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UPPER JURASSIC SOURCE ROCK EVALUATION AND THERMAL MATURITY EVOLUTION OF THE NW SAB'ATAYN BASIN, YEMEN

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Abstract

Of Yemen's Mesozoic basins, the Sab'atayn Basin offers the most significant potential for oil and gas exploration. The key consideration in the evaluation of source rocks to hydrocarbon exploration is the quantity and nature of the organic materials in sedimentations. Using organic geochemistry and total organic carbon content, organic-rich sediments from the Meem (Lower) and Lam (Upper) members from four wells in the NW Sab'atayn Basin were evaluated. The information gained reveals that the Meem source rocks have a total organic carbon content (TOC) value between 0.2–1.68 wt%, therefore suggests fair to very good source rocks. Only two samples in the Kamaran-01 well had values greater than 3 wt%, compared to the Lam source rocks' values, which range from 0.2 to 3.81 wt%, which suggest excellent source rocks. The majority of the samples are made up of reworked organic debris, with no possibility for interesting source rocks, according to the Rock-Eval pyrolysis data. The majority of the Meem and Lam source rocks samples under study have T_{max} values below 440 °C, placing them in the immature to marginally mature and on the main periphery of main phases of hydrocarbon formation. Based on the results of the Meem source rocks' generative potential (GP), it may be inferred that non-generative rocks status of Meem source rocks due to GP values less than 2 mg HC/gm rock. Additionally, if the burial depth is sufficient to generate the necessary temperature and pressure, source rocks with extraordinarily high GP values of more than 10 mg Hc/g rock may serve as an efficient source rock for the Dahamr Ali-01 well. On the other hand Lam source rock is classified as moderate source rocks. Non-generative potential has been reported from Lam source rock in Himyar-01 well where the GP is less than 1 mg HC/g rock. The cross-plots of pyrolysis characteristics, such as HI versus T_{max} (modified van Krevelen diagram) and TOC vs S2, which are most likely the result of deposition of more terrigenous type III organic materials derived from terrestrial in the study area, can be used to determine the kerogen type for Lam and Meem source units. The analysis of Meem source rocks demonstrated that they are typically plotted in the mature zone; however samples of Lam source rocks proved that they have been still immature, merely marginally mature in the Dahamr Ali-01 and Saba-01 wells.

Keywords: Upper Jurassic source rocks, thermal maturity, hydrocarbon generation potential, Sab'atayn Basin, Yemen

OCENA GÓRNOJURAJSKICH SKAŁ ŹRÓDŁOWYCH I EWOLUCJA DOJRZAŁOŚCI TERMICZNEJ W PÓŁNOCNO-ZACHODNIEJ CZĘŚCI BASENU SAB'ATAYN, JEMEN

Abstrakt

Spośród mezozoicznych basenów w Jemenie, Basen Sab'atay ma najbardziej znaczący potencjał dla poszukiwań ropy naftowej i gazu. Sprawą kluczową w ocenie skał źródłowych w aspekcie poszukiwania węglowodorów jest ilość i natura materii organicznej w osadach. Wykorzystując geochemię organiczną, całkowitą zawartość węgla organicznego, osady bogate w związki organiczne z Meem (dolnego) i Lam (górnego), przeanalizowano próbki z czterech studni w północno-zachodniej części Basenu Sab'atayn. Badania pokazały, że skały źródłowe z Meem mają całkowitą zawartość węgla organicznego (TOC) w granicach 0,2–1,68 wt%, co sugeruje oceny skały źródłowej od dostatecznej do bardzo dobrej. Tylko dwie próbki z odwiertu Kamaran-01 miały wartości powyżej 3 wt%, w porównaniu do skał źródłowych Lam, których wartości wahały się od 0,2 do 3,81 wt%, co sugeruje ocenę doskonałą. Większość próbek pochodzi z przetworzonych szczątków organicznych, bez możliwości stania się interesującymi skałami źródłowymi, według danych pirolizy Rock-Eval. Większość badanych próbek skał źródłowych Meem i Lam ma wartość maksymalną temperatury poniżej 440 °C, co umiejscawia je w grupie od niedojrzałych do słabo dojrzałych, oraz na peryferiach i w głównej części peryferyjnej formacji węglowodorów. Na podstawie wyników potencjału generatywnego (GP) skał źródłowych z Meem można wnioskować, że skały z Meem mają status skał płonnych, ze względu na wartości GP poniżej 2 mg HC/g skały. Ponadto, jeśli głębokość ok. 1,5 m wystarczy do wytworzenia potrzebnej temperatury i ciśnienia, skały źródłowe o niezwykle wysokich wartościach GP – ponad 10 mg Hc/g, skały mogą służyć jako wydajne źródło w odwiercie Dahamr Ali-01. Z drugiej strony skały źródłowe Lam klasyfikuje się jako umiarkowane skały źródłowe. Brak potencjału generatywnego odnotowano w skałach źródłowych z Lam w odwiercie Himyar-01, gdzie GP jest niższe niż 1 mg HC/g skałę. Wykresy cech pyrolizy, takich jak HI versus T_{max} (zmodyfikowany diagram van Krevelena) i TOC vs S2, będące najprawdopodobniej wynikiem odkładania się na obszarze badań materiałów organicznych typu III, pochodzących z lądu, mogą być użyte do określenia typu karogenu dla jednostek źródłowych z Lam i Meem. Analiza skał źródłowych Meem pokazała, że zazwyczaj układają się one w strefie dojrzałej; chociaż próbki skał źródłowych z Lam wykazały, że wciąż są one niedojrzałe lub zaledwie na granicy dojrzałości w odwiertach Dahamr Ali-01 i Saba-01.

Słowa kluczowe: górnojurajskie skały źródłowe, dojrzałość termiczna, potencjał tworzenia węglowodorów, Basen Sab'atayn, Jemen

1. INTRODUCTION

Yemen economies are reliant mostly on oil production. The annual petroleum consumption was over 168000 barrel per day in Yemen of 2011 census (Yemeni petroleum exploration & production Authority, (PEPA). The petroleum exploration and production activities have been affected by security issues since 2011, remarkable drop have affected the country economy as well. Worse still, the traditionally large Yemeni oilfields, including Alif, Kharir and Halewah fields are facing a crisis of production reduction. Therefore, reassessment of petroleum resource must be carried out in parts of sedimentary basins, previously little explored especially in northwestern part of the petroliferous Sab'atayn Basin (Fig. 1).

Because it contains every component of the petroleum system (source, reservoir and seal rocks); the Sab'atayn Basin, which preserved Mesozoic succession in its column, encouraged the deposition of petroleum. Because of its increased abundance of organic matter of oil-prone type across Yemen, the upper Lam member is the primary target of source rock assessment and hydrocarbon exploitation [1, 2]. The second target of source rock assessment has been the Lower Meem member, which is constituted of argillaceous limestone [3, 4, 5, 6]. Several wells were drilled in the NW portion of the Sab'atayn Basin over the last few decades, but the results were generally unimpressive. Due to the necessity to increases oil potential, we try to re-evaluate this part of the basin by using the available geochemical data from the source rocks. As a result, it is crucial to correctly assess the source rocks' qualities and maturity in this region of the basin. Our understanding of the development and maturation of the Lam and Meem source unit can be improved by this evaluation. The kerogen type, the amount of organic materials, and the maturity of the source rock are all variables of source rock eval-

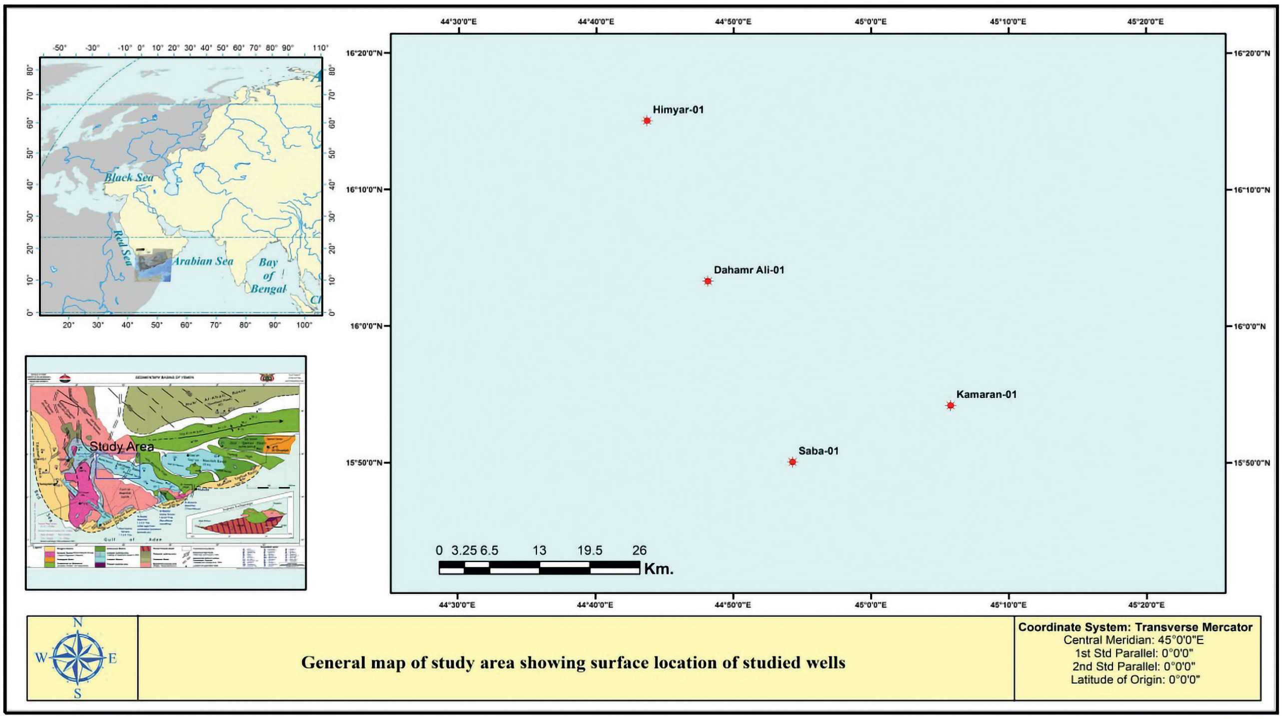

Fig. 1. Location map of the studied wells in the NW Sab'atayn Basin, central Yemen
Ryc. 1. Mapa przedstawiająca lokalizację badanych odwiertów in północno-zachodniej części Basenu Sab'atayn, środkowy Yemen

uation. The source rocks thermal maturity investigation primarily includes vitrinite reflectance (% Ro) and temperature maximum (T_{max}) from the Rock-Eval pyrolysis. The quantity of organic matter is commonly assessed by the measuring of total organic carbon content (TOC) in the rocks. Quality is measured by determining the types of kerogen contained in the organic matter. Thermal maturity is most often estimated by using vitrinite reflectance measurements in addition to data from pyrolysis analyses. However, because this region has not been subjected to substantial conventional oil and gas exploitation, there aren't enough drilling wells and samples to cover the entire NW part of the basin. Therefore, it is impossible to do any geochemical analysis and difficult to study using conventional experimental test methods due to core samples chips scarcity, only data of geochemical analysis can be obtained from [7] reports. Challenges and breakthroughs in recent research in hydrocarbon generation, expulsion, migration and accumulation led to better understanding of the whole process of hydrocarbon. Therefore, source rock investigation is of increasing importance because it reduces risk potential and gives a quick insight of concerned area. Quantitative research on the thermal maturity progression of source rocks throughout the geological period is of tremendous significance because it goes hand in hand with the advancement of petroleum geology theory and the widespread use of computing technology.

2. GEOLOGICAL FRAMEWORK

Yemen, which is geographically at the southern tip of the Arabian Peninsula, shares the same geological signature between the African and Arabian plates. The Tertiary triple junction between the Red Sea, Gulf of Aden, and Afar Plume is not far from where it is situated. The Marib-Shabwa-Hajar Basin, also recognized as the Marib-Shabwa Basin, is a Mesozoic rift basin in Yemen oriented NW-SE follows a deep-seated Proterozoic structural trend [1, 8, 9]. The divergence of India from Africa-Arabia caused many extensional phases, which culminated in the formation of the basin [8, 10]. Three tectono-stratigraphic megasequences can be identified within the basin: (a) a pre-rifting phase (Permian-Oxfordian/Kimmerdgian), (b) a syn-rifting period (Kimmerdgian-Tithonian), and (c) a post-rifting phase

(Early Cretaceous). However, the Permian pre-rift phase is not well established. Due to uplift and erosion, the NW portion of the basin has no sections from the syn-rifting phase (Kimmeridgian-Tithonian) and post-rifting phase (Early Cretaceous). Shallow marine carbonates (Shuqra Formation) are underlain by non-marine to shallow marine clastic rocks (Kuhlan Formation; [11], which represent pre-rift deposits. It is commonly agreed that both formations date to the last Triassic to Middle Jurassic [12], although [13] presented evidence that the lower Kuhlan Formation dates to the Late Carboniferous. Horst and nested faults blocks that formed the Late Jurassic to Lower Cretaceous period is what really make-up the syn-rift sediments of the Madbi Formation [8, 11]. Porous limestone to argillaceous lime mudstone makes up the Madbi Formation. The Meem Member, the lower section of this formation, has shales of good quality source rock and along the basin's edge, sandy turbidites, which may serve as reservoir rocks in some oilfields in the northwest Sab'atayn Basin. The Upper Lam Member is thought to be the basin's most abundant source rock for oil since it is primarily made up of laminated organic rich shales [1, 14]. Ocean circulation in the Sab'atayn Basin was restricted during the Tithonian period, late in the syn-rift phase, led to accumulation of evaporitic sediments (Safir Member), with an estimated original thickness of almost 731 m [15]. Massive halite is found in the basin's center, whereas anhydrite and clastic rocks are either extremely rare or nonexistent at the basin's periphery [16]. Safir member's interbedded thin shales layers are abounding in organic material [1]. The four members of the Sab'atayn Formation are Safir, Alif, Seen, and Yah Members. Fluvio-deltaic sandstone, mudstone, and evaporate predominate in the Yah Member, which is followed by Seen Member, the second clastic succession. Alif Member, the primary reservoir in Sab'atayn Basin, is made up of sandstone and shale. The Safir Member is divided into various bodies primarily composed of halite, with minor amounts of argillaceous, dolomite, and limestone with subordinate anhydrite interbedded with shale and sandstone. The interbedded organic rich shales within the Safir Member are considered to be the prolific oil-prone source rock in the Marib-Shabwa Basin within Sab'atayn Formation. The Safir Member contains some possible good local reservoir seal pairs in the intra evaporate clastics and evaporates, it provides a superior seal to the underlain Alif reservoir [11]. In the Northwestern part of the Sab'atayn basin during Tithonian time, deposition of late stages of the syn- rift phase clastic and evaporates sedimentations (Sab'atayn Formation) didn't extended and progressively thinned out for causes not well understood yet.

3. METHOLOGY

The estimation of the organic matter content, which is typically reported as total organic carbon (TOC), is necessary for the evaluation of source rocks within the study region. The type of organic matter (Kerogen) and quantity of organic content preserved in the petroleum source rocks, thermal maturity, and finally the generating potential of kerogen all affect the hydrocarbon potentiality. The geochemical information for the projected Upper Jurassic rock units in the Northwestern Sab'atayn Basin is provided and discussed, including total organic carbon (TOC), Rock-eval pyrolysis data, and vitrinite reflectance of the Dahamr Ali-01, Himyar-01, Kamaran-01 and Saba-01 wells. Using a Rock-Eval II device with a total organic carbon module, 100 mg crushed rock samples were heated up to 600°C in a helium environment for the TOC determination and Rock-Eval pyrolysis analysis parameters. Information on the quantity, quality, and maturity of organic matter present in the Lam and Meem rock units is available from Rock-Eval pyrolysis data (Table 2). In the investigated wells, 148 different rock samples were taken from the Lam and Meem Members' shales. The investigated shale samples were initially treated from drilling mud addition pollutants by repeatedly washing the samples with water until no mud was visible on their surface. Total organic carbon (TOC) in the rocks, free hydrocarbons (S1), remaining hydrocarbon generative potential (S2) and temperature of maximum pyrolysis production (T_{max}) are among the parameters examined. The indices for hydrogen (HI), production yields (PY), and production index (PI) were computed mathematically (Table 2). The temperature at which the maximum generation of the products of pyrolysis occurs was used to calculate the following:

Oxygen index (OI), [OI = (S3/TOC) x 100)]
Hydrogen index (HI), [HI = (S2/TOC) x 100].

Plot of HI versus OI can be used to deduce the type of organic matter present in the source rock.

Production index (PI), [PI = S1 / S1+S2)
Richness of hydrogen in the Kerogen = S2/S3
Genetic potential of the source rock (GP) = S1+S2

Table 1. Guidelines for interpreting source rock quantity, quality and maturation, and commonly used Rock-Eval parameters. Source [17, 18]
Tabela 1. Wytyczne dla interpretacji ilości, jakości i dojrzałości skał źródłowych oraz powszechnie stosowane parametry ewaluacji skał. Źródło [17, 18]

Quantity	TOC (wt%)	S1 (mg HC/g Rock)	S2 (mg HC/g Rock)
Poor	< 0.5	< 0.5	< 2.5
Fair	0.5–1	0.5–1	2.5–5
Good	1–2	1–2	5–10
Very Good	2–4	2–4	10–20
Excellent	> 4	> 4	> 20
Quality	**HI (mg HC/g Rock)**	**S2/S3**	**Kerogen Type**
None	< 50	< 1	IV
Gas	50–200	1–5	III
Gas and Oil	200–300	5–10	II/III
Oil	300–600	10–15	II
Oil	> 600	> 15	I
Maturation	**Ro (%)**	**T_{max} (°C)**	**TAI**
Immature	0.2–0.6	< 435	1.5–2.6
Early Mature	0.6–0.65	435–445	2.6–2.7
Peak Mature	0.65–0.9	445–450	2.7–2.9
Late Mature	0.9–1.35	450–470	2.9–3.3
Post Mature	> 1.35	> 470	> 3.3

Details on the Rock-Eval method and parameters as well as a summary of interpretive guidelines for Rock-Eval data are available in [17, 18, 19, 20] – table 1.

4. RESULTS & DISCUSSIONS

Any prospective reservoir's capacity is dependent totally on effective source rock. Petroleum geologists are finding utility in petroleum geochemistry as a tool for assessing source rocks and quantifying the components and processes that govern the production of oil and gas. In order to mitigate the inherent uncertainty in the exploration and production of frontier basins, geochemistry is a crucial tool. This section will examine fundamental geochemical techniques for assessing fresh prospects.

4.1. Quality and quantity of organic matter

The quantity and quality of organic materials (TOC) in sediments have such a significant impact on the production of hydrocarbons. Since different types of organic matter have different hydrocarbon production potential or quality, the quality term of organic matter refers to whether the source rock's organic matter is oil prone or gas prone. However, a wide range of environmental variables, including climate, have an impact on the amount of organic matter in source rocks. [18, 19, 20] presented a scale for the assessment of source rocks potentiality, based on the TOC weight % and Rock–Eval pyrolysis data, such as S_1 and S_2. According to the data gathered (Table 2), the Meem source rocks' total organic carbon content (TOC) values range between 0.2 to 1.68 wt%, indicating fair to good source rocks. While the values for the Lam source rocks are between 0.2 and 2.93 wt% indicating fair to excellent source rocks, only two samples have values more than 3 wt% in Kamaran-01 well. These conclusions are confirmed by the plots of total organic carbon (TOC wt%) versus remaining hydrocarbon (S2 mgHC/g rock) Fig. 2A. The total organic carbon is mostly very poor in studied wells. The Rock-Eval pyrolysis data in (Table 2) reveal that most of the samples consist of reworked organic matter with

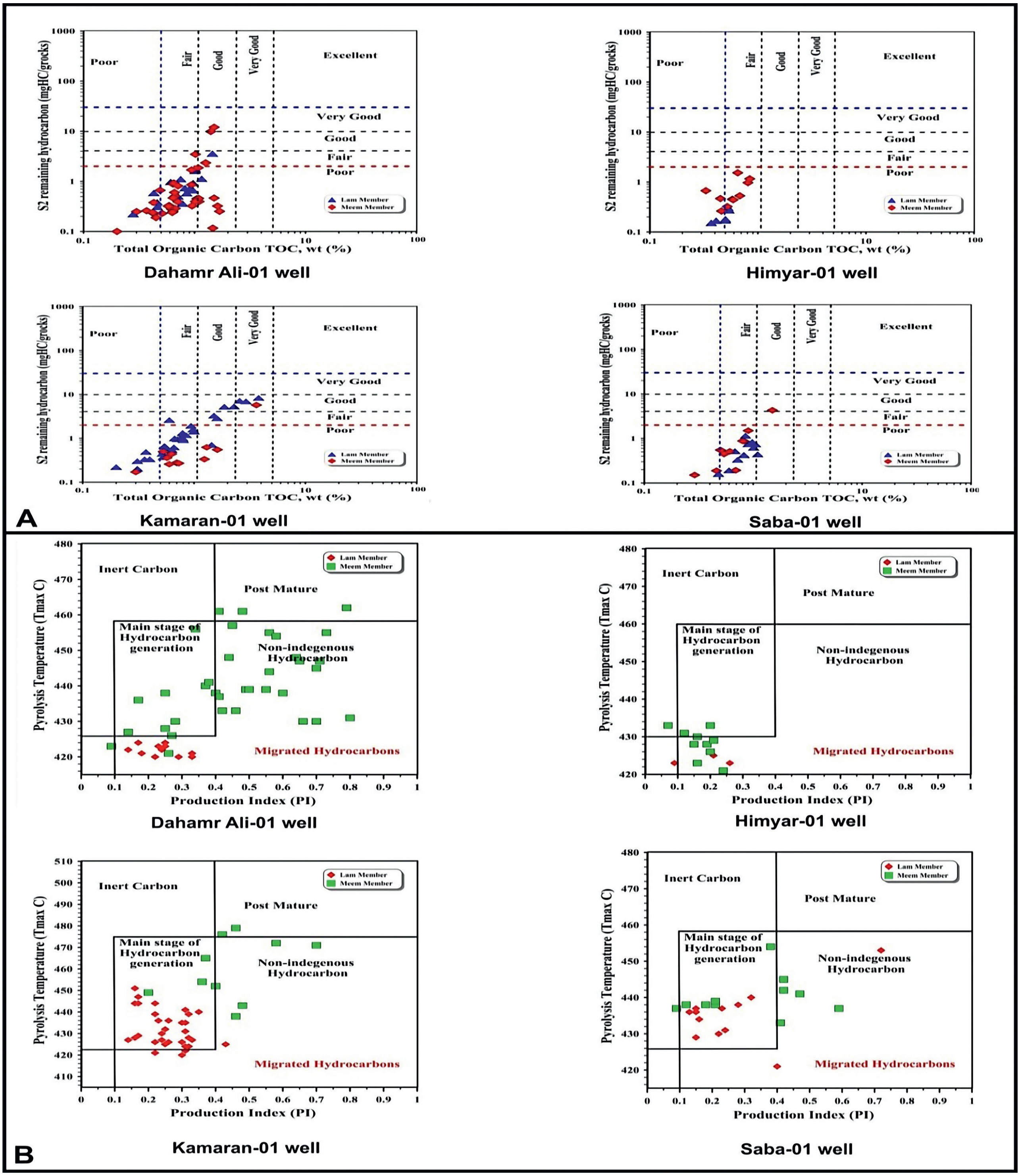

Fig. 2. Quality and quantity of organic matter of Meem and Lam source rocks, NW Sab'atayn Basin, Yemen

Ryc. 2. Jakość i ilość materii organicznej w skałach źródłowych Meem i Lam, północno-zachodnia część Basenu Sab'atayn, Jemen

Table 2. Rock–Eval pyrolysis data for Lam and Meem source rocks in the studied wells
Tabela 2. Dane z pirolizy w ocenie skał źródłowych z Lam i Meem w badanych odwiertach

Wells Name	Members	Depth (m)	TOC "wt%"	S1	S2	S1+S2	T_{max}	HI	PI
Dahamr Ali-01	**Lam Member**	203.7	1.01	0.60	1.62	2.21	426	160	0.27
		323.2	1.16	0.38	1.13	1.50	424	97	0.25
		405.5	0.78	0.15	0.36	0.51	414	46	0.29
		484.8	0.97	0.19	0.66	0.85	420	68	0.22
		594.5	0.82	0.23	0.73	0.96	422	89	0.24
		640.2	0.85	0.16	0.58	0.74	418	68	0.22
		703.7	0.71	0.24	0.50	0.74	421	70	0.33
		722.6	1.45	0.58	3.57	4.15	422	246	0.14
		731.7	1.02	0.35	1.72	2.08	424	169	0.17
		798.8	0.9	0.29	0.70	0.99	420	78	0.29
		817.1	0.97	0.36	0.92	1.28	417	95	0.28
		881.1	0.46	0.13	0.31	0.44	414	67	0.3
		981.7	0.75	0.24	1.10	1.34	421	147	0.18
		1073.2	0.46	0.15	0.38	0.53	418	83	0.28
		1201.2	0.43	0.19	0.58	0.78	423	136	0.25
		1320.1	0.61	0.29	0.97	1.26	423	159	0.23
		1356.7	0.28	0.11	0.22	0.33	420	79	0.33
		1420.7	0.3	0.09	0.25	0.34	421	83	0.26
	Meem Member	1457.3	0.64	0.29	0.88	1.18	428	138	0.25
		1459.7	0.65	0.15	0.93	1.08	427	143	0.14
		1530.5	1.5	48.18	12.05	60.23	431	803	0.8
		1535.4	1.4	0.98	9.91	10.89	423	708	0.09
		1539.6	1.02	1.28	3.47	4.75	426	340	0.27
		1622.0	0.94	0.35	1.69	2.04	436	180	0.17
		1723.2	1.26	0.91	2.34	3.26	430	186	0.28
		1759.1	0.71	0.48	0.81	1.28	440	114	0.37
		1832.3	1.08	0.62	1.87	2.49	438	173	0.25
		1841.5	0.49	0.48	0.66	1.14	433	135	0.42
		1914.6	0.67	0.34	0.51	0.85	438	76	0.4
		1987.8	0.37	0.25	0.26	0.51	439	70	0.49
		2020.1	0.94	0.59	0.86	1.45	437	91	0.41
		2051.8	0.66	0.60	0.60	1.20	439	91	0.5
		2088.4	0.43	0.32	0.38	0.70	433	88	0.46
		2152.4	1.05	0.88	0.45	1.33	430	43	0.66
		2243.9	1.1	0.74	0.40	1.13	447	36	0.65
		2298.8	0.71	0.59	0.39	0.98	438	55	0.6

Table 2 cont. / Tabela 2 cd.

Wells Name	Members	Depth (m)	TOC "wt%"	S1	S2	S1+S2	T_{max}	HI	PI
Dahamr Ali-01	Meem Member	2344.5	0.62	0.36	0.28	0.63	444	45	0.56
		2426.8	0.67	0.18	0.29	0.46	441	43	0.38
		2445.1	0.43	0.18	0.23	0.41	448	53	0.44
		2545.7	1.09	0.24	0.46	0.69	456	42	0.34
		2591.5	1.02	0.51	0.40	0.90	455	39	0.56
		2618.9	0.42	0.43	0.24	0.67	448	57	0.64
		2637.2	1.46	0.10	0.12	0.21	457	8	0.45
		2710.4	0.2	0.24	0.10	0.34	447	50	0.71
		2774.4	0.59	0.23	0.33	0.56	461	56	0.41
		2893.3	0.64	0.23	0.25	0.48	461	39	0.48
		3176.8	0.63	0.33	0.24	0.57	454	38	0.58
		3213.4	0.45	0.51	0.19	0.70	455	42	0.73
		3295.7	0.58	1.36	0.32	1.68	413	55	0.81
		3359.8	0.95	0.75	0.32	1.08	419	34	0.7
		3423.8	0.51	0.54	0.23	0.77	430	45	0.7
		3469.5	0.64	0.57	0.47	1.04	439	73	0.55
		3564.0	1.61	0.75	0.32	1.07	445	20	0.7
		3631.1	1.5	1.04	0.47	1.50	419	31	0.69
		3640.2	1.68	0.95	0.25	1.20	462	15	0.79
Himyer-01	Lam Member	91.5	0.50	0.03	0.27	0.297	423	54	0.09
		100.6	0.50	0.03	0.17	0.2	417	34	0.15
		295.7	0.50	0.02	0.18	0.2	419	36	0.1
		353.7	0.54	0.03	0.27	0.3	418	50	0.1
		362.8	0.41	0.06	0.17	0.227	423	41	0.26
		445.1	0.37	0.08	0.15	0.233	418	41	0.35
		454.3	0.37	0.08	0.15	0.23	418	41	0.34
		570.1	0.53	0.08	0.3	0.382	425	57	0.21
	Meem Member	628.0	0.52	0.08	0.32	0.403	426	62	0.2
		658.5	0.58	0.08	0.45	0.532	428	78	0.15
		686.0	0.45	0.09	0.47	0.557	423	104	0.16
		731.7	0.81	0.13	0.97	1.105	431	120	0.12
		750.0	0.84	0.09	1.16	1.246	433	138	0.07
		777.4	0.33	0.16	0.67	0.827	428	203	0.19
		817.0	0.59	0.11	0.44	0.553	433	75	0.2
		823.2	0.65	0.29	1.53	1.818	430	235	0.16
		828.0	0.46	0.08	0.26	0.345	421	57	0.24
		887.2	0.7	0.14	0.53	0.671	429	78	0.21

Wells Name	Members	Depth (m)	TOC "wt%"	S1	S2	S1+S2	T_{max}	HI	PI
Kamaran-01	Lam Member	920.50	1.61	0.46	2.85	3.314	427	177	0.14
		938.78	0.36	0.21	0.33	0.543	411	92	0.39
		975.36	0.53	0.15	0.37	0.523	418	70	0.29
		993.65	0.66	0.29	0.62	0.912	424	94	0.32
		1011.94	0.4	0.15	0.33	0.481	422	83	0.31
		1030.22	0.2	0.09	0.22	0.31	418	110	0.29
		1085.09	0.31	0.15	0.2	0.354	425	65	0.43
		1131.08	0.71	0.27	0.95	1.22	421	134	0.22
		1176.53	0.54	0.24	0.53	0.767	424	98	0.31
		1222.25	0.31	0.11	0.3	0.412	416	97	0.27
		1277.11	0.81	0.24	1.25	1.485	428	154	0.16
		1295.40	0.94	0.39	1.92	2.31	429	204	0.17
		1331.98	0.54	0.23	0.66	0.89	426	122	0.26
		1350.26	0.79	0.37	1.32	1.691	426	167	0.22
		1368.55	0.67	0.33	0.99	1.322	425	148	0.25
		1408.18	0.6	1.11	2.6	3.711	420	433	0.3
		1426.46	0.55	0.2	0.65	0.854	430	118	0.24
		1481.33	0.57	0.19	0.58	0.775	432	102	0.25
		1548.38	0.75	0.29	0.96	1.247	436	128	0.23
		1600.20	0.6	0.23	0.53	0.754	426	88	0.3
		1645.92	0.63	0.27	0.54	0.809	427	86	0.33
		1691.64	0.52	0.2	0.44	0.641	431	85	0.31
		1773.94	0.85	0.37	1.17	1.543	427	138	0.24
		1828.80	0.8	0.32	0.9	1.222	436	113	0.26
		1901.95	0.78	0.44	1.02	1.46	435	131	0.3
		2002.54	1	0.63	1.41	2.043	435	141	0.31
		2066.54	0.98	0.71	1.58	2.287	441	161	0.31
		2075.69	1.87	1.47	5.22	6.689	439	279	0.22
		2139.70	0.79	0.46	0.99	1.452	439	125	0.32
		2148.84	2.57	1.36	7.14	8.505	444	278	0.16
		2157.98	1.51	0.92	3.28	4.201	444	217	0.22
		2167.13	2.29	1.08	5.29	6.373	447	231	0.17
		2176.27	2.93	1.32	6.91	8.232	451	236	0.16
		2194.56	0.37	0.26	0.49	0.751	440	132	0.35
		2258.57	1.44	0.33	0.71	1.038	428	49	0.32
		2267.71	3.81	1.7	8.31	10.01	444	218	0.17
		2276.86	3.64	1.43	5.71	7.144	449	157	0.2

Table 2 cont. / Tabela 2 cd.

Wells Name	Members	Depth (m)	TOC "wt%"	S1	S2	S1+S2	T_{max}	HI	PI
Kamaran-01	Meem Member	2322.58	0.63	0.38	0.44	0.817	438	70	0.46
		2404.87	0.3	0.16	0.17	0.329	443	57	0.48
		2450.59	0.53	0.28	0.5	0.778	454	94	0.36
		2505.46	0.57	0.24	0.36	0.599	452	63	0.4
		2587.75	0.7	0.16	0.27	0.433	465	39	0.37
		2660.90	0.7	0.2	0.28	0.483	476	40	0.42
		2752.34	0.6	0.17	0.26	0.43	484	43	0.4
		2843.78	0.73	0.23	0.27	0.5	479	37	0.46
		2907.79	1.62	1.29	0.55	1.836	471	34	0.7
		2926.08	1.24	0.46	0.33	0.797	472	27	0.58
		2944.37	1.3	0.45	0.62	1.076	504	48	0.42
Saba-01	Lam Member	48.768	0.82	0.28	0.42	0.697	421	51	0.4
		67.056	1.05	0.13	0.74	0.865	429	70	0.15
		112.776	0.82	0.12	0.43	0.547	430	52	0.22
		149.352	0.48	0.05	0.16	0.208	431	33	0.24
		204.216	0.72	0.1	0.33	0.43	437	46	0.23
		240.792	0.6	0.09	0.19	0.282	440	32	0.32
		286.512	0.68	0.1	0.52	0.615	434	76	0.16
		329.184	1.01	0.11	0.62	0.725	437	61	0.15
		356.616	0.9	0.13	0.74	0.868	436	82	0.15
		396.24	0.98	0.12	0.83	0.957	436	85	0.13
		423.672	1.1	0.17	0.44	0.611	438	40	0.28
		460.248	0.6	0.12	0.05	0.171	453	8	0.72
		496.824	0.85	0.17	1.15	1.319	436	135	0.13
	Meem Member	524.256	0.5	0.38	0.55	0.932	433	110	0.41
		560.832	0.9	0.2	1.49	1.698	438	166	0.12
		579.12	1.5	0.43	4.31	4.731	437	287	0.09
		624.84	0.83	0.23	0.86	1.093	438	104	0.21
		707.136	0.8	0.19	0.88	1.073	438	110	0.18
		743.712	0.61	0.45	0.51	0.967	441	84	0.47
		780.288	0.64	0.1	0.07	0.172	437	11	0.59
		816.864	0.69	0.05	0.19	0.245	439	28	0.21
		853.44	0.62	0.23	0.06	0.295	450	10	0.79
		885.672	0.52	0.12	0.07	0.183	404	13	0.63
		917.448	0.55	0.19	0.1	0.291	430	18	0.66
		944.88	0.46	0.14	0.19	0.325	445	41	0.42
		981.456	0.29	0.11	0.15	0.26	442	52	0.42
		1018.032	0.54	0.27	0.45	0.723	454	83	0.38

no interesting source rocks potential. On the other hand, the plot of T_{max} versus production index (PI) Fig. 2B provides an indication of source rock maturity and hydrocarbon genesis. Type of source rock organic matter, the amount of excess free hydrocarbon present, as well as other elements including mineral composition, burial depth, and age, all effect thermal maturity [20]. T_{max} (°C), Production Index (PI), and Vitrinite Reflectance (% Ro) were used to calculate the degree of thermal development of the sedimentary organic matter. An increase in T_{max} is correlated with an increase in the organic matter's maturity level. The nature of the chemical processes that result from thermal cracking is connected to these phenomena. The stronger bonds endure until higher temperatures in the late stages while the weaker ones disintegrate in the early stages [21]. A useful technique for determining the maturity of organic matter is to combine and establish relationships between the crucial Rock-Eval parameter, T_{max}, and the computed production index (PI). The following relations between T_{max} and PI are observed:

1. Immature organic matter has T_{max} and PI values less than 430 °C and 0.10, respectively.
2. Mature organic matter has a range of 0.1 – 04 PI. At the top of oil window, T_{max} and PI reach 460 °C and 0.4, respectively.
3. Mature organic matter within the wet gas-zone has PI values greater than 0.4.
4. Post-mature organic matter usually has a high PI value and may reach 1.0 by the end of the dry-gas zone [18, 19, 22].

Most of the samples of Meem source rocks in the Dahamr Ali-01 well, particularly those from the lower part, have T_{max} value that is greater than 445 °C and PI ranges from 0.34 to 0.73. This suggests that the upper section is in the immature to early mature stages, while the lower part is in the mature stage. With the exception of a few samples that lie within the hydrocarbon generation zone, the majority of the specimens are non-indigenous hydrocarbons. Most of the samples in Himyar-01, Kamaran-01 and Saba-01 wells have T_{max} less than 445 °C, accordingly ranging from immature to early mature stage. Some samples are peak mature because their T_{max} is increased to more than 445 °C. All samples from the aforementioned wells — aside from four samples from the Kamaran-0I well—are in the pri-

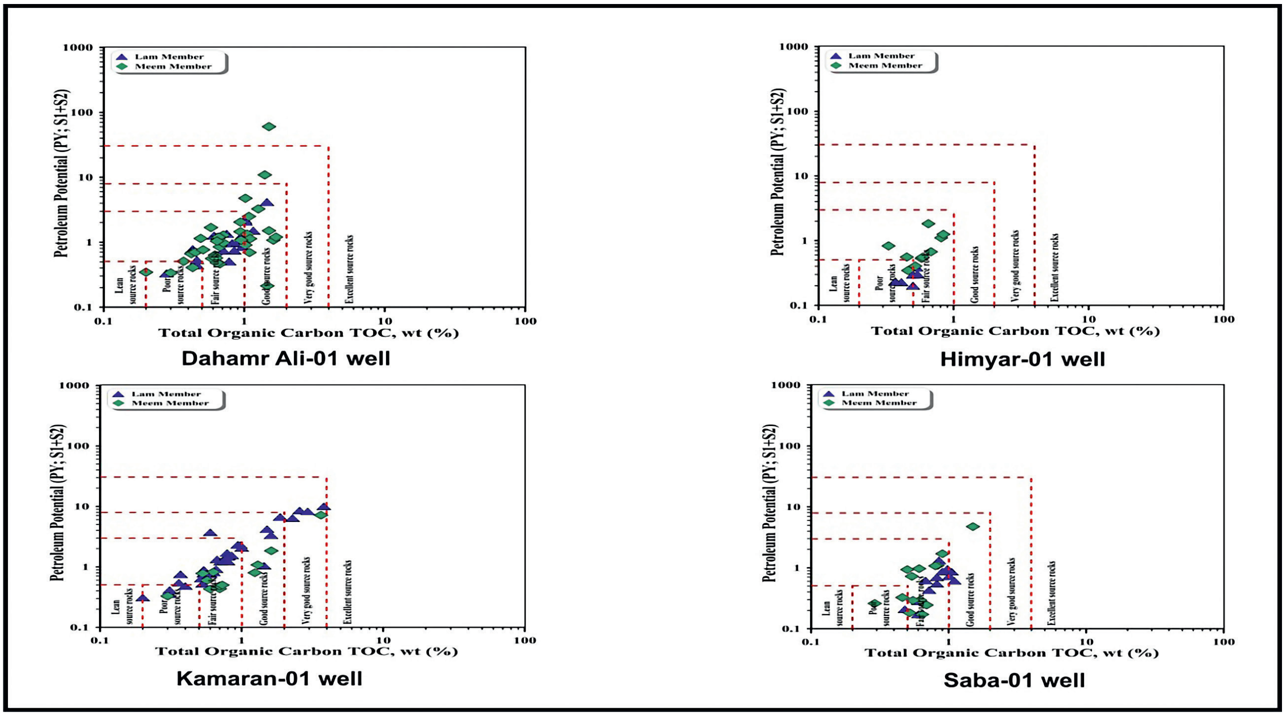

Fig. 3. Generating potentialities of Meem and Lam source rocks, NW Sab'atayn Basin, Yemen
Ryc. 3. Generowanie potencjalnych wartości skał źródłowych z Meem i Lam, północno-zachodnia część Basenu Sab'atayn

mary phases of the generation of hydrocarbons. They are non-indigenous hydrocarbons in the reset samples (Fig. 3). The vast majority of samples from the Lam source rocks in Dahamr Ali-01, Himyar-01, Kamaran-01 and Saba-01 wells are have T_{max} less than 435 °C, accordingly plotted in the immature zone.

4.2. Generating potentialities

The results of pyrolysis analysis can be used to calculate the producing potential of source rocks, which is used to assess their ability for hydrocarbon extraction. Tissot and Welte [20] proposed a genetic potential (GP = S1 + S2) for the classification of source rocks. According to their classification scheme, rocks having GP of less than 2 mg HC/g rock correspond to gas-prone rocks or non-generative ones, rocks with GP between 2 and 6 mg HC/g rock are moderate source rocks, and those with GP greater than 6 mg HC/g rock are good source rocks. Based on the above criteria, the Meem source rocks with a GP of less than 2 are non-generative rocks. Furthermore those source rocks with exceptionally high GP values in order of more than 10 mg HC/ g rock may provide also an excellent source rock in Dahamr Ali-01 well, if the burial depth is sufficient to build temperature and pressure. On the other hand, Lam source rock is classified as moderate source rock. Non-generative potential has been reported for Lam source rock in Himyar-01 well where the GP is less than 1 mg HC/g rock (Fig. 3). It is crucial to note that both source rocks are found in the research area at shallow depths, even closer to the surface in some well sites.

4.3. Genetic type of organic matter

For the accurate estimation of oil and potential, the initial genetic type of organic materials in a certain source rock is essential. The hydrogen index values (HI) were used to distinguish between the various forms of organic materials [23]. Hydrogen indices <150 mg/g indicate a potential source for generating gas (mainly type III kerogen). Hydrogen indices between 150 and 300 mg/g contain more type III kerogen than type II and therefore are capable of generating mixed gas and oil, but mainly gas. Kerogen with hydrogen indices >300 mg/g contains a substantial amount of type II macerals, and thus is considered to have good source potential for generating oil and minor gas. Kerogen with hydrogen indices >600 mg/g usually consists of nearly type I or type II kerogen; they have excellent potential to generate oil. Kerogen type for Lam and Meem source units can be deduced by the cross-plots of pyrolysis parameters, such as HI vs T_{max} (modified van Krevelen diagram, Fig. 4 and TOC vs S2 (Fig. 2A), probably resulted from deposition of more terrigenous type III organic matters sourced from terrestrial environment. Type III kerogen is composed of terrestrial organic material that is lacking in fatty or waxy components. Cellulose and lignin are major contributors. Type III kerogen have much lower hydrocarbon-generative capacities than Type II kerogen and, unless they have small inclusions of Type II material, they are normally considered to generate mainly gas. Majority of study area is dominated by type III kerogen, which is attributed to terrestrial environment where land derived organic matter prevails. This type of kerogen, characterized by small amount of hydrogen, is present; however it can generate gas only.

4.4. Thermal maturation

The degree to which heat-induced processes change the chemical composition of organic materials is referred to as thermal maturity. The type of organic matter and the degree of thermal maturity that the organic matter has influence the concentration and distribution of hydrocarbons that are present in a specific source rocks [24]. In the present paper, the thermal maturity level of the source rocks of Meem and Lam members has been determined by the study of the geochemical parameters as Rock–Eval temperature pyrolysis ‘‘T_{max}’’, Hydrogen index ‘‘HI’ (Fig. 4). Combining and finding relations between the essential Rock-Eval parameter, T_{max}, and calculated Rock-Eval parameter, HI, is a valuable method for indicating the thermal maturity of organic matter. Using the HI versus T_{max} plot (Fig. 4), developed by earlier works [25] to identify kerogen type and maturity level of pyrolysis data. The findings demonstrate that the studied Meem source rocks are typically located in the type III kerogen of mature status. Few samples in Dahamr Ali-01 well are upgraded to marginally mature zone. In addition Kamaran-01 well ranges from mature to post mature zone. The depth and overburden are responsible for the extreme differences in the maturity level of Meem source rocks. The source rocks are still in their immatu-

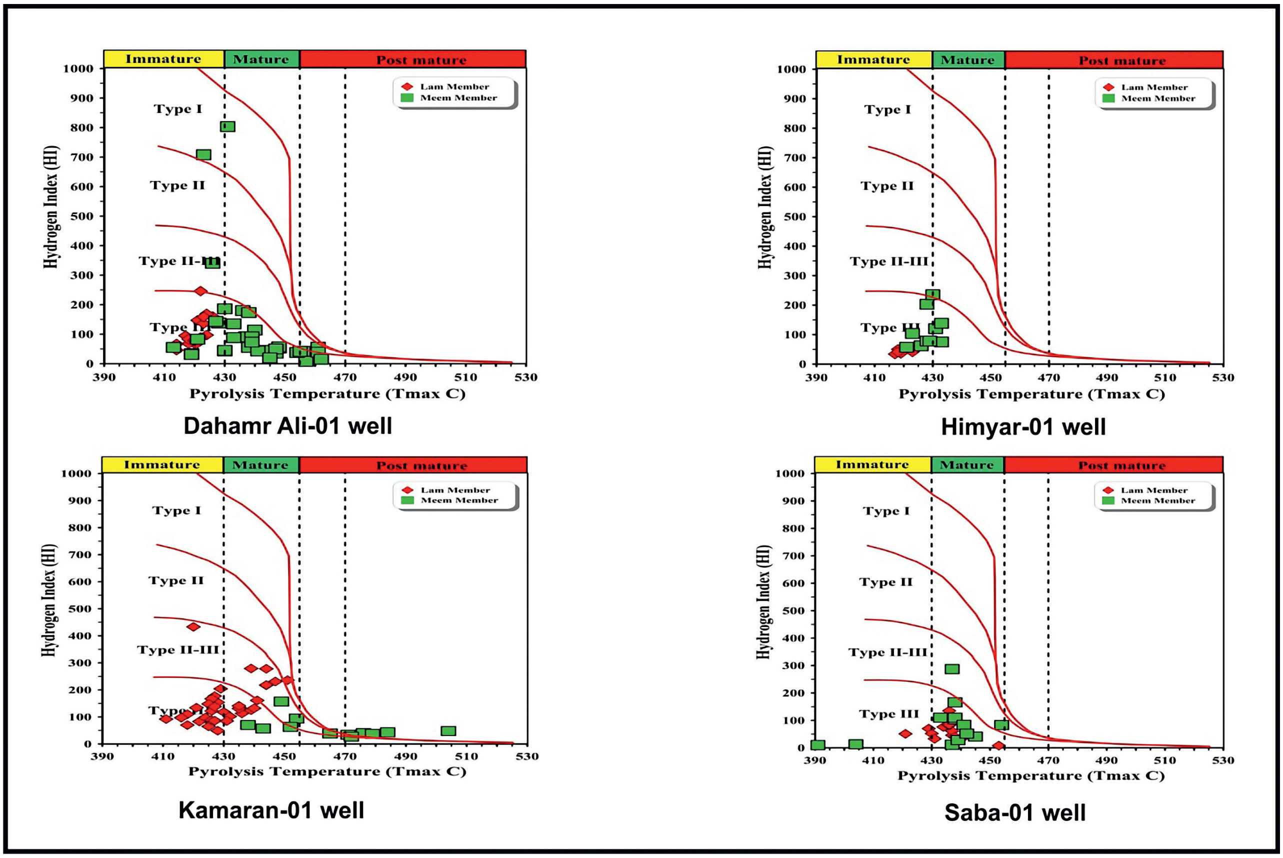

Fig. 4. Kerogen type and thermal maturation of Meem and Lam source rocks, NW Sab'atayn Basin, Yemen
Ryc. 4. Typ kerogenu i dojrzałość termiczna skał źródłowych z Meem i Lam, NW Sab'atayn Basin, północno-zachodnia część Basenu Sab'atayn, Yemen

rity according to the results of samples taken from Lam unit, whereas marginally mature in the Dahamr Ali-01 and Saba-01 wells. These findings have led to the classification of the Meem member as completely mature source rock, but the Lam Member is considered to be an immature source rock in the research region. This is due to the effect of structural setting that leads to deepening of Meem Member and shallowing of Lam Member.

5. CONCLUSION

Upper Jurassic source rocks in the NW Sab'atayn Basin central Yemen have been investigated. The main conclusions of the study are: Upper Jurassic source rocks consider the main source rocks in the study area. Deposition of the Meem and Lam source rocks succession did not result in a renewal of generation processes. As evident from kerogen type present in studied wells we can clearly state that this kerogen is 6derived from land derived organic matter. The Rock-Eval pyrolysis data show that the majority of the samples are composed of reworked organic materials that lack any promise for interesting source rocks. Organic rich source rock with poor to good potential to generate oil and gas is present in the Upper Jurassic Meem and Lam Members. Good to fair source rocks of Meem and Lam Members are located in the study area. Results of TOC for the studied wells show that the quantities of source rocks are fair to good, some samples are graded to excellent. Most of the Meem and Lam source rock samples under investigation have T_{max} values below 440°C, classifying them as immature to barely mature. It displays non-generative rocks based on the generative potential of Meem source unit. Type III organic materials derived from terrestrial environment, dominates the kerogen type for the Meem and Lam source unit.

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