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ROCK-EVAL ANALYSIS AND ORGANIC PETROGRAPHICAL CHARACTERIZATION OF THE UPPER JURASSIC NAOKELEKAN FORMATION, NORTHERN MESOPOTAMIAN BASIN, KURDISTAN REGION-IRAQ

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Abstract

The aim of this study is to assess the type, thermal maturity and the petroleum generation potential of the Upper Jurassic Naokelekan Formation, occurring across the Kurdistan Region of Iraq, by applying organic petrographical methods and Rock-Eval analysis. The Rock-Eval data would indicate the presence of kerogen types III, IV and II as the main constituents. However, the qualitative petrographical evaluation revealed that the main organic constituents are solid hydrocarbons, in the form of micrugranular migrabitumens, with minor amounts of pyrobitumens. These secondary particles have affected the results of the Rock-Eval analysis and would have led to misinterpretation of organic matter typification based on pyrolysis results only. The combined results of petrography and pyrolysis indicate an active petroleum system within the Upper Jurassic sequence, where hydrocarbons are generated and reservoired within suitable lithologies.

Keywords: *Naokelekan Formation, Upper Jurassic, migrabitumens, pyrobitumens, Rock-Eval, Kurdistan Region.*

ΠΕΡΙΛΗΨΗ

Στη συγκεκριμένη εργασία αξιολογείται ο τύπος και ο βαθμός ωρίμανσης του οργανικού υλικού, που περιέχεται στον Άνω-Ιουρασικό Σχηματισμό Naokelekan, στο Ιρακινό Κουρδιστάν, με στόχο την εκτίμηση του δυναμικού πετρελαιογένεσης. Κύριο αντικείμενο της μελέτης αποτέλεσε η μελέτη δειγμάτων του Σχηματισμού από πέντε επιφανειακές εμφανίσεις μέσω τεχνικών Οργανικής Πετρογραφίας, καθώς και Rock-Eval ανάλυσης. Τα δεδομένα της τεχνικής Rock-Eval υπέδειξαν την παρουσία των τύπων κηρογόνου III, IV και II. Ωστόσο η ποιοτική πετρογραφική αξιολόγηση αποκάλυψε ότι τα κύρια οργανικά συστατικά των υπό μελέτη δειγμάτων είναι στερεοί υδρογονάνθρακες με μορφή στερεών «μεταναστευόντων» βιτουμενίων (migrabitumen), και σε μικρότερο βαθμό με μορφή πυροβιτουμενίων. Ως εκ τούτου η παρουσία αυτών των στερεών βιτουμενίων έχει επηρεάσει την απόδοση της τεχνικής Rock-Eval, της οποίας η αποκλειστική εφαρμογή θα είχε οδηγήσει σε παρερμηνεία του τύπου κηρογόνου αλλά και του δυναμικού παραγωγής. Συνδυαστικά τα δεδομένα της Οργανικής Πετρογραφίας και της τεχνικής Rock-Eval συνηγορούν στην ύπαρξη ενός ενεργού συστήματος πετρελαίου εντός της Άνω-Ιουρασικής ιζηματογενούς ενότητας, όπου είναι δυνατόν να παράγονται και να αποθηκεύονται υδρογονάνθρακες σε κατάλληλες λιθολογικές δομές.

Λέξεις Κλειδιά: *Ιρακινό Κουρδιστάν, Σχηματισμός Naokelekan, Ανώτερο Ιουρασικό, υδρογονάνθρακες, Rock-Eval πυρόλυση*

1. INTRODUCTION

Naokelekan Formation, being part of the Imbricated Zone in Iraqi Kurdistan was first described and recognized by Wetzel and Morton , 1950 (*in* Bellen et al., 1959). It was deposited during Jurassic, in a brackish lagoon and shallow open marine environment under euxinic conditions in a slow subsiding basin (Buday, 1980; Aqrawi et al., 2010). The Naokelekan Fm is one of many Jurassic formations displaying hydrocarbons source rock characteristics all over Iraq (Jassim and Al-Gailani, 2006; Sachsenhofer et al., 2015). Regarding maturation Naokelekan Fm is thermally mature in the east of Tigris River (Al-Ameri and Zumberge, 2013) and it is within the oil generation window in Sargelu locality, in Kirkurk and Sulaimani areas (Lewan and Ruble, 2002; Baban and Ahmed, 2014; Mohialdeen et al., 2018).

However, organic petrographical studies across the Naokelekan Fm outcrops are limited and hence, this study aims to: (1) define the type of organic matter; (2)

determine the thermal maturity of the organic matter; and (3) assess hydrocarbon potentiality of Naokelekan Formation in Iraqi Kurdistan in five surface stratigraphic sections (Fig. 1a).

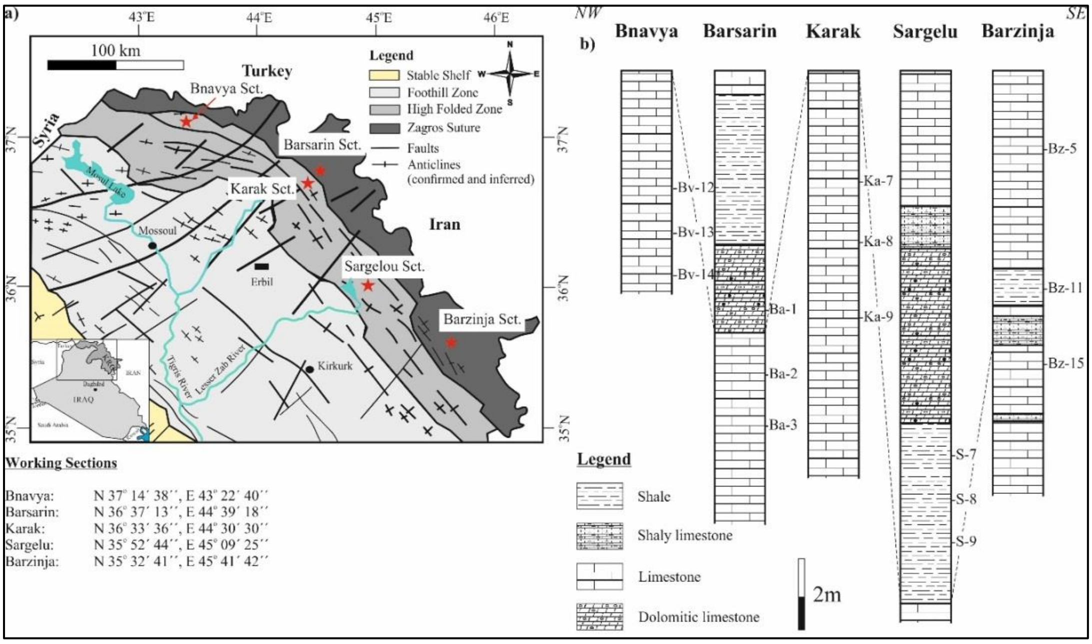

Fig. 1: a) Tectonic subdivision of northern Iraq (after Jassim and Buday, 2006) showing the sampling locations, b) Lithological columns of the studied sections, as well as the sampling scheme; correlation lines based on data in Abdula (2016).

2. GEOLOGICAL SETTING

Iraqi Kurdistan is situated on the north eastern edge of the Arabian Plate, being part of the Zagros Mountain belt. The studied outcrops are located within the High Folded, Imbricated Northern Thrust zones, which are extremely distorted, and characterized by asymmetric anticlines and accompanying narrow synclines. The core of these anticlines contains Jurassic and Cretaceous rocks, mostly limestone, whereas their flanks are covered by Tertiary limestones and clastic sedimentary rocks (Ameen, 1992; Jassim and Buday, 2006). In all the outcropping sections, the lower boundary of Naokelekan Formation with the underlain Sargelu Formation is traced within a thin-bedded limestone sequence (Jassim and Al-Gailani, 2006). Naokelekan Fm is distinguished by the lack of *Bositra* and disappearance of chert bands that occur within Sargelu Fm (Wetzel, 1948; *in* Bellen, 1959; Abdula et al., 2015). Naokelekan Fm is regularly overlain by Barsarin Fm with gradational and conformable contact (Buday, 1980; Jassim and Al-Gailani, 2006). The thickness of the Naokelekan Fm exposure ranges between 7 m and 34 m with most of the outcrops displaying a thickness less than 20 m (Wetzel and Morton, 1950; *in* Bellen, 1959). Based on lithological and petrographic features, a tripartite division of the Formation is recognizable in most sections (Wetzel and Morton, 1950; in Bellen, 1959). This division, from bottom to top, includes: (1) bituminous limestone and dolomite, with intercalated bituminous shale (Coal Bed); (2) dolomitic limestone or limestone (Motteled Bed); and (3) laminated shaly bituminous limestone.

3. METHODOLOGY

Five sections of Naokelekan Formation (Fig. 1) were sampled; 62 samples were analyzed using Rock-Eval (RE) 6 (Barsarin: 5, Bnavya:14, Barzinja: 22, Karak: 11 and Sargelu:10), whereas 15 sub-samples of those selected for RE and depending on the RE results, were further subjected to mineralogical and organic petrographical studies. The sub-sampling for the organic petrographical examinations was focused on the lower stratigraphical sections of the studied profiles, corresponding mainly to bituminous limestones (Fig. 1b). The mineralogical assemblages were determined by using a Bruker D8 X-ray Diffractometer, while quantification was performed by using TOPAS® software. Total organic carbon (TOC) content was also determined in selected 15 samples, three from each section, after HCl treatment (Van Iperen and Helder, 1985). Maceral identification and reflectance measurements were performed according to ASTM D7708 (ICCP, 2014), following the nomenclature of the Stopes-Heerlen System as modified by ICCP System 1994 (ICCP, 1998; ICCP, 2001; Sýkorová et al., 2005; Pickel et al., 2017).

4. RESULTS

4.1. Mineralogical Composition

Calcite is the predominant mineral in the majority of the studied samples with values up to 98% (Table 1). Regarding silicate minerals, all the samples contain quartz and mixed-layer clays ranging from 0.5 to 45 wt.% and 0.5 to 71.5 wt.%, respectively. Subordinately, mineral phases that were identified include K-feldspars, plagioclase, muscovite, chlorite, gypsum, anhydrite, barite, halite and geothite, without displaying any variation trend. Finally, pyrite occurs within all Karak samples, and minorly in Barsarin and Barzinja samples (Table 1).

Table 1. XRD quantitative evaluation (wt. % of the crystalline phases, Ba: Barsarin, Bv: Bnavya, Bz: Barzinja, Ka: Karak, S: Sargelu).

Sample/ Mineral	Calcite	Dolomite	Quartz	Mixed-layer clay[1]	K-Feldspar	Plagioclase	Muscovite	Chlorite	Gypsum	Anhydrite	Halite	Barite	Pyrite	Goethite
Ba-1	80.0		3.0	3.0					8.5			4.5	1.0	
Ba-2	83.5		7.0	8.5									1.0	
Ba-3	98.0		0.5	1.5										
Bv-12	44.5	4.0	45.0	5.5								1.0		
Bv-13	2.0		10.5	54.0		5.0	20.0	7.5		0.5	0.5			
Bv-14	2.0		6.0	71.5		3.5	10.0	6.5			0.5			
Bz-5	91.0		1.0	1.5	4.0						2.5			
Bz-11	90.0		2.0	2.0					6.0					
Bz-15	70.0		15.5	3.0						1.0			4.0	6.5
Ka-7	31.0	7.0	6.5	1.0	36.5				12.0		2.5		3.5	
Ka-8	88.0	2.0	0.5	5.0	3.5								1.0	
Ka-9	78.0	0.5	13.0	3.5		4.5							0.5	
S-7	12.5	50.0	13.5	0.5	23.5									
S-8	72.0		7.0	3.0	18.0									
S-9	76.0		8.0	1.0	15.0									

1: Mixed-layer clays: Illite-montmorillonite

4.2. Rock - Eval Analysis Data

According to Rock Eval data, Barsarin and Karak sections display similar results; TOC values range from 0.73 to 17.22 wt.% (Table 2). The S1 and S2 parameters fluctuate within the ranges of 0.18-3.49 and 1.7-21.7 mg HC/g rock respectively, indicating a wide range of poor to very good petroleum potential. The T_{max} ranges within 440 to 478°C, suggesting late to post-mature stage of thermal maturity. The Hydrogen Index (HI) parameter ranges within the range of 71-157 mg HC/g TOC, suggesting the occurrence of kerogen type III (Peters and Cassa, 1994), nevertheless, caution should be exercised in the interpretation of HI, as the maturity indicated by T_{max} is relatively high (e.g. Carvajal-Ortiz and Gentzis, 2018).

The obtained TOC values for Barzinja, Bnavya and Sargelu samples range within 0.03-11.25 wt.%, respectively with most samples displaying values <1 wt.%. The S1 and S2 parameters fluctuate within 0.02-0.18 and 0.06-5.75 mg HC/g rock respectively, indicating poor petroleum potential for these sections. The T_{max} ranges within 306 to 594°C, corresponding to almost all the stages of thermal maturity from the immature to post-mature. The HI fluctuates within the wide range of 9-333 mg HC/g TOC, corresponding to a scattered occurrence of kerogen types IV, III and mixture of III & II.

Table 2. Total organic carbon and Rock-Eval pyrolysis data of the studied Naokelekan Fm samples (Ba: Barsarin, Bv: Bnavya, Bz: Barzinja, Ka: Karak, S: Sargelu).

	TOC[1]	TOC[2]	S1	S2	S3	T_{max}	PI	GP	HI	OI	PCI	S1/TOC	S2/S3
Sample	wt.%		mg HC/g rock		mg CO_2/g rock	°C			mg HC/g TOC				
Ba-1	0.7	1.78	0.67	1.30	0.17	478	0.34	1.97	73	10	1.64	0.15	7.65
Ba-2	2.8	5.04	0.70	3.59	0.79	467	0.16	4.29	71	16	3.56	0.18	4.54
Ba-3	6.6	11.90	2.17	14.34	0.33	462	0.13	16.51	121	3	13.70	0.08	43.46
Ba-4		11.57	1.11	10.96		472	0.09	12.07	95	12	10.02	0.18	
Ba-5		4.80	0.30	3.62		473	0.08	3.92	75	25	3.25	0.40	
Bv-1		0.20	0.03	0.27	0.20	433	0.09	0.30	135	100	0.25	0.76	1.35
Bv-2		0.17	0.04	0.13	0.29	484	0.21	0.17	76	171	0.14	0.69	0.45
Bv-3		0.06	0.04	0.13	0.05	429	0.25	0.17	217	83	0.14	0.48	2.60
Bv-4		0.35	0.02	0.13	0.38	438	0.16	0.15	37	109	0.12	0.37	0.34
Bv-5		0.18	0.02	0.12	0.16	439	0.15	0.14	67	89	0.12	0.37	0.75
Bv-6		0.29	0.03	0.20	0.34	418	0.15	0.23	69	117	0.19	0.52	0.59
Bv-7		0.23	0.02	0.09	0.36	483	0.15	0.11	39	157	0.09	0.47	0.25
Bv-8		0.62	0.05	0.22	0.99	394	0.20	0.27	35	160	0.22	0.73	0.22
Bv-9		0.38	0.04	0.21	0.59	393	0.15	0.25	55	155	0.21	0.50	0.36
Bv-10		3.38	0.03	0.38	5.16	533	0.08	0.41	11	153	0.34	0.50	0.07
Bv-11		4.61	0.04	0.51	5.75	528	0.07	0.55	11	125	0.46	0.87	0.09
Bv-12	1.7	2.41	0.06	0.51	4.67	397	0.10	0.57	21	194	0.47	1.31	0.11
Bv-13	2.9	2.39	0.03	0.28	4.48	513	0.10	0.31	12	187	0.26	0.91	0.06
BV-14	2.2	1.48	0.02	0.13	1.79	534	0.13	0.15	9	121	0.12	0.97	0.07
Bz-1		0.20	0.11	0.12	0.22	464	0.49	0.23	60	110	0.19	0.29	0.55
Bz-2		0.19	0.08	0.12	0.16	450	0.41	0.20	63	84	0.17	0.16	0.75
Bz-3		0.53	0.06	0.14	0.38	481	0.31	0.20	26	72	0.17	0.18	0.37
Bz-4		0.52	0.04	0.11	0.29	457	0.25	0.15	21	56	0.12	0.16	0.38
Bz-5	0.6	0.61	0.06	0.14	0.97	472	0.31	0.20	23	159	0.17	0.22	0.14
Bz-6		0.24	0.05	0.11	0.18	337	0.30	0.16	46	75	0.13	0.32	0.61
Bz-7		0.18	0.04	0.15	0.46	411	0.20	0.19	83	256	0.16	0.21	0.33
Bz-8		0.03	0.04	0.10	0.10	458	0.28	0.14	333	333	0.12	0.80	1.00
Bz-9		0.17	0.02	0.10	0.19	464	0.19	0.12	59	112	0.10	0.42	0.53
Bz-10		0.25	0.04	0.13	0.81	445	0.21	0.17	52	324	0.14	1.19	0.16
Bz-11	0.4	0.22	0.05	0.12	0.17	466	0.29	0.17	55	77	0.14	0.26	0.71
Bz-12		0.03	0.03	0.09	0.06	456	0.23	0.12	300	200	0.10	0.36	1.50
Bz-13		1.04	0.03	0.15	1.48	518	0.15	0.18	14	142	0.15	0.57	0.10
Bz-14		0.20	0.02	0.09	0.41	492	0.17	0.11	45	205	0.09	0.37	0.22
Bz-15	0.8	0.52	0.02	0.12	1.12	500	0.14	0.14	23	215	0.12	0.35	0.11
Bz-16		0.62	0.64	0.14	0.79	495	0.82	0.78	23	127	0.65	0.40	0.18
Bz-17		0.43	3.84	0.43	0.16	328	0.90	0.27	100	37	0.22	0.32	2.69
Bz-18		0.32	0.50	0.14	0.18	316	0.78	0.64	44	56	0.55	0.41	0.78
Bz-19		0.56	3.88	0.29	0.18	311	0.93	4.17	52	32	3.46	0.46	1.61
Bz-20		0.76	0.77	0.24	0.41	306	0.76	1.01	32	54	0.84	0.49	0.59
Bz-21		0.47	1.22	0.21	0.23	316	0.85	1.43	45	49	1.19	0.37	0.91
Bz-22		0.60	0.21	0.09	0.64	498	0.70	0.30	15	107	0.25	0.31	0.14
Ka-1		1.30	0.51	2.04	0.31	440	0.20	2.55	157	24	2.12	0.30	6.58
Ka-2		1.89	0.61	2.15	0.35	464	0.22	2.76	114	19	2.29	0.26	6.14
Ka-3		1.43	0.53	1.70	0.20	456	0.24	2.23	119	14	1.85	0.26	8.50
Ka-4		2.21	0.87	2.54	0.45	449	0.26	3.41	115	20	2.83	0.26	5.64
Ka-5		11.22	2.25	13.91	0.38	470	0.14	16.16	124	3	13.41	0.26	36.61
Ka-6		0.73	0.18	1.20	0.30	436	0.13	1.38	164	41	1.15	0.25	4.00
Ka-7	12.1	13.09	2.32	15.64	0.40	462	0.13	17.96	119	3	14.91	0.25	39.10
Ka-8	5.6	6.71	1.25	8.50	0.47	466	0.13	9.75	127	7	8.09	0.86	18.09
Ka-9	10.4	13.04	1.72	14.13	1.77	463	0.11	15.85	108	14	13.16	0.67	7.98
Ka-10		17.22	3.49	21.70	0.65	464	0.14	25.19	126	4	20.91	0.62	33.39
Ka-11		11.28	1.86	13.36	0.65	463	0.12	15.22	118	6	12.63	0.50	20.55

Table 2. Continues

Sample	TOC1	TOC2	S1	S2	S3	Tmax	PI	GP	HI	OI	PCI	S1/TOC	S2/S3
	wt.%		mg HC/g rock		mg CO_2/g rock	°C			mg HC/g TOC				
S-1		0.17	0.05	0.06	0.04	388	0.45	0.11	35	24	0.09	0.98	1.50
S-2		1.50	0.18	0.78	0.20	493	0.19	0.96	52	13	0.80	0.74	3.90
S-3		0.13	0.06	0.05	0.07	387	0.55	0.11	38	54	0.09	0.94	0.71
S-4		2.94	0.04	0.17	1.66	522	0.19	0.21	6	56	0.17	0.87	0.10
S-5		11.25	0.07	0.97	5.08	530	0.07	1.04	9	45	0.86	0.94	0.19
S-6		0.13	0.06	0.12	0.13	456	0.34	0.18	92	100	0.15	1.11	0.92
S-7	2.5	2.41	0.08	0.21	1.15	496	0.28	0.29	9	48	0.24	0.60	0.18
S-8	4.2	1.13	0.03	0.25	1.93	508	0.10	0.28	22	171	0.23	0.13	0.13
S-9	2.9	2.93	0.02	0.27	1.79	512	0.07	0.29	9	61	0.24	0.12	0.15
S-10		0.51	0.08	0.19	0.54	508	0.30	0.27	36	106	0.22	0.15	0.35

[1]: TOC determined using van Iperen and Helder (1985),

[2]: TOC determined from Rock-Eval analyses.

4.3. Organic Petrographical Data

The samples from each of the five studied sections displayed similar organic petrographical pattern, both in terms of maceral occurrences, as well as in relation to reflectance values. The predominant organic feature observed in the Barsarin samples is represented by solid bitumens, in the form of microgranular (B1) and homogenous (B2) (Fig. 2). The vitrinite equivalent reflectance ranges between 0.66-0.68% and 0.83-1.12%, respectively (Table 3). Pyrobitumens were secondarily identified, mainly in fracture-filling form of, displaying original reflectance values in the range of 1.1-1.35%. Vitrinite particles are rare in the Barsarin samples, whereas the ones measured are probably reworked. Very fine fluorescing organic matter was subordinately observed, probably representing lamalginite residuals. Finally, scattered needle-shaped inertodetrinite particles are present in small amount.

The samples of the Bnavya section displayed a less complex organic petrographical pattern. Medium-rich to poor in organic matter, the studied blocks mainly contain microgranular migrabitumens (B1), with vitrinite equivalent reflectance in the range of 0.73-0.8%. Pyrobitumens were also observed in structural association with calcite grains; the original pyrobitumen reflectance values fluctuate from 1.57 to 1.61%. In rare cases, immature orange-reflected bituminite was traced, displaying 0.11-0.21% reflectance values (Table 3).

Table 3. Results of TOC (wt.%) and random reflectance (Rr) measurements (B1: microgranular migrabitumen; B2: homogenous migrabitumen; PyB: pyrobitumen; Bit.: bituminite; V: vitrinite; RV: reworked vitrinite, EqV1, EqV2: equivalent vitrinite reflectance values according to Jacob (1989) for B1 and B2 solid bitumens, respectively; Ba: Barsarin, Bv: Bnavya, Bz: Barzinja, Ka: Karak, S: Sargelu).

Sample	B1Rr %	B2Rr %	PyBR %	Bit.	VRr	RVRr	EqV1	EqV2
Ba-1	0.45	0.69	1.01			1.12	0.68	0.83
Ba-2	0.42	0.86	1.35				0.66	0.93
Ba-3	0.43	1.16					0.67	1.12
Bv-12	0.64			0.21	0.82		0.80	
Bv-13	0.53		1.61	0.11			0.73	
Bv-14	0.54		1.57	0.16			0.73	
Bz-5	0.47	0.91			0.87		0.69	0.96
Bz-11	0.64						0.80	
Bz-15	0.30		1.62	0.16	0.49		0.59	
Ka-7	0.57	0.97					0.75	1.00
Ka-8	0.67	0.96					0.81	0.99
Ka-9	0.52	0.85					0.72	0.93
S-7	0.56	0.92			0.74		0.75	0.97
S-8	0.39	0.74			0.52		0.64	0.86
S-9	0.47	0.84		0.18	1.07		0.69	0.92

Jacob (1989) equation: *EqVRr% = 0.618 X BRr% + 0.40*

EqV1: by using B1Rr, and EqV2 by using B2Rr%.

Barzinja section is poor in organic matter; microgranular bitumens (B1) participate in all the studied blocks, with vitrinite equivalent reflectance values in the range of 0.59-0.8%, whereas homogenous bitumens (B2) were observed only in sample Bz-15, averaging at the vitrinite equivalent reflectance value of 0.96%, which should be critically taken under consideration. At the lowest studied sample of Barzinja section, scattered bituminite macerals of average reflectance value 0.16% and frequent pyrobitumen particles were identified (Table 3).

The Karak studied samples appeared to be the richest in organic matter, displaying a quite homogenous petrographical pattern (Fig. 2). Migrabitumens in the form of microgranular (B1) and homogenous (B2) comprise the predominant organic particles in all of the Karak samples. The vitrinite equivalent reflectance values of the microgranular bitumens fluctuate within the range of 0.72-0.81%, while the equivalent reflectance range of the homogenous bitumens corresponds to 0.93-1.0% (Table 3). Migrabitumens of both B1 and B2 types were frequently observed surrounding calcite crystals and filling pores or fractures. The complete absence of inertinite fragments and liptinitic material is notable.

Similarly to the Karak section, the Sargelu samples are relatively rich-in migrabitumens, in the form of fragmented structures of both microgranular (B1) and homogenous (B2). The equivalent vitrinite reflectance ranges of the B1 and B2 migrabitumen families correspond to 0.64-0.75% and 0.86-0.97%, respectively (Table 3). Vitrinite particles were occasionally observed, whereas liptinite macerals are completely absent in this section as well.

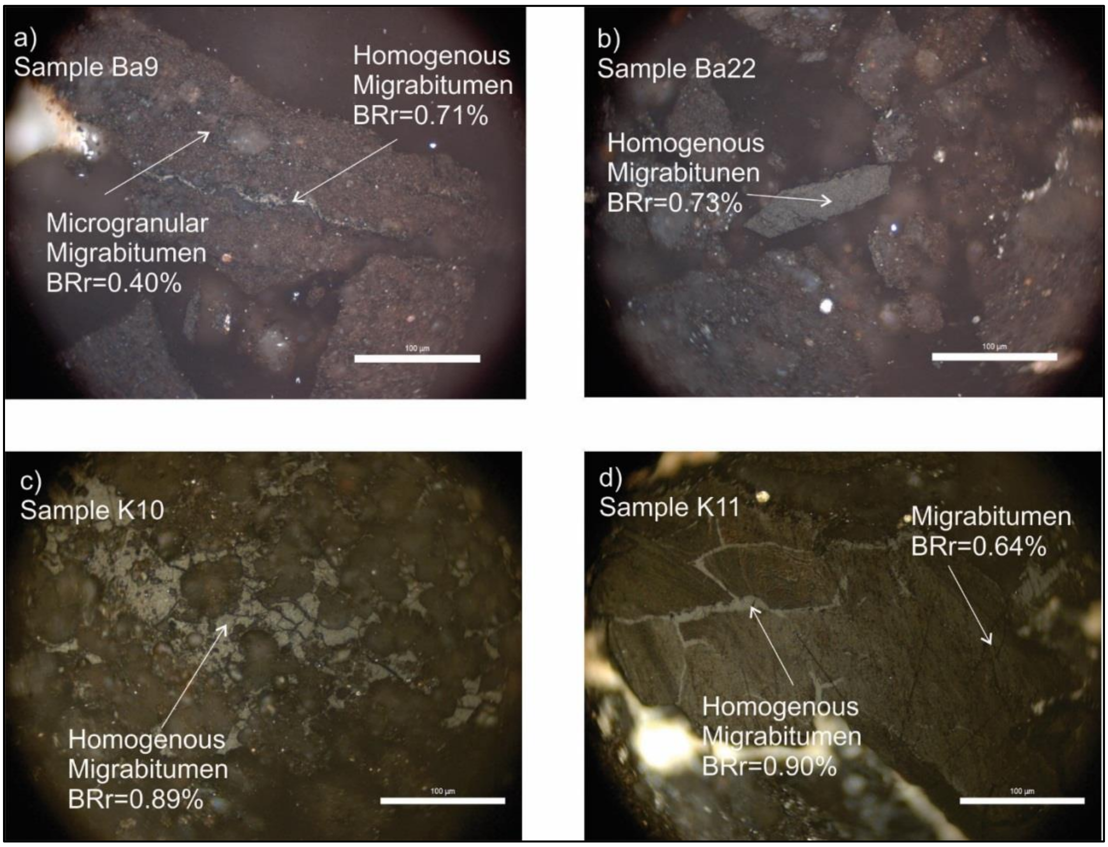

Fig. 2. Photomicrographs of the studied Naokelekan Fm samples viewed under white reflected light, oil objective, magnification x500. The samples contain organic particles; mainly migrabitumens in the form of microgranular and homogenous in different amounts.

5. DISCUSSION

5.1. Organic Matter Type and Palaeoenvironmental Setting

The type of organic matter can be inferred from the macerals recognized under the optical microscope, as well as by the kerogen types suggested by the various parameters of the Rock-Eval pyrolysis. The OI *vs*. HI plot (Fig. 3) suggests the occurrence of Kerogen Types IV and III for Barzinja, Bnavya and Sargelu sections, while Types III and II are suggested for Barsarin and Karak; similar outcomes are indicated from the T_{max} *vs*. HI diagram. However, the organic petrographical data do not support the interpretation obtained from the established Rock-Eval parameters and plots, as mentioned above.

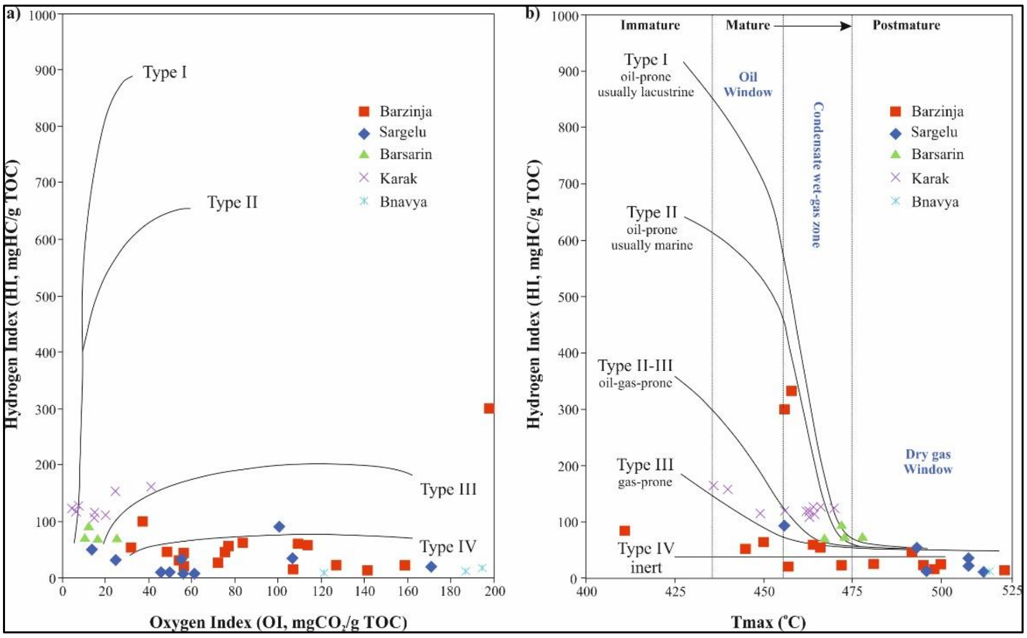

Fig. 3. a) Oxygen index (OI) *versus* hydrogen index (OI), and b) Hydrogen index *versus* T_{max} plot for Naokelekan Formation at different localities in Iraqi Kurdistan (adapted from Espitalié, 1986). For greater detail of this Figure see supplementary section.

In particular, the maceral identification revealed that the predominant organic features in all the studied sections are the migrabitumens, in the form of both microgranular and homogenous ones. The solid bitumens are secondary organic particles mainly originating from algae-like material (Jacob, 1989) indirectly corresponding to the kerogen types I and II (Tissot and Welte, 1984). The common observation of lenticular bituminite, which comprises decomposition product of algae (Teichmüller and Ottenjann, 1977), as well as a minor contribution of fine lamalginite residuals in Barsarin section, supports the occurrence of the kerogen Types I and II. The lack of vitrinite, excepting two samples that belong to the Sargelu section, suggest the absence of kerogen Type III. Finally, the scatter occurrence of inertinite indicates a minor contribution of the kerogen Type IV.

The comparison of petrographical and mineralogical data with Rock-Eval parameters indicates that at least OI has been significantly affected by the abundant carbonate minerals comprising the Naokelekan Fm, as deduced by the x-ray diffraction results (Katz, 1983).

In terms of palaeoenvironmental conditions, mainly the participation of kerogen Types II and III is inferred, pointing to a mixture of marine and terrestrial organic matter. The main indigenous maceral observed is the lenticular, occasionally brown-fluorescing bituminite, which is generally indicative of lacustrine and marine environments (Pickel et al., 2017). The co-occurrence of bituminite with framboidal pyrite, which is produced by sulfate-reducing bacteria (Teichmüller et al., 1998), supports the predominance of anoxic conditions. Finally, the abundant presence of evaporate minerals in all the outcrop sections, except Sargelu, but also the alternation with clastic silicate-dominant layers suggests proximity to coastline. Therefore, all the mentioned above palaeoenvironmental indications point to a dysoxic/anoxic marine setting favoring the preservation of the organic matter, with a proximity to coastline, which resulted in secondary terrestrial inputs as reflected on the variable to low amounts of vitrinite and/or inertinite fragments.

5.2. Naokelekan Fm as a Source Rock in the Studied Sections

In this study, the degree of thermal alteration can be deduced by the Rock-Eval parameters of T_{max} and PI, as well as by the EqVRr%, calculated by converting the original measurements of the migrabitumens observed under the optical microscope. The obtained values of T_{max} are probably affected by various parameters, such as significant inputs of carbonate phases, abundant argillaceous matrix and abundance of solid bitumens (Katz, 1983). Accordingly, in many samples of the present study the T_{max} is hardly collating with the EqVRr%, whereas in some of the samples the contrast between the ranges of T_{max} and EqVRr% is acceptable.

Additionally, the PI values fluctuate within very wide ranges for all the outcrops except Karak (see Table 2, Fig. 4), suggesting all the stages between the immature to late mature. The PI range for the Karak section corresponds to the early/peak stage, which as well has to be taken under consideration critically.

Among the two families of the observed migrabitumens, the homogenous family is more reliable in order to assess the thermal maturity (Petersen et al., 2013). The general range of the homogenous migrabitumens EqVRr% for all the studied samples is 0.83-1.0%, suggesting peak to late stage of thermal maturity for the Naokelekan Fm in the studied outcrops. In the cases of the Barsarin and Karak sections, the T_{max} ranges (Table 2) indicate late to post-mature and early to late mature stage, respectively, suggesting similar maturity to the EqVRr% ranges. As for the three rest outcrops, the T_{max} values cover a chaotic range of values referring to all the stages of maturity, and thus, it's impossible to deduce any kind of information. In these cases, the EqVRr% is taken into consideration as the most reliable thermal maturity indicator.

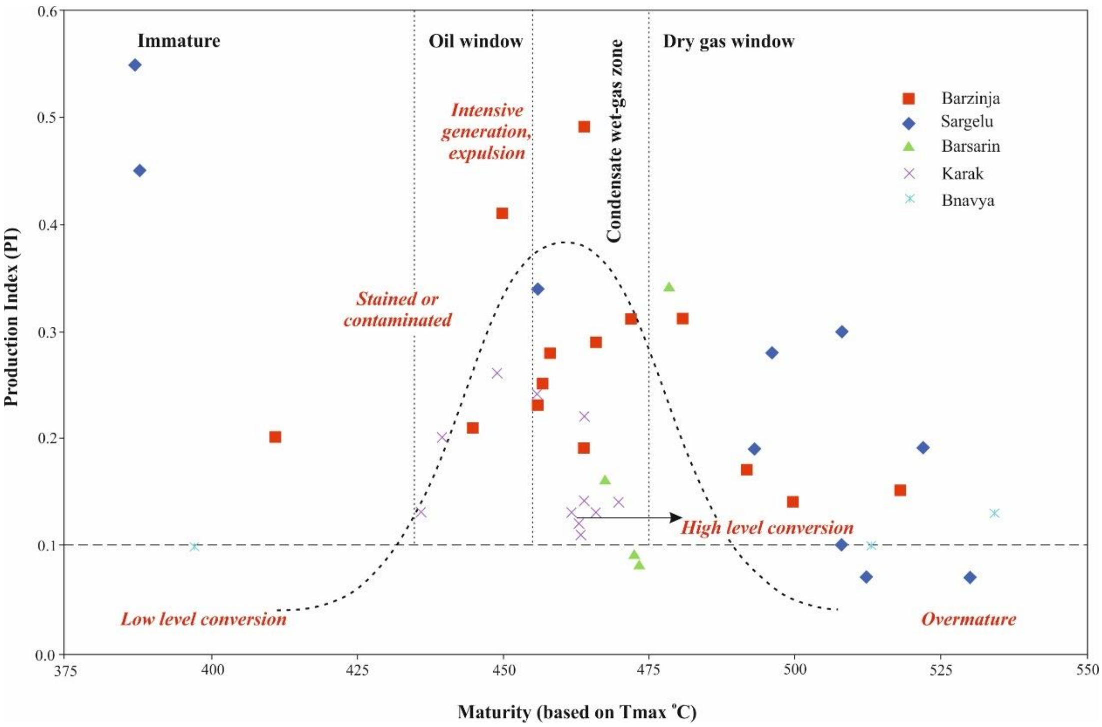

Fig. 4. T_{max} vs. Production Index for Naokelekan Fm (for T_{max} and PI data see Table 2). For greater detail of this Figure see supplementary section.

The organic petrographical pattern of Naokelekan Fm in the present study revealed the occurrence of both indigenous and secondary organic features. Taking into consideration the peak-to-late maturity stage of the solid migra-bitumens (Table 3), as well as the sufficient TOC wt. % values (Table 2), the mixed indigenous/non-indigenous occurrence of the organic features indicates that Naokelekan Fm in the studied sections reflects the profile of a source rock, reservoir, a combination of the two, or even a migration pathway.

Middle Jurassic Sargelu Fm, first recognized and described by Wetzel (1948, *in* Bellen, 1959), underlies Naokelekan Fm as one of the major source rock formations in Northern Iraq, displaying high petroleum potentiality and containing thermally mature organic matter (Al-Ameri and Zumberge, 2013; Abdula, 2014). According to recent scientific research (e.g. Al-Ameri and Zumberge, 2012; Al-Ameri et al., 2013), Sargelu Fm contains mixed kerogen types II & III, as in the case of Naokelekan Fm in this study, and T_{max} in the range of 439–450 °C that achieve production index of 0.11–0.55 and very good PP of 0.58-50.90 kg HC/t rock, satisfying the requirements of a possible source rock of the secondary organic matter observed in the Naokelekan samples.

Nevertheless, an additional aspect to consider is that the in-depth organic petrographical data presented within this paper correspond mostly to the bituminous strata of the lower parts of the Naokelekan Fm, as defined by Abdula (2016) and presented in Fig. 1b. Therefore, in order to clarify and/or confirm the organic type attributes of Naokelekan Fm, further organic petrographical examinations in conjunction to organic geochemical evaluation, including GC-MS analyses, are necessary to be conducted. In this case, various parameters indicating the origin of the organic matter observed and further information regarding the palaeoenvironmental depositional setting of the organic structures will be inferred.

6. CONCLUSIONS

The qualitative petrographical evaluation of Naokelekan Fm in five sections across Kurdistan Region of Iraq revealed that the main organic constituents are solid hydrocarbons, in the form of microgranular migrabitumens, with minor amounts of pyrobitumens and subordinately bituminite and vitrinite.

Equivalent vitrinite reflectance values indicate that Naokelekan Fm has reached the peak (northwestern) to late (southeastern part) stage of thermal maturity.

In terms of productivity, Naokelekan seems to be more "oil" than "gas" prone Formation.

Regarding the palaeoenvironmental setting, a proximal dysoxic/anoxic marine environment is inferred, at least for the lower parts of the sequence.

However, in order to assess the nature of Naokelekan Fm a more detailed organic petrographical and organic geochemical study is required, since the up-today results are not conclusive, whether Naokelekan Fm represents a sole source rock and/or reservoir.

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