite Reflectance histograms for the selected samples of M-3 and M-4 wells.

The reason of higher maturity level for both M3-36 and M4-27 samples is probably related to the existence of bimodal VRo in the vitrinite histogram (Figure 10). Baban and Ahmed (2013), and Petersen et al. (2013) pointed out that the existence of bimodal VRo in the vitrinite histogram are mostly related to either more oxidized organic matter or recycled vitrinite particles from older beds, which experienced higher maturity as well as higher VRo.

Another most important factor which related to the high anomaly of VRo for both mentioned samples is related to the presence of anhydrite (as a dominant lithology) beneath the Sargelu Formation (Figure 2). We take M-3 well as an example to describe this situation. According to the master log of M-3 well the thickness of these formations situated beneath Sargelu Formation is recorded as the following descending order: Alan Formation 178.4m, Mus Formation 109.4m, Adaiyah Formation 205.7m, Butmah Formation more than 425m. The total thickness of these formations is more than 900m and the most obvious lithology for these formations is anhydrite (master log of M-3 well). Based on the assumption of Allen and Allen (2005), anhydrite has high thermal conductivity and thus associated with higher heat flow. Therefore, this condition might be produced a good conductor to transfer heat from deeper part of the crust to the lower part of Sargelu Formation and the net result is causing of increase in thermal maturity.

Conclusions

1- Richness and Potentiality

The Sargelu Formation is rich in organic matter content in the selected wells. This rock unit is classified as a very good source rock based on TOC% content, whereas the same rock unit has low potentiality to generate hydrocarbons, as classified as poor to fair source rock.

2- Types of Organic Matter and Expelled Hydrocarbons

The main kerogen type in Sargelu Formation is a mixed type II/III kerogen in both wells. However, the analyzed samples also contain type IV kerogen. Microscopical examination elucidated that the dominant organic matter content in the samples is solid bitumen. The main expelled hydrocarbon at the present time is only gas, which means that the ability of Sargelu Formation in the selected wells remains only for gas generation.

3- Maturity Assessment

According to the Production Index (PI) parameter, the Sargelu Formation in both wells is thermally mature and in the peak of maturity. The maturity based on microscopical method is showing higher values than PI. Accordingly, the Sargelu Formation in both wells is thermally postmature and in the gas generation zone.

4- Data anomalies

First; the value of T_{max} for the majority of the samples are very low and below expectation. This anomaly of T_{max} data become controversial with the other maturity parameters such as PI, and eq.VRo%. The existence of mud additives (lignite), Bimodal S2 peak confirmed that the T_{max} values are unreliable.

Second; presence of two samples in M-3 and M-4 wells with high values of eq.VRo (1.94%) also make data anomalies. The existence of bimodal vitrinite histogram and thick anhydrite layer beneath Sargelu Formation are interpreted as the causatives of the high maturity level of these two samples.

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