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Source Rock Assessment of Naokelekan Formation in Iraqi Kurdistan

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Abstract

The Callovian-Kimeridgian Naokelekan Formation is a heterogeneous sequence consisting principally of bituminous shales with bituminous limestone and dolomitic limestones. It is 48 m thick maximally in some parts of the area. One hundred forty four rock and cutting samples from six outcrops and eight boreholes in different parts of Iraqi Kurdistan have been studied using the Rock-Eval technique with the primary purpose of assessing their potentiality as promising source rocks for petroleum. The outcomes of the Rock-Eval study for examined samples shows that TOC ranges from 0.4 to 18.8 wt. % and types II and III kerogens are the main components of organic matter.
Qualitative evaluations are also done by textural microscopy used in assessing amorphous organic matter for palynofacies. The organic matters are mature that have thermal alteration index of 2.6-3.2 by Pearson's scale with palynomorphs of dark orange and light brown colors and T_{max} ranges between 434 to 493ºC. Thus the Naokelekan Formation can be considered as a source rock for generation and expulsion of oil and/or gas that has been charged largely oil fields in the area.
Maturity increases toward the northeastern part of the studied area. Furthermore, the study revealed that Naokelekan Formation is within dry gas and/or late oil zone in the eastern part, early oil window in the central part and immature in the western part of the studied area.

Introduction

Naokelekan Formation in the Naokelekan Village, Rawanduz area of the Imbricated Zone in Iraqi Kurdistan, was first described and recognized by Wetzel and Morton [1]. The dark shaly inlayers in the Cudi Group could be equivalent to Naokelekan Formation in southeastern Turkey [2]. Naokelekan Formation was included in Upper Jurassic succession [3]. The formation was deposited in an euxinic and slow subsiding basin [4]. This explanation was similarly recognized by Al-Sayyab et al. [5] but they have reversed the sequence. The types II and III kerogens are dominant types in Naokelekan Formation [6]. The existing kerogen which occurs within Naokelekan Formation in Kirkuk-109 Well is Type II-S and had approximately completed oil generation [7]. This Upper Jurassic formation is one of the main sources of hydrocarbons formed in the Zagros Basin [8; 9]. It is considered as an excellent source rock in Sargelu and Hanjeera villages [10]. Naokelekan Formation represents a highly condensed unit [11]. This potential, thermally mature source rock is within the oil zone in Banik Village and Derash Valley [12]. The TOC content ranges from 5.4 to 25.6 wt. % in the former section [13] and contains 14.6 wt. % in well Ajeel-8 at depth 3240m and contains 2.8 wt. % and 34.8 wt. % at depths 3490m and 3500m, respectively in Ajeel-12 Well [14]. The organic matter is mature and within the oil generation window (0.79-1.25 % vitrinite reflectance in immersion oil) in Sargelu locality [15]. This formation is 25 m thick in well Shorish-1, Erbil Province, Iraqi Kurdistan and contains 5.14 wt. % TOC [16]. Finally, the Naokelekan/basinal Najmah might have generated up to 1,100 BBOE and 1800 BBOE petroleum in the Mesopotamian Foredeep Basin and in the Zagros Fold Belt, respectively [17].
This study aims to find hydrocarbon potential of the Upper Jurassic Naokelekan Formation in Iraqi Kurdistan and their charging productivity to the petroleum reservoirs of this studied region.

Study Area

This study focuses on Iraqi Kurdistan (Figure. 1) and includes 144 samples from six surface outcrops and eight subsurface stratigraphic sections of Naokelekan Formation (Table 1). All the outcrop sections are located in the High Folded Zone of the mountain front and the subsurface stratigraphic sections are located in both High Folded and Low Folded zones throughout region that follows the line between 600 km from East-Northeast to North-Northwest of Iraq.

The outcrop locations are: Barzinja (Bz) section runs along a road cut and is located at 2 km to the northeast of Chinara Village and 10 km to the east of Barzinja Town; Zewa (Ze) section is located at the western limb of Makok anticline west of Zewa Village about 15 km northwest of Betwata Town in Ranya area; Karak (K) section lies in the core of the Korak anticline, east-southeast of Karak Village and about 7 km south of Rawanduz Town; Zrara (Zr) is located on a bank of Chama Stream near Chama Village and 7 km south of Shearwan Mazin; Bnavya (Bv) section runs along a

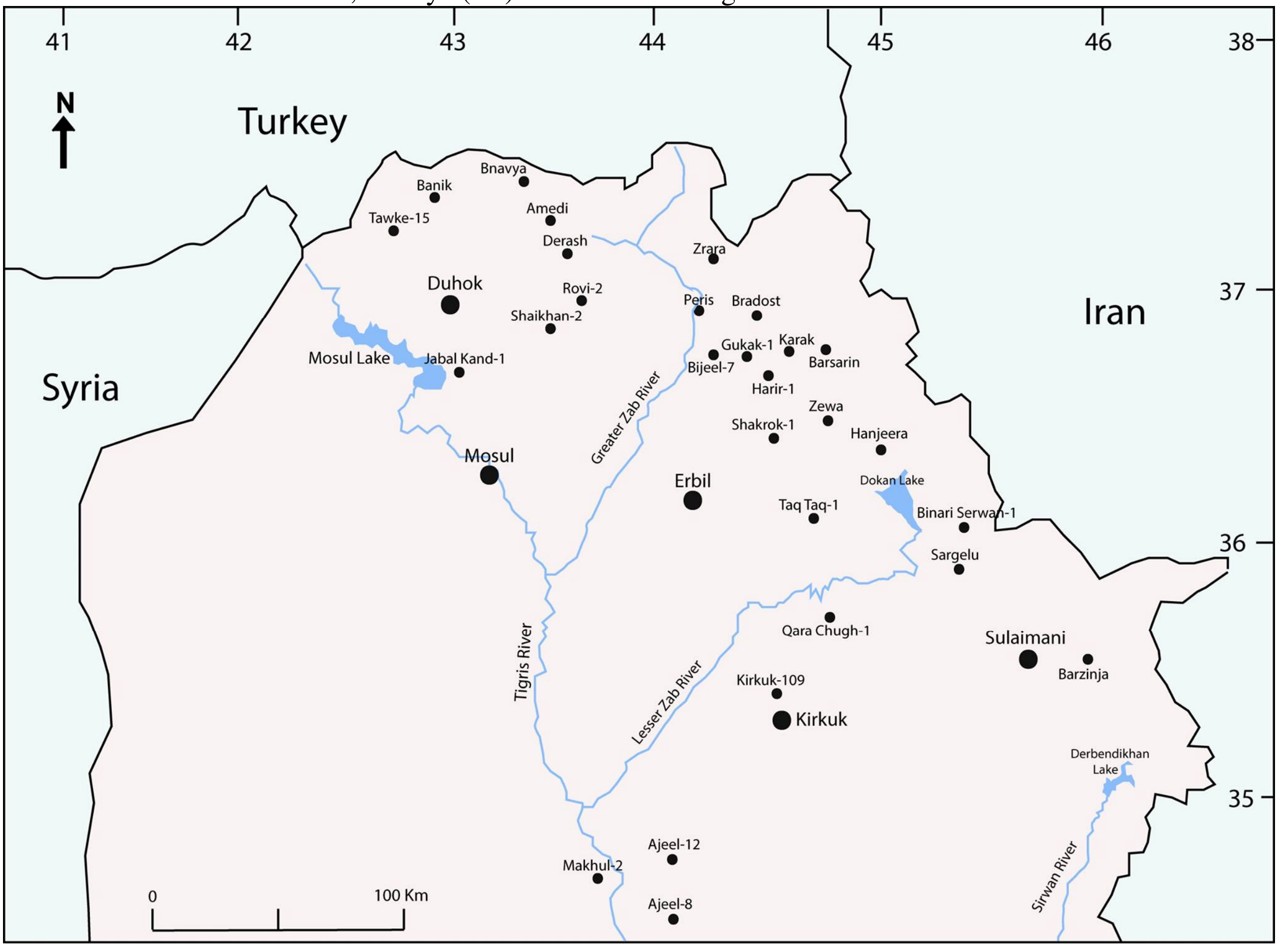

Figure 1: Map of Iraqi Kurdistan showing the studied locations.

Table 1: Location names, tectonic zones, longitude/latitude, number of samples, and source of data that were collected from each locality for geochemical analysis.

No.	Location	Tectonic zones	Longitude			Latitude			No. of samples	Source of Data
			D	M	S	D	M	S		
1	Barzinja	Imbricated	35	32	41	45	41	42	22	This study
2	Zewa	High Folded	36	23	32	44	38	16	13	This study
3	Karak	High Folded	36	37	30	44	29	49	11	This study
4	Zrara	High Folded	36	56	45	44	11	41	4	This study
5	Bnavya	High Folded	37	14	38	43	22	40	14	This study
6	Banik	High Folded	37	13	33	42	58	03	4	This study; [12; 13]
7	Amedi	High Folded	37	07	28	43	29	08	1	[18]

8	Bradost	High Folded	36	44	32	44	22	07	1	[18]
9	Peris	High Folded	36	47	19	44	06	41	2	[18]
11	Derash	High Folded	37	00	01	43	32	26	9	[12]
12	Sargelu	High Folded	35	52	44	45	09	25	12	[10; 19]
	Barsarin	Imbricated							5	[18; 19]
13	Hanjeera	High Folded	36	17	08	44	51	52	9	[10; 19]
Outcrop samples									Subtotal	107
14	Binari Serwan-1	High Folded	36	00	36	45	11	43	13	This study
15	Harir-1	Low Folded	36	33	25	44	23	39	14	This study
16	Shakrok-1	High Folded	36	21	33	44	23	32	4	This study
17	Gulak-1	High Folded	36	37	07	44	18	12	11	This study
18	Bijeel-7	Low Folded	36	38	41	44	09	28	18	This study
19	Rovi-2	High Folded	36	51	02	43	35	35	6	This study
20	Shaikhan-2	High Folded	36	46	22	43	26	43	7	This study
21	Jabal Kand-1	Low Folded	36	39	53	43	01	37	3	This study
22	Makhul-2	Low Folded	35	01	30	43	28	10	7	[20; 21]
23	Taq Taq-1	Low Folded	36	05	33	44	32	26	5	[6; 20]
24	Kirkuk-109	Low Folded	35	33	08	44	18	55	6	[10]
25	Qara Chugh-1	Low Folded	35	46	14	44	34	30	1	[6; 20]
26	Tawke-15	High Folded	37	07	55	42	46	47	1	[19]
27	Ajeel-8	Low Folded	34	52	35	43	47	10	1	[20]
28	Ajeel-12	Low Folded	35	04	02	43	48	09	2	[21; 22]
Cutting samples									Subtotal	99
Total										206

road cut between Bnavya and Hidena villages and is located at 5 km to the northwest of Kani Masi Town; and Banik (Bn) Village, also known among resident farmers as Banik Haji Ghazi Village, nearly 100 m far from the west of the village, about 25 km to northeast of Zakho Town.

The subsurface samples are from: Binari Serwan-1 (BS) 20 km east of Dokan Town; Harir-1 (Ha) 7 km northeast of Harir Town; Shakrok-1 (Sk) 40 km northeast of Erbil Governorate; Gulak-1 (G) 5 km northwest of Harir Town; Bijeel-7 (Bi) is located 20 km southeast of Akre Town; Rovi-2 (R) 30 km northwest of Akre; Shaikhan-2 (Sh) is located west of Akre and situated about 85 km to the northwest of Erbil Governorate; and Jabal Kand-1 (Jk) Well is located near Mosul City 30 km to north, close to Butmah Field 30 km to west.

A total of 62 data points from earlier studies were added to the obtained data from this study. The data are from: Amedi (Am), Bradost (Br), Peris (P), Barsarin (B), Derash (D), Sargelu (S), Hanjeera (H), Makhul-2 (MK), Taq Taq-1 (TT), Kirkuk-109 (K), Qara Chugh-1 (QC), Tawke-15 (TA), Ajeel-8 (A), and Ajeel-12 (Aj).

Methods and Materials

The selected 144 samples are from outcrops and bore holes. Field work on Naokelekan outcrops was performed during the summer of 2015. The outcrop samples were collected along a traverse perpendicular to the bedding plane based on vertical lithological and facies changes. Cuttings samples were similarly obtained from some of wells. These cuttings were acquired from the North Petroleum Company Storage in Kirkuk and from the Geological Survey Storage in Erbil. The cutting samples were collected from intervals that represent the different lithologies of Naokelekan Formation with a spacing range of 2 m to 10 m. All 144 samples were analyzed using a Rock-Eval 6 pyroanalyzer. A total of 62 geochemical data points from seven surface and seven subsurface sections (Table 2) were obtained from numerous previous published and unpublished studies (including MSc theses and PhD dissertations: [6; 10; 12; 13; 14; 18; 19; 22; 23]. The entire attained data were reviewed and used to draw precise regional mapping of the source rocks and their parameters.

Organic matters were attained from the rocks by ordinary palynological methods of dissolving the carbonate and silicates of the rock with *Hydrochloric* (HCl) and *Hydrofluoric* (HF) acids and stabbing the organic matters on scatter slides for additional microscopic studies.

Structural Setting and Stratigraphy of the Area

Iraqi Kurdistan is located on the north eastern boundary of the Arabian Plate and is a portion of an Alpine Mountain belt. This belt has a northwest–southeast trend in the northeastern part and east–west direction in the northern part. Within the Taurus–Zagros belt, two main sectors are recognized: (1) the Folded Zone and (2) the Thrust Zone [24]. The former can be subdivided based on the intensity of folding into two parts. These are the Simply Folded Zone which occurs as a less deformed smaller fold zone and Imbricated (Crushed) Folded Zone. The Simple Folded Zone involves two additional subzones: the Foothills Zone, which seems to be relatively small anticlines and the High Folded (Mountainous) Zone, which is comprised of asymmetric anticlines and accompanying narrow synclines. The core of these anticlines contains Jurassic and Cretaceous rocks, mostly limestone and their flanks are covered by Tertiary limestones and clastics. The latter, Imbricated Zone is extremely distorted [4; 24; 25]. The Thrust Zone is located next to the Iraq and Iran's border in the northeast and outside the Iraq and Turkey's border in the north [4; 24; 25].

Naokelekan Formation (Callovian-Kimeridgian) occurs on the surface in several localities including the following: (1) Northern Thrust Zone; (2) High Folded, Balambo–Tanjero tectonic zones; and (3) within the Qulqula–Khwakurk tectonic zones [4; 25].

In all the outcrop sites and subsurface sections, Naokelekan Formation is underlain by Sargelu Formation. In the Northern Thrust, Imbricated, and High Folded zones, the recognition of the lower boundary of the formation is harder. This is due to ambiguity between the shale of Naokelekan Formation and upper units of the underlying Sargelu; thus, the change is assumed to be gradational [4; 26]. The lower boundary of Naokelekan can be placed within a thin-bedded limestone sequence. Naokelekan Formation can be distinguished by lack of *Bositra* (previously known as *Posidonia*) and ammonites and disappearance of chert bands that occur within Sargelu Formation [1; 26; 27; 28]. Furthermore, the exceptionally bituminous and naturally biased nature of the bed from Sargelu Formation is distinguishable [1].

In all outcrop sites and the subsurface sections, Naokelekan Formation is overlain by Barsarin Formation. Regularly, the upper contact is gradational and conformable [4; 25] situated at the top of argillaceous limestone of Naokelekan Formation and at the base of stratiform stromatolite of the Barsarin Formation [27] but this is not always the case because the upper part of Naokelekan Formation is obscured at type section and at other localities such as Hanjeera, Zewa, Karak, Bin Kelan, Zrara, Banik, Gali Derash, Shiranish, and Bnavya. Therefore the position of the upper boundary is doubtful. The upper part was possibly not deposited or eroded.

Table 2: Total organic carbon and Rock-Eval pyrolysis data on samples selected from Naokelekan Formation at different localities in Iraqi Kurdistan. The colored values are rejected according to conditions on table 3.

Location	Sample NO.	Depth (m)	TOC wt. %	S1 (mg HC /g TOC)	S2(mg HC /g TOC)	S3 (mg CO2 /g TOC)	Tmax (°C)	GP (mg HC /g TOC)	PI	HI (mg HC /g TOC)	OI (mg HC /g TOC)	PCI (mg HC /g TOC)	S1/TOC	Ro %	S2/S3
Barzinja	Bz-1	Surface	0.20	0.11	0.12	0.22	464	0.23	0.49	60	110	0.19	0.29		0.55
	Bz-2	Surface	0.19	0.08	0.12	0.16	450	0.20	0.41	63	84	0.17	0.16		0.75
	Bz-3	Surface	0.53	0.06	0.14	0.38	481	0.20	0.31	26	72	0.17	0.18		0.37
	Bz-4	Surface	0.52	0.04	0.11	0.29	457	0.15	0.25	21	56	0.12	0.16		0.38
	Bz-5	Surface	0.61	0.06	0.14	0.97	472	0.20	0.31	23	159	0.17	0.22		0.14
	Bz-6	Surface	0.24	0.05	0.11	0.18	337	0.16	0.30	46	75	0.13	0.32		0.61
	Bz-7	Surface	0.18	0.04	0.15	0.46	411	0.19	0.20	83	256	0.16	0.21		0.33
	Bz-8	Surface	0.03	0.04	0.10	0.10	458	0.14	0.28	333	333	0.12	0.80		1.00
	Bz-9	Surface	0.17	0.02	0.10	0.19	464	0.12	0.19	59	112	0.10	0.42		0.53
	Bz-10	Surface	0.25	0.04	0.13	0.81	445	0.17	0.21	52	324	0.14	1.19		0.16
	Bz-11	Surface	0.22	0.05	0.12	0.17	466	0.17	0.29	55	77	0.14	0.26		0.71
	Bz-12	Surface	0.03	0.03	0.09	0.06	456	0.12	0.23	300	200	0.10	0.36		1.50
	Bz-13	Surface	1.04	0.03	0.15	1.48	518	0.18	0.15	14	142	0.15	0.57		0.10
	Bz-14	Surface	0.20	0.02	0.09	0.41	492	0.11	0.17	45	205	0.09	0.37		0.22
	Bz-15	Surface	0.52	0.02	0.12	1.12	500	0.14	0.14	23	215	0.12	0.35		0.11
	Bz-16	Surface	0.62	0.64	0.14	0.79	495	0.78	0.82	23	127	0.65	0.40		0.18
	Bz-17	Surface	0.43	3.84	0.43	0.16	328	0.27	0.90	100	37	0.22	0.32		2.69
	Bz-18	Surface	0.32	0.50	0.14	0.18	316	0.64	0.78	44	56	0.55	0.41		0.78
	Bz-19	Surface	0.56	3.88	0.29	0.18	311	4.17	0.93	52	32	3.46	0.46		1.61
	Bz-20	Surface	0.76	0.77	0.24	0.41	306	1.01	0.76	32	54	0.84	0.49		0.59
	Bz-21	Surface	0.47	1.22	0.21	0.23	316	1.43	0.85	45	49	1.19	0.37		0.91
	Bz-22	Surface	0.60	0.21	0.09	0.64	498	0.30	0.70	15	107	0.25	0.31		0.14
Zewa	Ze-1	Surface	0.49	0.03	0.32	0.71	430	0.35	0.09	65	145	0.29	0.28		0.45
	Ze-2	Surface	0.15	0.10	0.31	0.46	432	0.41	0.24	207	307	0.34	0.31		0.67
	Ze-3	Surface	1.04	0.03	0.20	1.82	506	0.23	0.12	19	175	0.19	0.46		0.11
	Ze-4	Surface	0.42	0.02	0.55	0.51	436	0.57	0.04	131	121	0.47	0.32		1.08
	Ze-5	Surface	0.31	0.06	0.30	0.59	392	0.36	0.16	97	190	0.30	0.40		0.51
	Ze-6	Surface	0.56	0.04	0.22	1.15	425	0.26	0.16	39	205	0.22	0.49		0.19
	Ze-7	Surface	0.11	0.04	0.22	0.11	444	0.26	0.15	200	100	0.22	0.69		2.00
	Ze-8	Surface	2.38	0.03	0.17	2.60	558	0.20	0.16	7	109	0.17	0.84		0.07
	Ze-9	Surface	0.62	0.04	0.17	0.83	495	0.21	0.18	27	134	0.17	0.30		0.21
	Ze-10	Surface	1.36	0.03	0.16	1.69	591	0.19	0.14	12	124	0.16	0.36		0.10
	Ze-11	Surface	0.62	0.03	0.13	0.83	551	0.16	0.17	21	134	0.13	0.38		0.16
	Ze-12	Surface	5.80	0.05	0.22	5.40	554	0.27	0.18	3.5	94	0.22	0.37		0.04
	Ze-13	Surface	3.17	0.03	0.12	3.85	563	0.15	0.19	3.5	122	0.12	0.37		0.03
Karak	Ka-1	Surface	1.30	0.51	2.04	0.31	440	2.55	0.20	157	24	2.12	0.30	0.76	6.58
	Ka-2	Surface	1.89	0.61	2.15	0.35	464	2.76	0.22	114	19	2.29	0.26	1.19	6.14
	Ka-3	Surface	1.43	0.53	1.70	0.20	456	2.23	0.24	119	14	1.85	0.26	1.05	8.50
	Ka-4	Surface	2.21	0.87	2.54	0.45	449	3.41	0.26	115	20	2.83	0.26	0.92	5.64
	Ka-5	Surface	11.22	2.25	13.91	0.38	470	16.16	0.14	124	3	13.41	0.26	1,.3	36.61
	Ka-6	Surface	0.73	0.18	1.20	0.30	436	1.38	0.13	164	41	1.15	0.25	0.69	4.00
	Ka-7	Surface	13.09	2.32	15.64	0.40	462	17.96	0.13	119	3	14.91	0.25	1.16	39.10
	Ka-8	Surface	6.71	1.25	8.50	0.47	466	9.75	0.13	127	7	8.09	0.86	1.23	18.09
	Ka-9	Surface	13.04	1.72	14.13	1.77	463	15.85	0.11	108	14	13.16	0.67	1.17	7.98
	Ka-10	Surface	17.22	3.49	21.70	0.65	464	25.19	0.14	126	4	20.91	0.62	1.19	33.39
	Ka-11	Surface	11.28	1.86	13.36	0.65	463	15.22	0.12	118	6	12.63	0.50	1.17	20.55
Bnavya	Bv-1	Surface	0.20	0.03	0.27	0.20	433	0.30	0.09	135	100	0.25	0.76		1.35
	Bv-2	Surface	0.17	0.04	0.13	0.29	484	0.17	0.21	76	171	0.14	0.69		0.45
	Bv-3	Surface	0.06	0.04	0.13	0.05	429	0.17	0.25	217	83	0.14	0.48		2.60
	Bv-4	Surface	0.35	0.02	0.13	0.38	438	0.15	0.16	37	109	0.12	0.37		0.34
	Bv-5	Surface	0.18	0.02	0.12	0.16	439	0.14	0.15	67	89	0.12	0.37		0.75
	Bv-6	Surface	0.29	0.03	0.20	0.34	418	0.23	0.15	69	117	0.19	0.52		0.59
	Bv-7	Surface	0.23	0.02	0.09	0.36	483	0.11	0.15	39	157	0.09	0.47		0.25
	Bv-8	Surface	0.62	0.05	0.22	0.99	394	0.27	0.20	35	160	0.22	0.73		0.22
	Bv-9	Surface	0.38	0.04	0.21	0.59	393	0.25	0.15	55	155	0.21	0.50		0.36
	Bv-10	Surface	3.38	0.03	0.38	5.16	533	0.41	0.08	11	153	0.34	0.50		0.07
	Bv-11	Surface	4.61	0.04	0.51	5.75	528	0.55	0.07	11	125	0.46	0.87		0.09
	Bv-12	Surface	2.41	0.06	0.51	4.67	397	0.57	0.10	21	194	0.47	1.31		0.11
	Bv-13	Surface	2.39	0.03	0.28	4.48	513	0.31	0.10	12	187	0.26	0.91		0.06
	BV-14	Surface	1.48	0.02	0.13	1.79	534	0.15	0.13	9	121	0.12	0.97		0.07

TOC total organic carbon; S1 total free hydrocarbons (from S1 peaks); S2 amount of remaining hydrocarbon or amount of hydrocarbon obtained by heating during pyrolysis (from S2 peaks); S3 amount of carbon dioxide (CO_2) released through heating organic matter (from S3 peaks); HI hydrogen index; OI oxygen index; GP genetic potential; PI production index; PCI pyrolyzable carbon index; Ro vitrinite reflectance

Table 2 (Continued): Total organic carbon and Rock-Eval pyrolysis data on samples selected from Naokelekan Formation at different localities in Iraqi Kurdistan. The colored values are rejected according to conditions on table 3.

Location	Sample NO.	Depth (m)	TOC wt. %	S1 (mg HC /g rock)	S2(mg HC /g rock)	S3 (mg CO2 /g rock)	Tmax (°C)	GP (mg HC /g rock)	PI	HI (mg HC /g TOC)	OI (mg HC /g TOC)	PCI (mg HC /g TOC)	S1/TOC	Ro %	S2/S3
Zrara	Zr-1	Surface	0.21	0.07	0.28	0.34	437	0.35	0.19	133	162	0.29	0.50		0.82
	Zr-2	Surface	0.19	0.11	0.57	0.51	315	0.68	0.16	300	268	0.56	0.62		1.12
	Zr-3	Surface	3.08	0.11	0.67	1.74	463	0.78	0.15	22	56	0.65	0.84		0.39
	Zr-4	Surface	0.26	0.12	0.43	0.29	427	0.55	0.22	165	112	0.46	0.90		1.48
Banik	Bn-1	Surface	3.06	0.12	4.90	1.87	441	5.02	0.02	160	61	4.17	0.96	0.78	2.62
	Bn-2	Surface	21.95	0.27	48.24	12.33	441	48.51	0.01	220	56	40.26	1.11	0.78	3.91
	Bn-3	Surface	25.32	5.00	104.34	0.87	444	109.34	0.05	412	3	90.75	0.84	0.83	119.93
	Bn-4	Surface	22.07	4.13	92.23	1.28	442	96.36	0.04	418	6	79.98	0.72	0.80	72.06
Sargelu	S-1	Surface	0.17	0.05	0.06	0.04	388	0.11	0.45	35	24	0.09	0.98		1.50
	S-2	Surface	1.50	0.18	0.78	0.20	493	0.96	0.19	52	13	0.80	0.74	1.71	3.90
	S-3	Surface	0.13	0.06	0.05	0.07	387	0.11	0.55	38	54	0.09	0.94		0.71
	S-4	Surface	2.94	0.04	0.17	1.66	522	0.21	0.19	6	56	0.17	0.87		0.10
	S-5	Surface	11.25	0.07	0.97	5.08	530	1.04	0.07	9	45	0.86	0.94		0.19
	S-6	Surface	0.13	0.06	0.12	0.13	456	0.18	0.34	92	100	0.15	1.11		0.92
	S-7	Surface	1.61										0.60		
	S-8	Surface	2.41	0.08	0.21	1.15	496	0.29	0.28	9	48	0.24	0.60		0.18
	S-9	Surface	1.13	0.03	0.25	1.93	508	0.28	0.10	22	171	0.23	0.13		0.13
	S-10	Surface	4.01										0.13		
	S-11	Surface	2.93	0.02	0.27	1.79	512	0.29	0.07	9	61	0.24	0.12		0.15
	S-12	Surface	0.51	0.08	0.19	0.54	508	0.27	0.30	36	106	0.22	0.15		0.35
Barsarin	B-1	Surface	1.78	0.67	1.30	0.17	478	1.97	0.34	73	10	1.64	0.15	1.44	7.65
	B-2	Surface	5.04	0.70	3.59	0.79	467	4.29	0.16	71	16	3.56	0.18	1.25	4.54
	B-3	Surface	11.90	2.17	14.34	0.33	462	16.51	0.13	121	3	13.70	0.08	1.16	43.46
	B-4	Surface	11.57	1.11	10.96		472	12.07	0.09	95	12	10.02	0.18	1.34	
	B-5	Surface	4.80	0.30	3.62		473	3.92	0.08	75	25	3.25	0.40	1.35	
Hanjeera	H-1	Surface	0.12	0.04	0.06	0.06	395	0.10	0.40	50	38	0.08	0.28		1.00
	H-2	Surface	1.07	0.07	0.12	0.41	358	0.19	0.37	11		0.16	0.44		0.29
	H-3	Surface	0.05	0.01	0.05		439	0.06	0.23	100	160	0.05	0.23		
	H-4	Surface	0.13										0.15		
	H-5	Surface		0.02	0.14		434	0.16	0.13				0.19		
	H-6	Surface	0.38	0.03	0.15		387	0.18	0.17	39	51	0.15	0.33		
	H-7	Surface	1.12		0.09		445	0.09		8	97	0.07	0.27		
	H-8	Surface	0.70	0.05	0.20		429	0.25	0.21	29	269	0.21	0.15		
	H-9	Surface	0.03	0.01	0.05		368	0.06	0.18	150		0.05	0.01		
Derash	D-1	Surface	2.09	0.38	8.67	0.64	433	9.05	0.04	414.8	30.6	7.51		0.63	13.55
	D-2	Surface	0.36	0.06	0.97	0.60	434	1.03	0.06	269.4	166.7	0.85			1.62
	D-3	Surface		1.31	112.55	1.23	437	113.86	0.01						91.50
	D-4	Surface		0.59	97.11	2.26	433	97.70	0.01						42.97
	D-5	Surface	9.56	0.30	45.73	3.27	436	46.03	0.01	478.3	34.2	38.20		0.69	13.99
	D-6	Surface	1.62	0.10	6.38		437	6.48	0.02	394	33	5.80		0.71	
	D-7	Surface	13.87	0.52	71.98		434	72.50	0.01	519	28	60.18		0.65	
	D-8	Surface	18.70	0.44	112.32		438	112.76	0.00	601	11	93.59		0.72	
	D-9	Surface	14.49	0.61	88.77		440	89.38	0.01	613	3	74.19		0.76	
Amedi	Am-1	Surface	12.38	0.47	48.80	3.48	434	49.27	0.01	394	28	40.89		0.65	14.02
Peris	P-1	Surface	3.61	0.36	13.38		438	13.74	0.03	371	33	11.40		0.72	
	P-2	Surface	3.13	0.32	8.68		437	9.00	0.04	277	42	7.47		0.71	
Bradost	Br-1	Surface	3.50	0.87	4.25		461	5.12	0.17	121	10	4.25		1.14	
Binari Serwan-1	BS-1	774	1.91	0.56	0.99	1.02	344	1.55	0.36	52	53	1.29			0.97
	BS-2	780	3.37	0.55	1.43	1.22	343	1.98	0.28	42	36	1.64			1.17
	BS-3	786	4.08	0.75	1.64	1.27	348	2.39	0.31	40	31	1.98			1.29
	BS-4	792	4.55	0.73	1.98	1.15	343	2.71	0.27	44	25	2.25			1.72
	BS-5	804	5.67	1.26	2.01	1.79	337	3.27	0.39	35	32	2.71			1.12
	BS-6	840	4.38	1.40	1.82	1.50	335	3.22	0.43	42	34	2.67			1.21
	BS-7	846	4.52	0.95	2.08	1.89	344	3.03	0.31	46	42	2.51			1.10
	BS-8	848	1.23	0.99	1.69	1.34	353	2.68	0.37	137	109	2.22			1.26
	BS-9	1915	5.01	2.11	2.39	1.98	332	4.50	0.47	48	40	3.74			1.21
	BS-10	1918	2.06	2.45	2.12	2.62	305	4.57	0.54	103	127	3.79			0.81
	BS-11	1921	16.49	4.26	4.83	2.97	315	9.09	0.47	29	18	7.54			1.63
	BS-12	1939	5.88	2.11	2.76	2.01	328	4.87	0.43	47	34	4.04			1.37
	BS-13	1948	4.50	2.57	2.12	1.48	334	4.69	0.55	47	33	3.89			1.43

TOC total organic carbon; S1 total free hydrocarbons (from S1 peaks); S2 amount of remaining hydrocarbon or amount of hydrocarbon obtained by heating during pyrolysis (from S2 peaks); S3 amount of carbon dioxide (CO_2) released through heating organic matter (from S3 peaks); HI hydrogen index; OI oxygen index; GP genetic potential; PI production index; PCI pyrolyzable carbon index; Ro vitrinite reflectance

Table 2 (Continued): Total organic carbon and Rock-Eval pyrolysis data on samples selected from Naokelekan Formation at different localities in Iraqi Kurdistan. The colored values are rejected according to conditions on table 3.

Location	Sample NO.	Depth (m)	TOC wt. %	S1 (mg HC /g rock)	S2(mg HC /g rock)	S3 (mg CO2 /g rock)	Tmax (°C)	GP (mg HC /g rock)	PI	HI (mg HC /g TOC)	OI (mg HC /g TOC)	PCI (mg HC /g TOC)	S1/TOC	Ro %	S2/S3
Harir-1	Ha-1	1375	2.19	0.81	1.74	0.42	463	2.55	0.32	79	19	2.12		1.17	4.14
	Ha-2	1376	1.94	0.67	1.35	0.32	462	2.02	0.33	70	16	1.68		1.16	4.22
	Ha-3	1380	1.64	0.66	1.22	0.38	456	1.88	0.35	74	23	1.56		1.05	3.21
	Ha-4	1383	3.65	1.16	2.68	0.42	457	3.84	0.30	73	12	3.19		1.07	6.38
	Ha-5	1385	1.81	0.74	1.87	0.48	451	2.61	0.28	103	27	2.17		0.96	3.90
	Ha-6	1388	0.96	0.44	1.18	0.63	449	1.62	0.27	123	66	1.34		0.92	1.87
	Ha-7	1390	2.05	1.01	2.45	0.81	452	3.46	0.29	120	40	2.87		0.98	3.03
	Ha-8	1393	6.05	2.21	6.99	0.78	455	9.20	0.24	116	13	7.64		1.03	8.96
	Ha-9	1395	9.10	2.79	10.77	0.77	456	13.56	0.21	118	8	11.25		1.05	13.99
	Ha-10	1398	7.30	2.05	8.29	0.54	457	10.34	0.20	114	7	8.58		1.07	15.35
	Ha-11	1400	4.12	1.27	4.65	0.40	457	5.92	0.21	113	10	4.91		1.07	11.63
	Ha-12	1403	3.42	1.57	4.18	0.43	454	5.75	0.27	122	13	4.77		1.01	9.72
	Ha-13	1405	4.07	1.30	4.60	0.48	454	5.90	0.22	113	12	4.90		1.01	9.58
	Ha-14	1408	4.06	1.62	4.66	0.50	454	6.28	0.26	115	12	5.21		1.01	9.32
Shakrok-1	SK-1	965	3.98	1.96	3.09	1.42	456	5.05	0.39	78	36	4.19		1.05	2.18
	SK-2	968	0.96	0.66	0.81	1.64	435	1.47	0.45	84	171	1.22			0.49
	SK-3	971	1.64	1.38	1.77	1.63	442	3.15	0.44	108	99	2.61			1.09
	SK-4	974	8.86	2.67	10.22	1.10	460	12.89	0.21	115	12	10.70		1.12	9.29
Gulak-1	G-1	2383	2.47	0.88	2.51	0.40	454	3.39	0.26	102	16	2.81		1.01	6.28
	G-2	2384	2.27	0.86	2.65	0.43	449	3.51	0.25	117	19	2.91		0.92	6.16
	G-3	2386	2.17	0.81	2.46	0.37	454	3.27	0.25	113	17	2.71		1.01	6.65
	G-4	2388	2.08	0.77	2.48	0.31	454	3.25	0.24	119	15	2.70		1.01	8.00
	G-5	2392	4.39	1.32	5.15	0.47	453	6.47	0.20	117	11	5.37		0.99	10.96
	G-6	2394	7.21	1.90	9.58	0.40	453	11.48	0.17	133	6	9.53		0.99	23.95
	G-7	2396	6.23	1.61	7.90	0.35	457	9.51	0.17	127	6	7.89		1.07	22.57
	G-8	2398	4.72	1.25	6.01	0.45	453	7.26	0.17	127	10	6.03		0.99	13.36
	G-9	2400	6.46	1.69	8.14	0.47	455	9.83	0.17	126	7	8.16		1.03	17.32
	G-10	2402	6.55	1.66	8.25	0.40	456	9.91	0.17	126	6	8.23		1.05	20.63
	G-11	2404	5.99	1.51	7.73	0.37	455	9.24	0.16	129	6	7.67		1.03	20.89
Bijeel-7	Bi-1	3772	0.50	0.43	1.08	0.87	423	1.51	0.29	216	174	1.25			1.24
	Bi-2	3774	1.23	0.82	1.80	2.06	423	2.62	0.31	146	167	2.17			0.87
	Bi-3	3776	1.42	0.88	2.29	1.73	427	3.17	0.28	161	122	2.63			1.32
	Bi-4	3778	2.30	1.16	3.97	1.31	433	5.13	0.23	173	57	4.26			3.03
	Bi-5	3780	2.24	1.11	3.69	1.32	434	4.80	0.23	165	59	3.98			2.80
	Bi-6	3782	1.58	0.98	2.78	1.19	432	3.76	0.26	176	75	3.12			2.34
	Bi-7	3784	0.81	0.68	1.61	1.21	424	2.29	0.30	199	149	1.90			1.33
	Bi-8	3786	0.70	0.63	1.54	1.47	427	2.17	0.29	220	210	1.80			1.05
	Bi-9	3788	1.66	1.26	3.37	1.72	435	4.63	0.27	203	104	3.84		0.67	1.96
	Bi-10	3790	1.78	1.23	3.69	1.83	432	4.92	0.25	207	103	4.08			2.02
	Bi-11	3792	1.19	0.57	2.33	1.36	440	2.90	0.20	196	114	2.41		0.76	1.71
	Bi-12	3794	2.95	1.10	5.60	1.11	442	6.70	0.16	190	38	5.56		0.80	5.05
	Bi-13	3796	3.51	1.31	6.97	1.00	443	8.28	0.16	199	28	6.87		0.81	6.97
	Bi-14	3798	4.29	2.25	7.66	1.67	443	9.91	0.23	179	39	8.23		0.81	4.59
	Bi-15	3800	3.47	1.63	6.55	0.99	442	8.18	0.20	189	29	6.79		0.80	6.62
	Bi-16	3802	1.20	0.88	2.47	0.82	441	3.35	0.26	206	68	2.78		0.78	3.01
	Bi-17	3804	3.70	1.85	7.01	0.89	445	8.86	0.21	189	24	7.35		0.85	7.88
	Bi-18	3806	4.31	2.14	8.31	1.01	445	10.45	0.20	193	23	8.67		0.85	8.23
Rovi-2	R-1	3255	2.55	2.23	8.81	1.67	433	11.04	0.20	345	65	9.16			5.28
	R-2	3260	1.73	2.27	5.31	1.61	428	7.58	0.30	307	93	6.29			3.30
	R-3	3265	2.19	2.00	6.65	1.74	429	8.65	0.23	304	79	7.18			3.82
	R-4	3270	2.27	2.21	7.10	1.86	429	9.31	0.24	313	82	7.73			3.82
	R-5	3275	2.43	2.34	7.97	1.88	430	10.31	0.23	328	77	8.56			4.24
	R-6	3280	2.44	2.70	7.77	1.85	429	10.47	0.26	318	76	8.69			4.20
Shaikhan-2	Sh-1	1675	1.68	1.41	6.21	1.56	428	7.62	0.18	370	93	6.32			3.98
	Sh-2	1680	1.38	1.00	5.39	1.47	433	6.39	0.16	391	107	5.30			3.67
	Sh-3	1685	1.32	1.30	5.35	1.75	429	6.65	0.20	405	133	5.52			3.06
	Sh-4	1690	1.58	1.17	4.57	1.88	426	5.74	0.20	289	119	4.76			2.43
	Sh-5	1695	1.17	1.10	4.76	1.64	426	5.86	0.19	407	140	4.86			2.90
	Sh-6	1700	1.49	1.30	6.55	1.66	428	7.85	0.17	440	111	6.52			3.95
	Sh-7	1705	1.55	1.46	7.16	1.61	429	8.62	0.17	462	104	7.15			4.45

TOC total organic carbon; S1 total free hydrocarbons (from S1 peaks); S2 amount of remaining hydrocarbon or amount of hydrocarbon obtained by heating during pyrolysis (from S2 peaks); S3 amount of carbon dioxide (CO_2) released through heating organic matter (from S3 peaks); HI hydrogen index; OI oxygen index; GP genetic potential; PI production index; PCI pyrolyzable carbon index; Ro vitrinite reflectance

Table 2 (Continued): Total organic carbon and Rock-Eval pyrolysis data on samples selected from Naokelekan Formation at different localities in Iraqi Kurdistan. The colored values are rejected according to conditions on table 3.

Location	Sample NO.	Depth (m)	TOC wt. %	S1 (mg HC /g rock)	S2(mg HC /g rock)	S3 (mg CO2 /g rock)	Tmax (°C)	GP (mg HC /g rock)	PI	HI (mg HC /g TOC)	OI (mg HC /g TOC)	PCI (mg HC /g TOC)	S1/TOC	Ro %	S2/S3
Jabal Kand-1	JK-1	2110	3.07	3.41	14.85	0.72	427	18.26	0.19	484	23	15.16			20.63
	JK-2	2125	3.24	1.95	11.51	0.96	431	13.46	0.14	355	30	11.17			11.99
	JK-3	2134	5.47	3.29	27.00	0.50	436	30.29	0.11	494	9	25.14		0.69	54.00
Makhul-2	MK-1	2256	16.20	2.16	80.89	0.84	441	83.05	0.03	499	5	68.93		0.78	96.30
	MK-2	2258	19.77	2.65	94.69	0.58	444	97.34	0.03	479	3	80.79		0.83	163.26
	MK-3	2260	20.69	2.53	80.51	0.76	440	83.04	0.03	389	4	68.92		0.76	105.93
	MK-4	2264	16.09	2.48	66.95	1.39	439	69.43	0.04	416	9	57.63		0.74	48.17
	MK-5	2264	13.08	2.02	78.77	0.80	440	80.79	0.03	576	6	67.06		0.76	98.46
	MK-6	2266	4.47	0.81	23.39	0.68	439	24.20	0.03	523	15	20.09		0.74	34.40
	MK-7	2268	13.04	0.99	50.81	0.86	439	51.80	0.02	390	7	42.99		0.74	59.08
Taq Taq-1	TT-1	3225	0.74	0.21	0.22	0.40	338	0.43	0.49	30	54	0.36			0.55
	TT-2	3230	1.29	0.57	0.48	0.38	492	1.05	0.54	37	29	0.87			1.26
	TT-3	3235	8.64	1.96	2.61	0.75	584	4.57	0.43	30	9	3.79			3.48
	TT-4	3244	7.53	1.39	1.59	0.38	584	2.98	0.47	21	5	2.47			4.18
	TT-5	3250	1.39	0.55	0.49	0.13	567	1.04	0.53	35	9	0.86			3.77
Kirkuk-109	Ka-1	3375	3.00				580		0.30	69					
	Ka-2	3377		1.34	5.05	1.22	446	6.39	0.21						4.14
	Ka-3	3383	6.23	0.92	4.40	0.43	458	5.32	0.17	71	7	4.42		1.08	10.23
	Ka-4	3395	1.90	0.37	1.03	0.58	458	1.40	0.27	54	31	1.16		1.08	1.78
	Ka-5	3399	2.16												
	Ka-6		4.01						0.22						
Qara Chauq-1	QC-1		4.31						0.18						
Tawke-15	TA-1	2830	0.52	0.17	2.29	0.27	425	2.46	0.07	440	50	2.04			8.48
Ajeel-8	A-1	3240	14.57	3.89	30.03		445	33.92	0.11	206		28.15		0.85	
Ajeel-12	Aj-1	3490	2.75	0.42	1.35		334	1.77	0.24	49		1.47			
	Aj-2	3500	34.82	0.18	2.66		447	2.84	0.07	11		2.36			

TOC total organic carbon; S1 total free hydrocarbons (from S1 peaks); S2 amount of remaining hydrocarbon or amount of hydrocarbon obtained by heating during pyrolysis (from S2 peaks); S3 amount of carbon dioxide (CO_2) released through heating organic matter (from S3 peaks); HI hydrogen index; OI oxygen index; GP genetic potential;PI production index; PCI pyrolyzable carbon index; Ro vitrinite reflectance

The age equivalent units to Naokelekan and Barsarin formations, in the Low Folded Zone, are Najmah and Gotnia formations [29]. Naokelekan Formation is transitional to the south with the neritic and lagoonal oolitic limestone of Najmah Formation [4; 26].

The thicknesses of Naokelekan at subsurface sections range between 6m at Bekhme-1 Well (44° 17' 47.6" and 36° 40' 33.1") and 48m at Sarta-SC-A1 Well (43° 59' 19.3" and 36° 30' 52.4"). The minimum thickness of formation on surface is 7m at Banik and reaches its maximum thickness of 34m at Ru Kuchuk [1], but only 12 of the 33 measured sections show more than 20m.

The formation shows roughly the same lithological composition and sequence in all known occurrences [4]. Based on field measurements and petrographic analysis, the tripartite division of the formation is recognizable in most sections [1; 31] and is as follows (from bottom to top): (1) bituminous limestone and dolomites, with intercalated bituminous shale; (2) dolomitic limestone or limestones; and (3) laminated shaly bituminous limestones [1].

Results and Discussion

Rock-Eval data

The total of 144 samples, including 68 surface rock samples and 76 subsurface cutting samples from Naokelekan Formation were analyzed in order to evaluate Naokelekan Formation quantitatively and qualitatively. In addition, the data of 39 surface rock samples and 23 subsurface cutting samples from earlier studies were collected and used to build on previous work (Table 1).

The Rock-Eval data for all 206 samples (Table 2) were screened based on the conditions that are shown on table 3 and figure 2. Samples from Barzinja, Zewa, Sargelu, Banavya, and Hanjeera localities have very small TOC, S1, and S2 values (Table 2) therefore their hydrogen index (HI) and oxygen index (OI) values are unreliable and the data are meaningless due to dividing one small number by another small number [32]. Therefore the whole or partial data was rejected and the remaining was used.

Table 2 shows the TOC wt. % for each single sample and figure 3 shows the mean TOC wt. % for Naokelekan Formation in each locality in Iraqi Kurdistan. Naokelekan Formation has the highest TOC wt. % in the well Ajeel-12 (average 18.8 wt. %) in the southwestern part of the study area and the lowest TOC wt. % in Barzinja locality (average 0.4 wt. %) in the southeastern part of the study area. The 23.6 wt. % mean

TOC for Banik section that was documented by Al-Badry [12] was neither confirmed by the data that [13] obtained (mean 17.8 wt. %) nor by the similar data that were obtained through this study (mean 18.1 wt. %).

It is observed that TOC wt. % of Naokelekan Formation varies from a location to another location (Figure. 4). This variation is due to the change of lithofacies as a result of environmental condition variability. It is noticed that the lower part which is informally called Coal Bed is the richest part regarding organic matter content. Therefore the average richness increases when the lower part is thick such as in Ajeel-12, Ajeel-8, Banik, Amedi, Derash, Barsarin, Karak, Binary Sirwan-1, Gulak-1, and Harir-1 and vice versa. It is clear that the quantity of organic matter is moderate in the middle part and is high in the northeastern, northwestern, and southern parts of the study area. The lowest TOC wt. % content appears in the southeastern and western parts of the region. The TOC wt. % distribution throughout the studied area is not consistent and the increase or decrease doesn't follow any specific trend. This inconsistency reflects the paleogeographic condition during the deposition of Naokelekan Formation that was characterized by the existence of isolated basins [4]. Thus the contour map drawn by Aqrawi and Badics [17] which shows gradational increase of TOC wt. % toward northeastern Iraq was not confirmed.

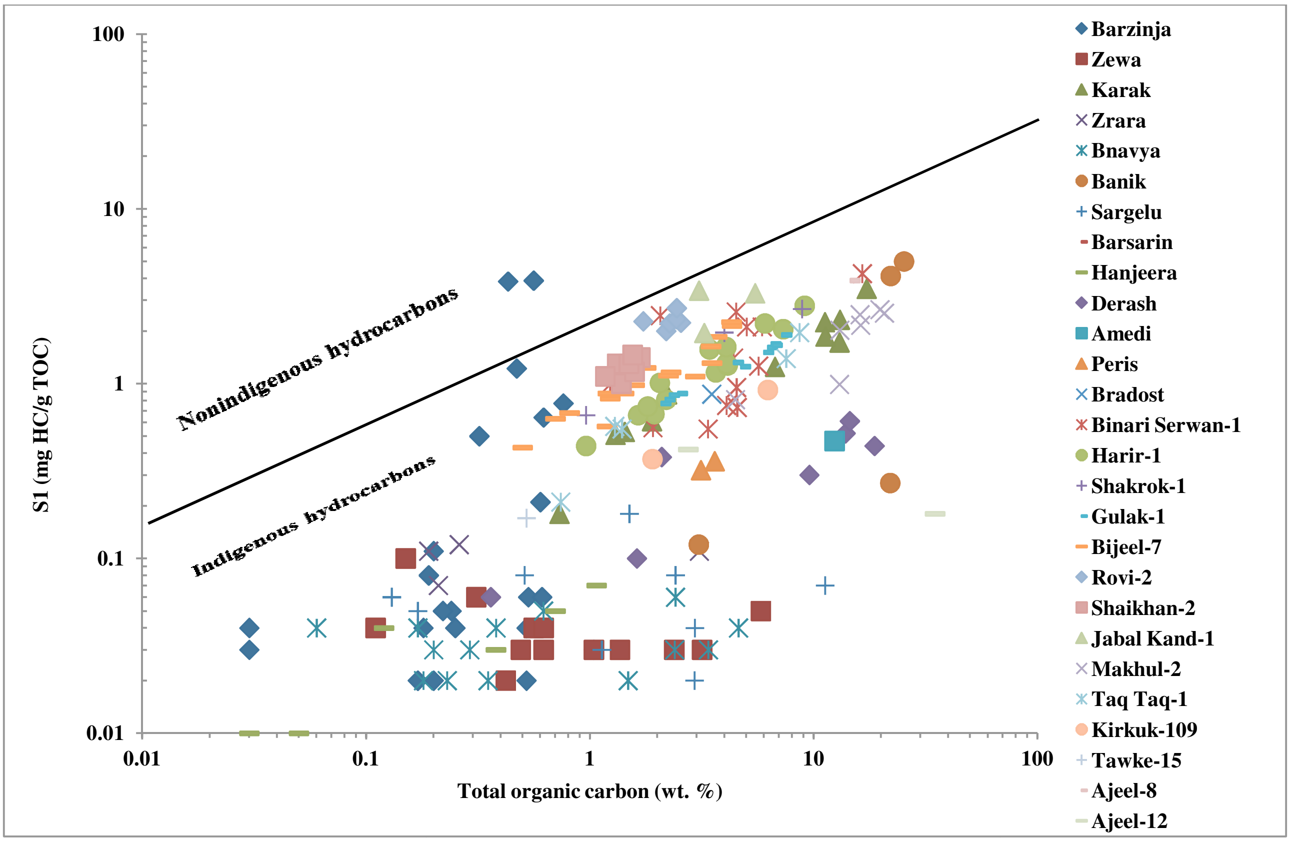

Figure 2: Total organic carbon versus S1 for identifying migrated hydrocarbons for Naokelekan Formation's samples at different localities in Iraqi Kurdistan (after [37]).

Table 3: Rock-Eval Screening Parameters. Screening parameters modified from [37; 38].

Conditions	Actions
S2< 0.5	Reject T_{max}
T_{max}< 395	Reject T_{max}
HI< 50;TOC >1	Reject T_{max}
T_{max}< 435;S1*1000/TOC >300	Reject T_{max}
T_{max}< 435;(S1/S2) >0.3	Reject T_{max}
390< T_{max}< 435;PI >0.1	Reject T_{max}
T_{max}< 435;PI >0.2	Reject T_{max}
435< T_{max}<445;PI >0.3	Reject T_{max}
445< T_{max}< 460;PI >0.4	Reject T_{max}
GP< 2;HI< 50 and OI >300	Reject PI
S2< 0.2	Reject PI
OI >300	Reject OI
TOC< 0.5	Reject T_{max}, HI, and OI
S1/TOC >1.5	Reject pyrolysis data

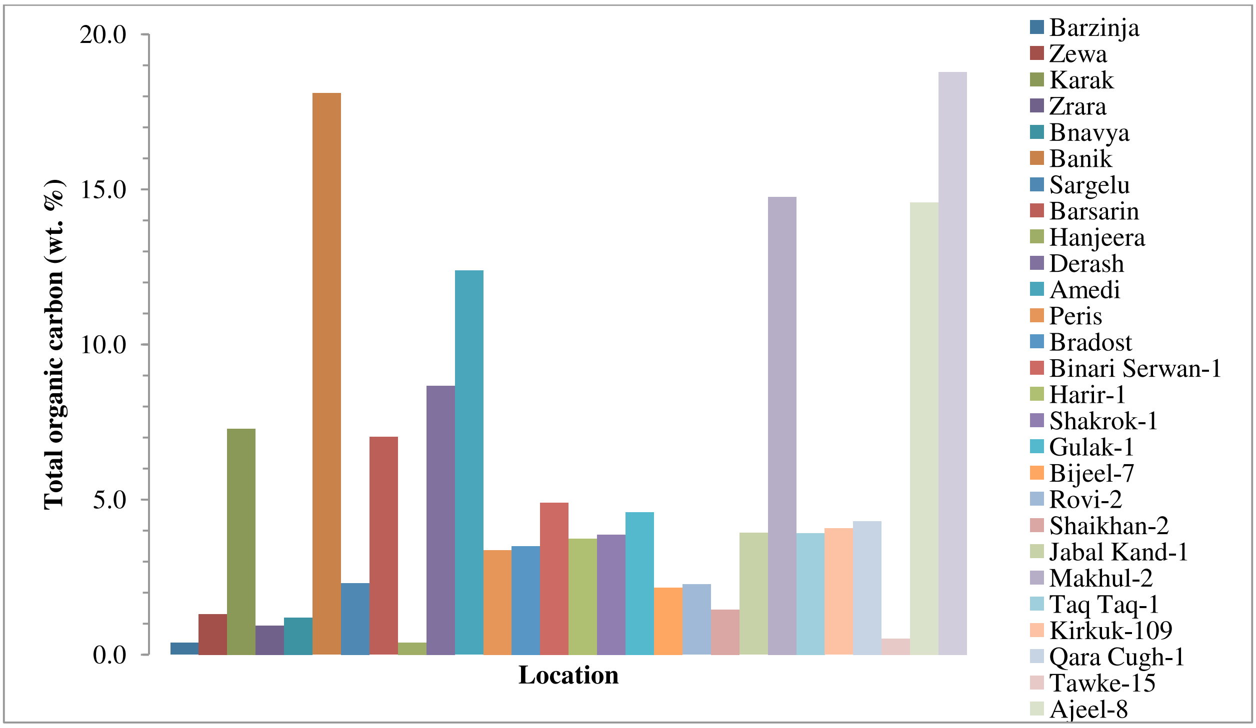

Figure 3: Histogram showing the mean distribution of total organic carbon for Naokelekan Formation at different localities in Iraqi Kurdistan.

Evaluating sediments based on their TOC wt. % content only is not sufficient to fulfill all the requirements of an actual source rock. Consequently, and reliant on Peters' [32] cataloguing and Dembicki's [35] classification of TOC wt. % associated with S2, Naokelekan Formation can be considered a good source rock. Thus the samples from Barzinja, Zrara, Bnavya, Hanjeera, and Zewa are poor while the samples from Makhul-2, Amedi, Derash, Karak, Banik, and Peris are excellent. The samples from Shaikhan-2 are good and samples from Harir-1, Rovi-2 and one third of Bijeel-7's samples are good to excellent. The rest of samples are fair to good (Figure. 5).

It is observed that organic matter in Naokelekan Formation at Derash Valley has the highest HI (613 mg HC/g TOC) with a mean of (503 mg HC/g TOC), and the lowest HI is at Zewa (3.5 mg

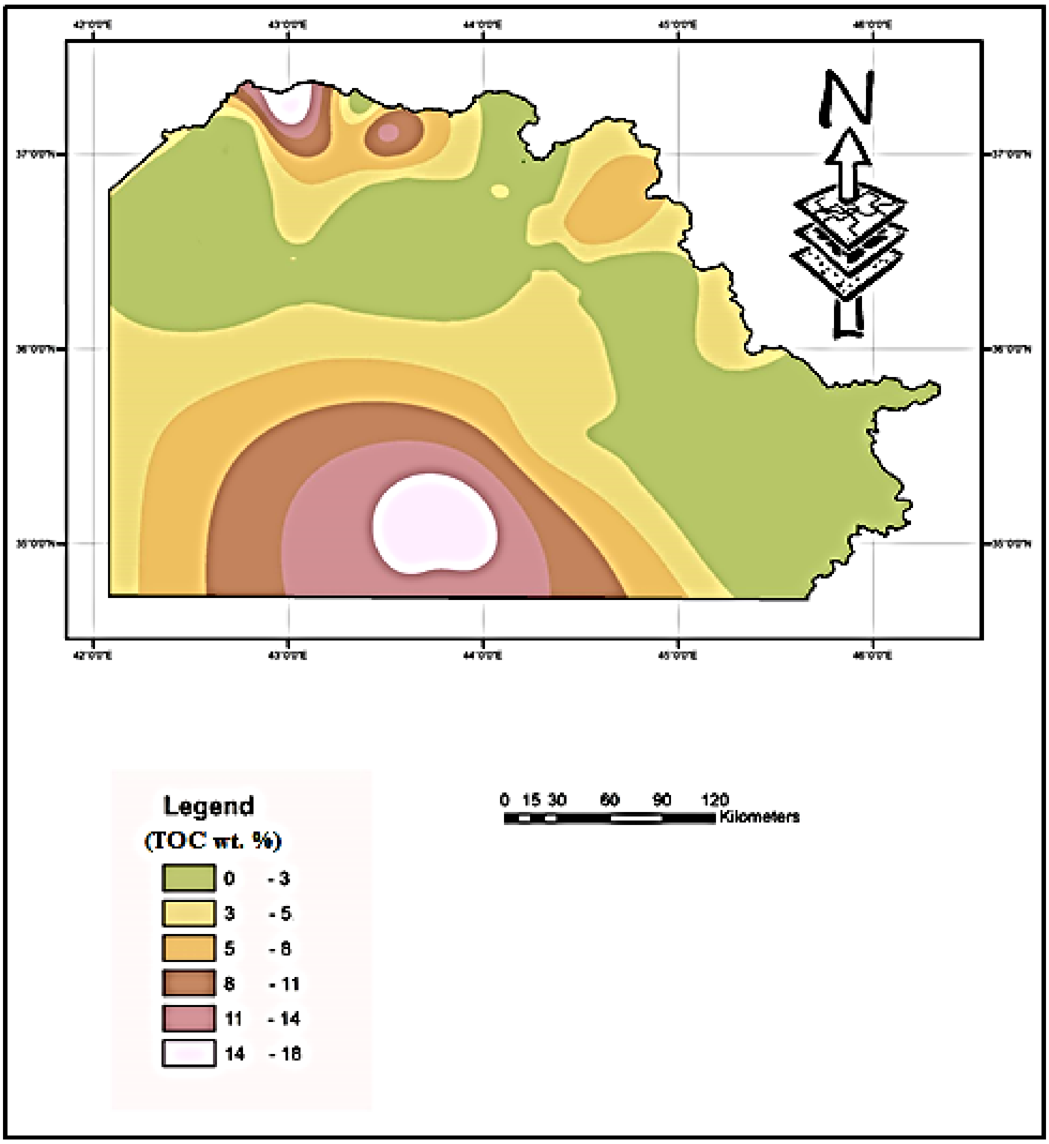

Figure 4: Total organic carbon weight percent (TOC wt. %) distribution contour map for Naokelekan Formation in Iraqi Kurdistan.

HC/g TOC) but the lowest mean HI was observed in Bnavya (17 mg HC/g TOC) (Table 2). The regional mean HI is 189 mg HC/g TOC. The variations of HI values among localities are due to organic matter types and their maturity level. Generally the samples have low OI ranging from 3 to 269 mg HC/g TOC with an average of 55 mg HC/g TOC. Samples from all localities have lower OI than HI except Barzinja, Bnavya, Sargelu, Barsarin, and Zewa samples (Figure. 6).

According to evaluation of Tissot and Welte [36] of source rock in general, 81 samples are poor, 50 samples are moderate, and 64 samples are good because they have genetic potential of less than 2 mg HC/g rock, between 2 and 6 mg HC/g rock, and more than 6 mg HC/g rock, respectively. The minimum genetic potential value is recorded in Hanjeera (0.06 mg HC/g rock) and maximum value is recorded in Derash (113.9 mg HC/g rock). The mean genetic potential of samples is good at 12 localities (Makhul-2, Banik, Derash, Amedi, Ajeel-8, Jabal Kand-1, Peris, Karak, Rovi-2, Barsarin, Gulak-1, and Shaikhan-2), moderate at 9 localities (Shakrok-1, Harir-1, Bijeel-7, Bradost, Kirkuk-109, Binari Serwan-1, Tawke-15, Ajeel-12, and Taq Taq-1), and poor for 6 localities (Zrara, Sargelu, Zewa, Bnavya, Barzinja, and Hanjeera) (Table 2). The general regional genetic potential mean is 14.5 mg HC/g rock. It is noticed that samples from Hanjeera Village have extremely poor genetic potential, averaging 0.14 mg HC/g rock. On the other hand, samples from Makhul-2 have extremely high genetic potential with an average of 69.5 mg HC/g rock (Table 2).

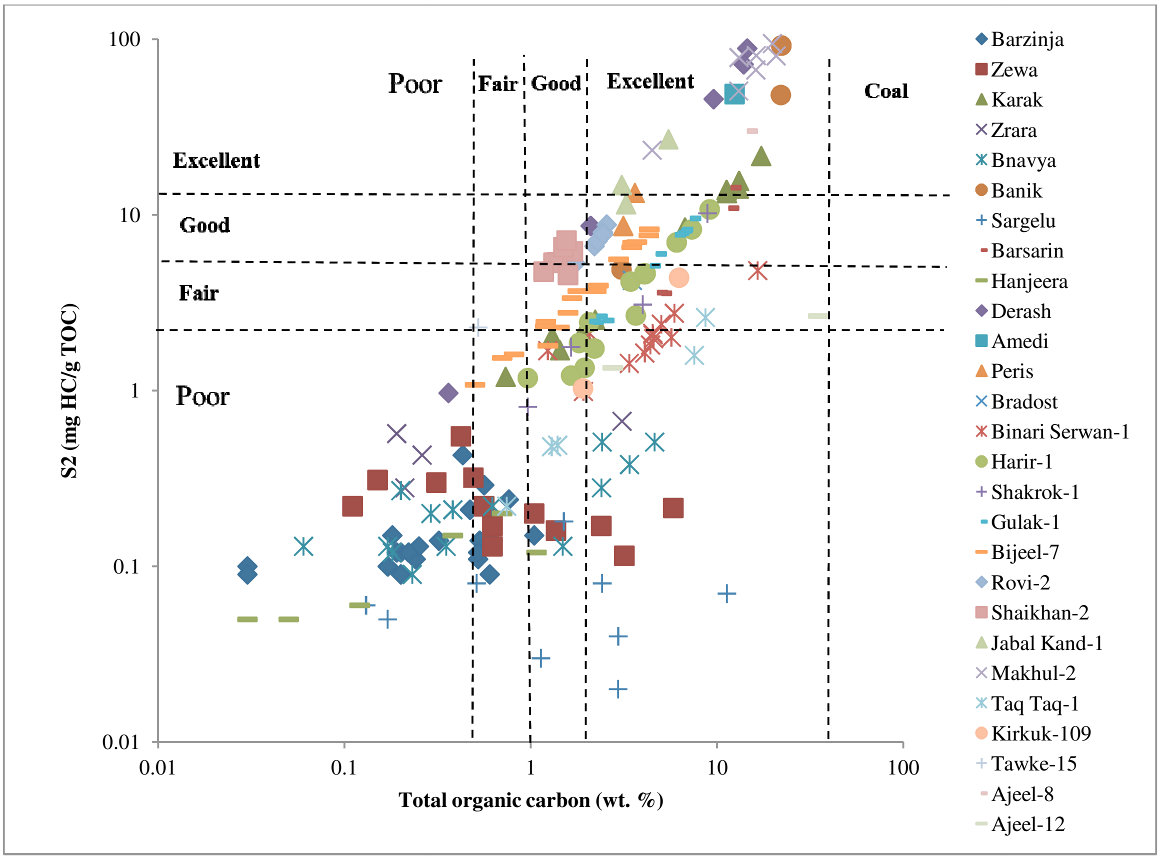

Figure 5: Cross plot of total organic carbon weight percent versus S2 shows the quality of organic matter in Naokelekan Formation at different localities in Iraqi Kurdistan (after [39]).

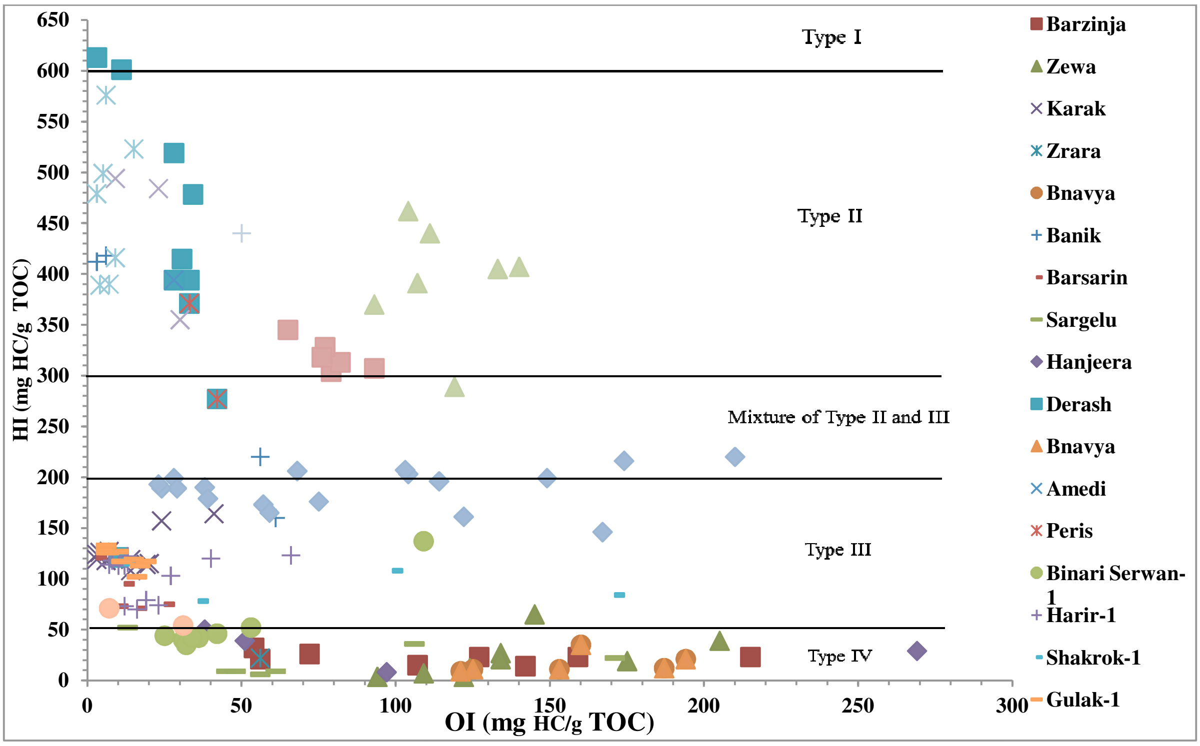

Figure 6: Oxygen index (OI versus hydrogen index (HI) showing kerogen types of Naokelekan Formation at different localities in Iraqi Kurdistan. The plot shows types II and III are dominant kerogen types.

Determining kerogen type using T_{max} versus HI (Figure. 7) appears to be more accurate than OI versus HI (Figure. 8). The discrepancy between the results is predictable since Naokelekan Formation is dominated by carbonates which affect the OI. The increasing OI of the HI versus OI diagram in figure 8 indicates possible oxidation trend, which could be the result of outcrop weathering or oxic conditions in the depositional environment. It is observed from the T_{max} versus HI plot that samples from Makhul-2, Derash, Peris, Banik, Bradost, Jabal Kand-1, and Amedi are Type II. Samples from Bijeel-7, Karak, Harir-1, Shakrok-1, Gulak-1, Ajeel-8, Kirkuk-109, Barsarin, and Sargelu are Type III.

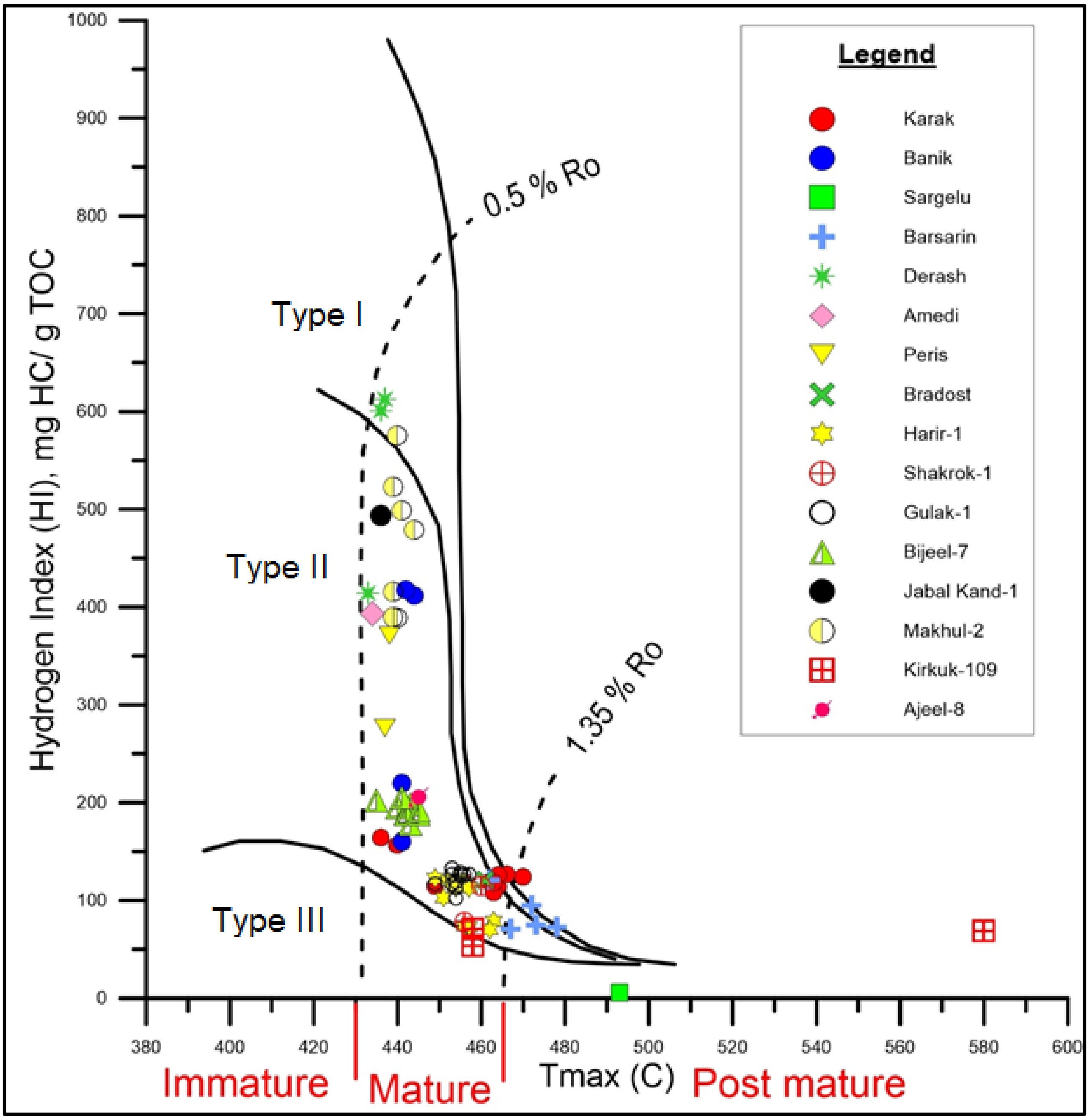

Figure 7: Hydrogen index versus T_{max} plot for Naokelekan Formation samples at different localities in Iraqi Kurdistan (adapted from [45]).

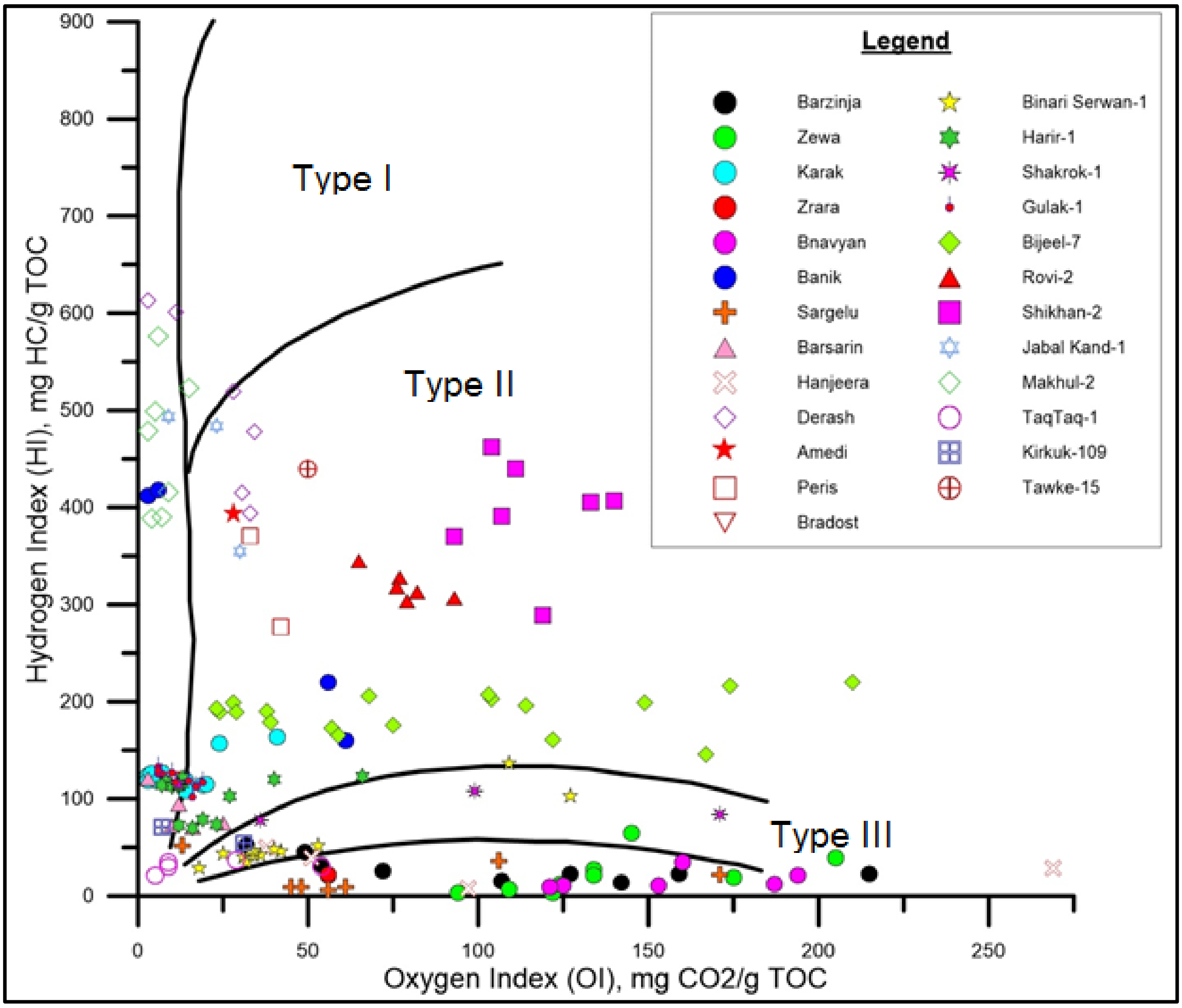

Figure 8: Oxygen index (OI) versus hydrogen index (OI) plot for samples from Naokelekan Formation at different localities in Iraqi Kurdistan (adapted from [46]).

The other samples were not plotted due to their rejected T_{max}. The HI versus OI showed different numbers for each type. The latter showed 34 samples Type II, 12 mixture of types II and III, 46 Type III. The remaining samples belong to Type IV, and 10 were located in the lower left corner, assuming that all samples are immature (Figure. 8). The HI value of one sample is more than 600 mg HC/g TOC, which means it is Type I; greater than 300 mg HC/g TOC for 32 samples which is typical of Type II; more than 200 mg HC/g TOC for 10 of them, which means they are a mixture of types II and III; greater than 50 for 67 samples signifying Type III; and less than 50 for 48 samples, which indicates Type IV [34; 36]. The kerogen type for 53 samples was not determined because of their rejected HI values or data were not available. As observed, the facies turn into more sandy and silty (with rise in types III and IV) in Bnavya and Zrara. The organic matter might have been better quality initially especially in Barzinja, but the maturity overprint may have decreased their quality.

It is observed that organic matter in Naokelekan Formation at Derash Valley has the highest HI (613 mg HC/g TOC) with a mean of (503 mg HC/g TOC), and the lowest HI is at Zewa (3.5 mg HC/g TOC) but the lowest mean HI was observed in Bnavya (17 mg HC/g TOC) (Table 2). The regional mean HI is 189 mg HC/g TOC. The variations of HI values among localities are due to organic matter types and their maturity level. Generally the samples have low OI ranging from 3 to 269 mg HC/g TOC with an average of 55 mg HC/g TOC.

The pyrolyzable carbon index (PCI) which mathematically can be expressed as PCI=0.83× (S1+S2) [37; 38; 39; 40] indicates that 177 samples from Naokelekan Formation are Type III, which are gas prone. Seven samples are mixed types II and III, 3 are Type II, 6 are mixed types I and II, and 6 are Type I (Table 2). The

samples from Naokelekan Formation in Makhul-2, Banik, Bradost, Derash and Amedi belong to Type I and mixture of types I and II. The rest of the samples represent Type III and a mixture of types II and III according to their PCI values (Figure. 9). The TOC wt. % versus S2 diagram shows that the majority of the samples are Type II (Figure. 10).
Each diagram shows different numbers for different types, but all of the diagrams indicate that the majority of the samples are types II and III.

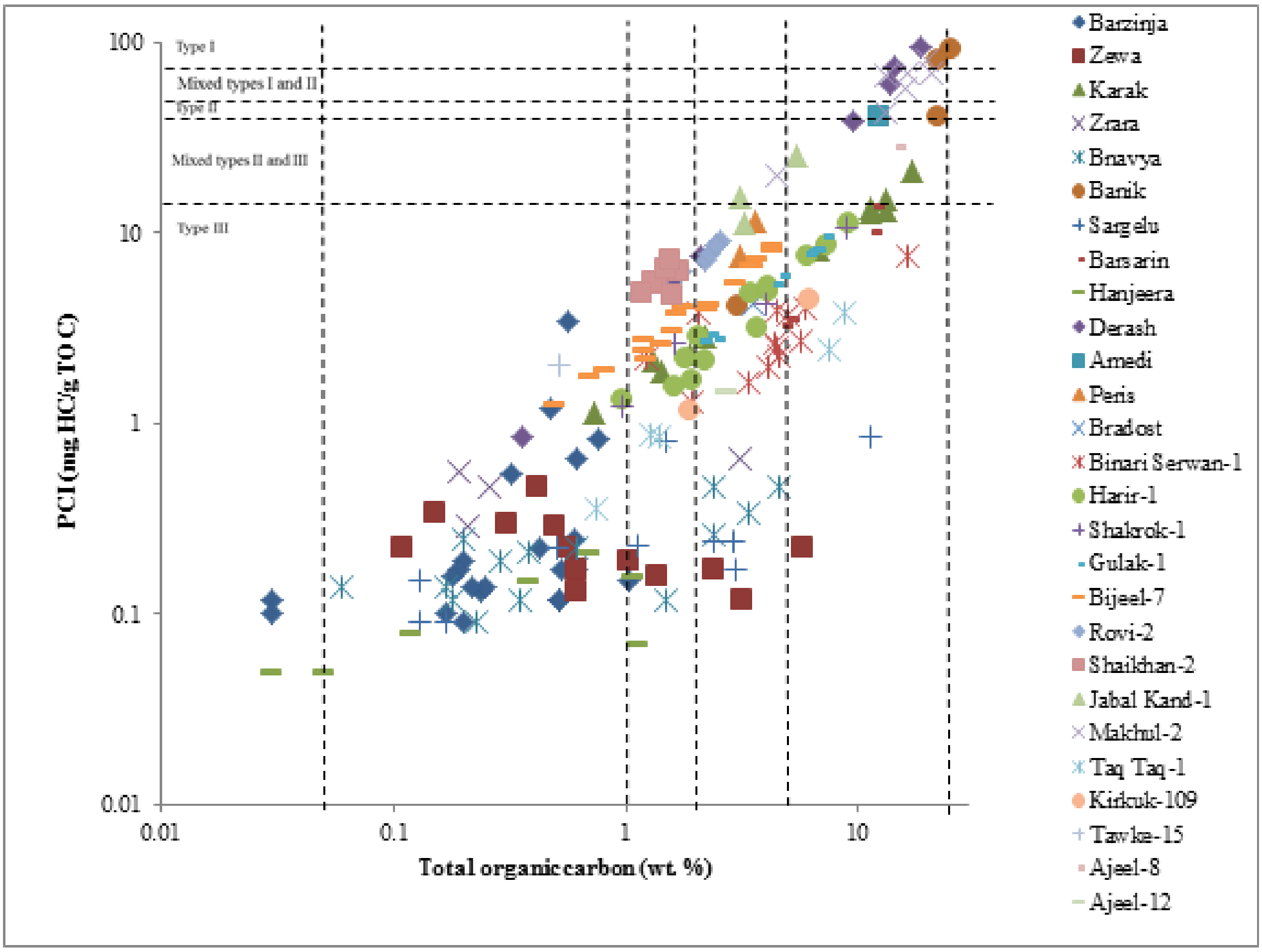

Figure 9: Total organic carbon weight percent (wt. %) versus pyrolyzable carbon index (PCI) indicates the quality of the organic matter in Naokelekan Formation at studied localities in Iraqi Kurdistan (after [44]).

Kerogen microscopy

The palynological assemblages isolated from the samples examined contain amorphous organic matter (AOM). In some samples, AOM comprises up to 100 % of the palynological content. Palynological assemblages of Naokelekan Formation are dominated by amorphous organic material, with a low abundance of palynomorphs due to masking. Diagnostic palynomorphs are not performed.

The level of thermal maturity for miscellaneous types of kerogen might be assessed from the T_{max} range [34; 45]. The highest T_{max} value during pyrolysis analysis of organic material was recorded for samples from Sargelu (493ºC) and the lowest T_{max} was in Derash (433ºC). The lowest mean T_{max} value was recorded in Amedi (434ºC) and highest mean T_{max} value belongs to samples from Sargelu (493ºC).The regional average is 451ºC (Table 2). The maturation T_{max} contour map of organic matter in Naokelekan Formation in Iraqi Kurdistan is shown in figure 11. Only 79 data points were used in this figure and the use of 127 data points were omitted because they did not resemble to reasonable conditions that are shown in table 3. The vitrinite reflectance (Ro%) values were obtained by converting T_{max}.

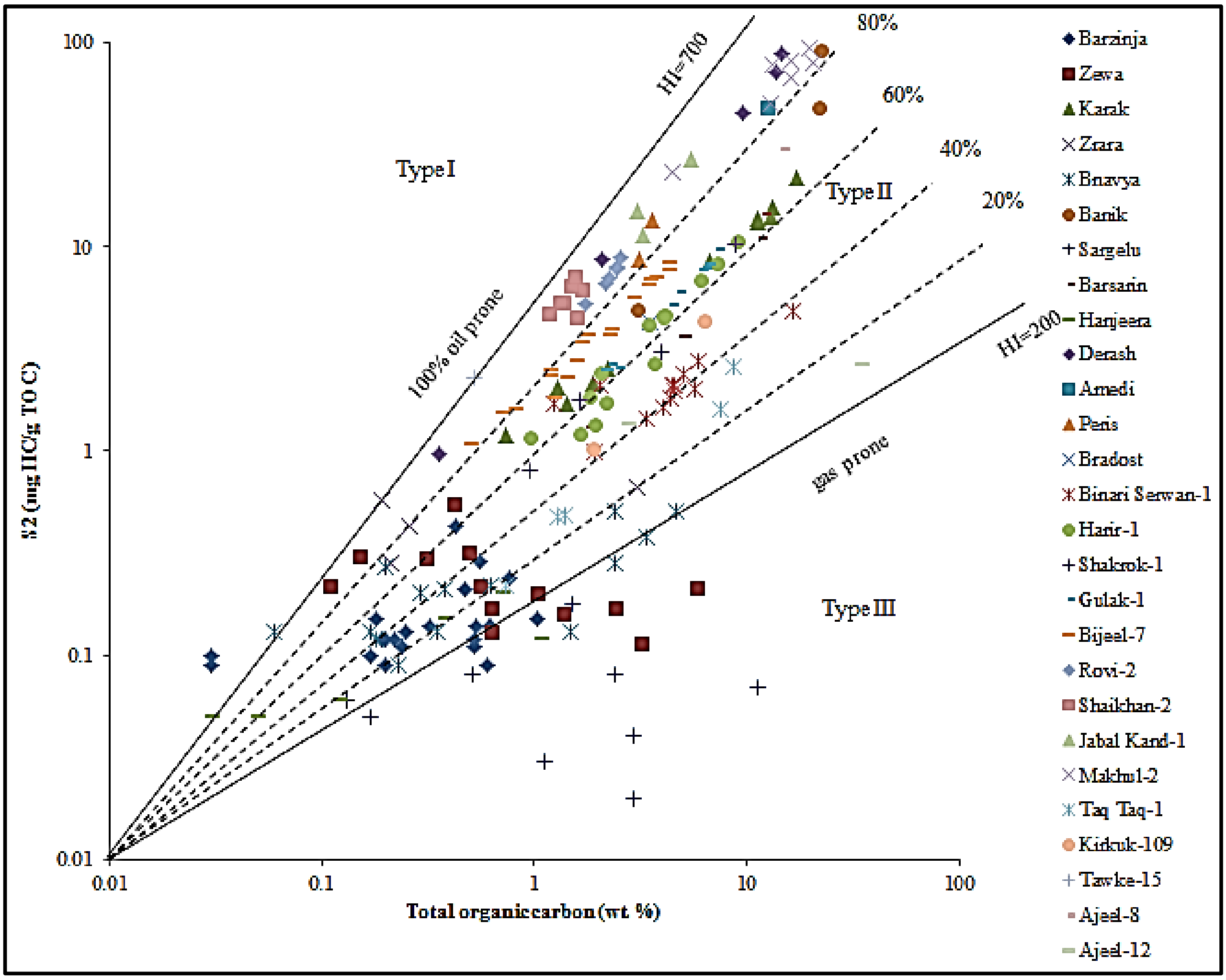

Figure 10: Plot of total organic carbon weight percent (wt. %) versus Rock-Eval pyrolysis S2 shows the kerogen type for samples from Naokelekan Formation at different localities in Iraqi Kurdistan. The plot also indicates whether kerogen is oil or gas prone (after [47; 48].

The conversion can be mathematically expressed as Ro (calculated) = (0.018) x (T_{max}) −7.16 [46]. To achieve realistic Ro data, the exceeding formula was not applied on samples that have S2 values smaller than 0.5 mg HC/g rock and samples with T_{max}< 420 or >500°C.

The calculated vitrinite reflectance of samples from Naokelekan Formation in Iraqi Kurdistan is shown in table 2. The maturity of organic matter constructed on (T_{max}) and (Ro) (Figure. 7 and Table 2, respectively) increases progressively toward the east. This escalation of maturity in the direction of the east may also be noticed from the contour maps of maturity zones for the Middle Jurassic Sargelu Formation that were drawn by [8; 19; 20]. This progressive increase of maturity can also be observed from the T_{max} versus HI and OI versus HI plots (Figures. 7 and 8). It is clear that samples from Binari Serwan-1, Harir-1, Gulak-1, Kirkuk-109, and Sargelu localities emerge in the lower left corner in the plot of HI versus OI and in the mature and gas zone area in figure 7. The T_{max} values fluctuate back and forth due to organic matter's hydrogen content. A low-hydrogen organic matter commonly has a high T_{max}, and a high-hydrogen organic matter has a low T_{max} [33].

The samples in Binari Serwan-1 locality have comparatively low T_{max} values and high OI. The OI ranges between 18 to 127 mg HC/g TOC with an average 47mg HC/g TOC, which may be a result of weathering and/or lithology and mineral matrix [32]. The data obtained from Binari Serwan-1 Well's samples appear to be anomalous because they have high production index (PI) values that range between 0.3 and 0.6 with an average 0.4 and T_{max} values that range from 305 to 353°C with an average 336°C. Additionally, the samples have S2 values 0.99 to 4.83 mg HC/g rock which is insignificant. This might be owing to the accumulation of migrated oil and drilling or mud additives that caused a decrease in the T_{max} of kerogen. Since oil contains more hydrogen than kerogen, any oil additives into the mud may lower the T_{max}. When the hydrogen in kerogen is increased, both the T_{max} and the vitrinite reflectance go down [33].

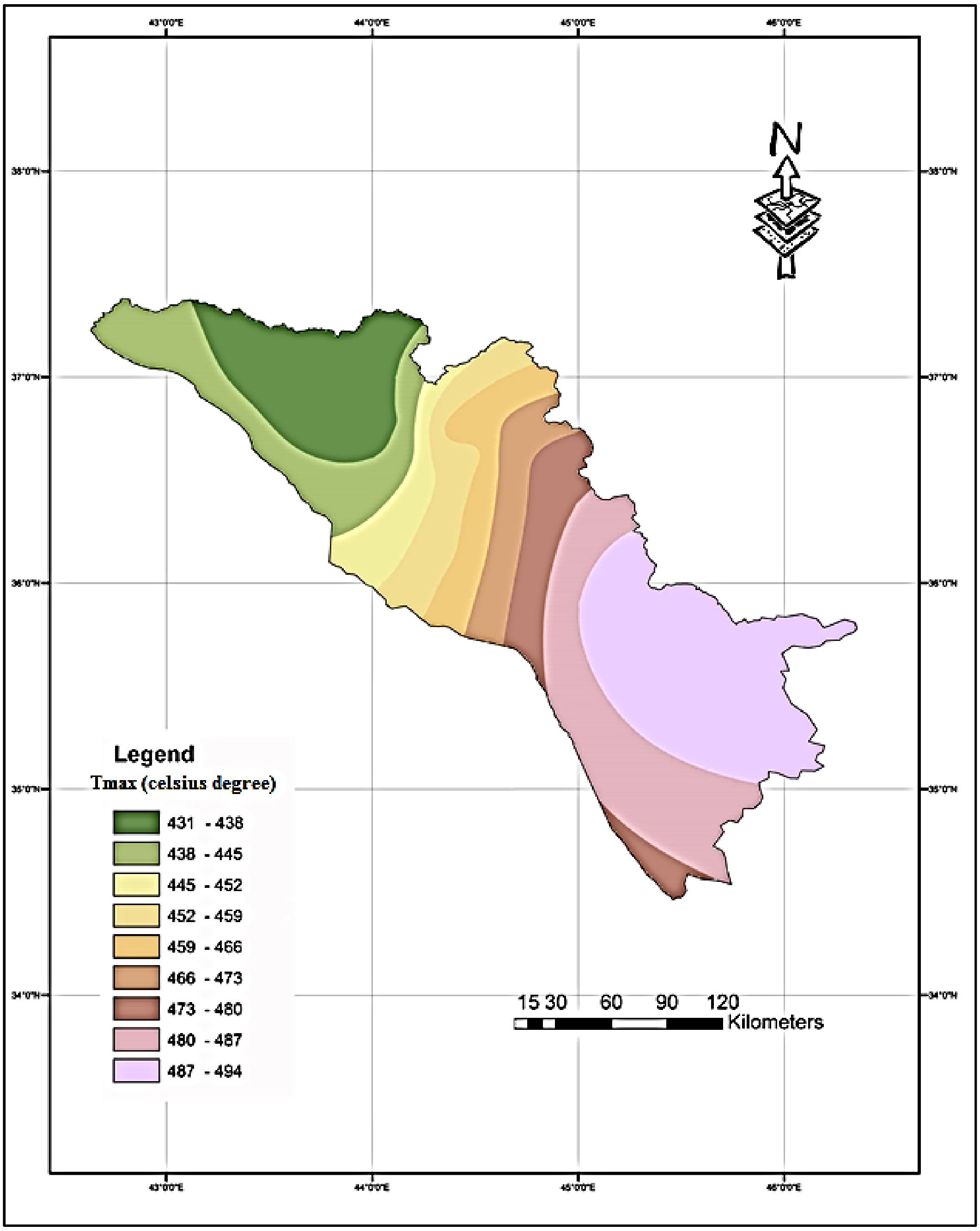

Figure 11: Contour map of maturity zones (T_{max}) for Naokelekan Formation's organic matter in Iraqi Kurdistan.

According to [32; 34;45], in their designation for maturity level constructed on T_{max} and PI (Table 4), Naokelekan Formation is immature in Banik, Derash, Amedi, Jabal Kand-1, Peris, and Makhul-2; mature in Karak, Harir-1, Shakrok-1, Gulak-1, Bijeel-7, Kirkuk-109, and Ajeel-8; and postmature in Sargelu, Barsarin, and Bradost. The production indices of mature samples appear to be higher than normal values for regular Type II kerogen therefore the organic matter may belong to Type II-S kerogen. The Type II-S kerogen has a lower cracking point. Naokelekan Formation is within the wet gas zone in the Bradost and dry gas zone in Barsarin and Sargelu but appears to be within the oil window in the mentioned mature localities and peak oil window in Harir-1.

Table 4: Guidelines for describing stage of thermal maturity (after [38]).

Stage of Thermal Maturity of Oil		T_{max} for Type I	T_{max} for Type II	T_{max} for Type III	Production Index
Immature		< 440	< 435	< 445	< 0.10
Mature	Early	440	435	445	0.10-0.25
	Peak	445	440	450	0.25-0.40
	Late	450	460	470	> 0.40
Postmature		> 450	> 460	> 470	-

The thermal maturity of the examined samples from the studied area in Binary Serwan-1, Rovi-2, Shaikhan-2, Karak, and Zrara were re-evaluated by thermal alteration index (TAI). Maturation evaluations for palynofacies in the Naokelekan Formation were based on TAI (following [47]) designates the existence of mature organic matter of dark orange and light brown with TAI: 2.7-3.2; 2.6-3.3; 2.7-3.0; 2.7-3.0; and 2.5-2.8 for Binary Serwan-1, Rovi-2, Shaikhan-2, Karak, and Zrara, respectively (Figure. 12). Amorphous kerogen has a spotted, intersected grid or a faintly polygonal texture. It commonly occurs in bulky, dense masses that display a reddish-brown color beneath transmitted light.

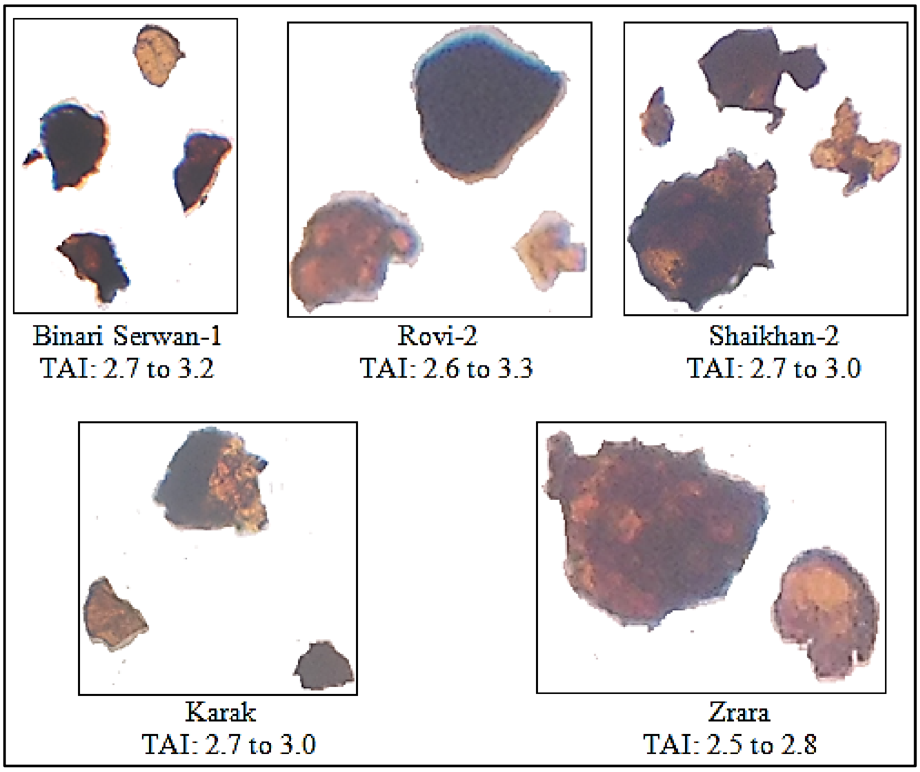

Figure 12: Color change in the studied samples in Naokelekan Formation in different localities in Iraqi Kurdistan.

The western portion of the study area signifies an immature zone whereas the eastern portion is postmature (Figure. 11 and Table 2). All production index values are less than 1 excluding values of Tawke-15, Makhul-2, and Ajeel-12. The Tawke-15 has a production index value of 0.07 at depth 2830-2840m. This value indicates that Naokelekan Formation is not mature in this area regardless to its high migration index (MI), S1/TOC [48]. The boundary depth between mature and immature zones for TA-15 Well was determined by Abdula [19] to be 2880 m. In the same way, the value of 0.07 at depth 3500m in Ajeel-12 indicates immaturity of Naokelekan's organic matter. According to Smith [49] and Hunt [33], the expulsion of oil starts when the MI ranges between 0.1 and 0.2. The values of MI rise with depth because of a rise of thermal maturity supposing facies are the same. This rise lasts to the top of the oil window and then stays approximately stable for a short distance. This case may apply on Naokelekan in well Makhul-2. In this well, the MI starts to increase from 0.13 to 0.18 at depth 2255.5 to 2265.9m then drops to 0.08 at 2267.7m. The high values of MI agree with production index values and T_{max} values and accordingly Naokelekan Formation's organic matter would be mature and within early oil window.

By applying Peters' [32] guidelines on samples from studied localities, the HI and S2/S3 values in Table 2, Naokelekan Formation is oil prone in the Rovi-2, Jabal Kand-1, and Makhul-2 wells. It is a mixture of oil and gas prone in Harir-1, Gulak-1, Bijeel-7, and Shaikhan-2 wells whereas it is gas prone in other areas. This can similarly be configured from figure 10.

Conclusions

The TOC wt. % of the sampled Naokelekan Formation decreases toward the west, north, and southeastern parts of studied area. The mean of TOC wt. % is 0.4 in the southeastern part and it is 18.8 in the southern part of the region. The quality of organic matter is affected by high maturity especially toward the east and southeast. The organic material is characterized by types II and III kerogens.

The thermal maturity rises to the east of the region from 434ºC T_{max} in Amedi to 493ºC T_{max} in Sargelu Village. Maturation based on thermal alteration index indicates the presence of mature organic matter of dark orange and light brown with TAI 2.5-3.3. Organic matter is within the dry gas zone in the eastern part, oil window in the central portion, and marginally mature and immature further to the west and northwest in Amedi and Derash.

The results of this study show that the T_{max} values obtained for all the analyzed samples are less than the threshold T_{max} value for obtaining the high production indices (higher than 0.1 except for Makhul-2 and two samples from Ajeel 8 and Ajeel-12) which suggest the presence of Type II-S kerogen. However, these results need further investigations because the pyrolysis T_{max} parameter is partly dependent on the type of organic matter and can vary from one sedimentary basin to another.

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