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Source rock evaluation and hydrocarbon generation potential of Mid-Late Cretaceous sediments from Mintaq-01 well in the Wadi Hajar of Southern Sabatayn Basin, Yemen

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ABSTRACT

Twenty-five cutting shale and coal samples from the Mid-Late Cretaceous Mukalla and Harshiyat formations in the Mintaq-01 well, Wadi Hajar of Southern Sabatayn Basin were investigated using organic geochemical methods. The geochemical results indicate that the analyzed shale and coal samples are fair to excellent source rocks, with TOC values between 0.50 and 53.13%. The analyzed samples also have Rock-Eval HI between 99 and 676 mg HC/g TOC, indicating types I/II and II/III kerogen and thus are oil and gas-prone source rocks. However, these Mid-Late Cretaceous sediments of the Wadi Hajar are still in an immature to very early mature stage, and they have not yet generated oil or gas.

KEYWORDS

coal; geochemistry; Mid-Late Cretaceous; oil and gas generation; Sabatayn Basin; Shale; Wadi Hajar

1. Introduction

The Sabatayn Basin extends from the north-western to south-eastern of Yemen. The basin is subdivided into three grabens including Wadi Hajar (Figure 1). The Wadi Hajar graben is situated in south-eastern portion of the Sabatayn Basin (Figure 1), where the available data for the potential source rocks are limited (SPT 1994; Hakimi and Ahmed 2016). The presence of the oil staining and minor gas in the studied Mintaq-01 well (e.g., SPT 1994) encouraged exploration activities related to finding the petroleum resources. The Mintaq-01 well penetrated sedimentary rocks, belonging to the Middle Jurassic-Eocene formations (Figure 2). The organic-rich intervals are mainly encountered within the Late Jurassic-Early Cretaceous rock units represented by the Sabatayn, Madbi and Naifa formations (Hakimi and Ahmed 2016), whereby they were reported to have higher potential in oil and gas generation (Hakimi and Ahmed 2016). The Late Jurassic Madbi shales are likely to be the main source rocks, which possess higher thermal maturity than the Late Jurassic Sabatayn and Late Jurassic-Early Cretaceous Naifa formations (Hakimi and Ahmed 2016). Based on a basin modeling study by Hakimi and Ahmed (2016), the results indicated that most of the discovered oil and gas in the Mintaq-01 well are generated from both Madbi units, with high amounts of gas contributing from the Meem unit. Within this sedimentary sequence, the organic-rich shales and coals in the Mukalla and Harshiyat Formations have

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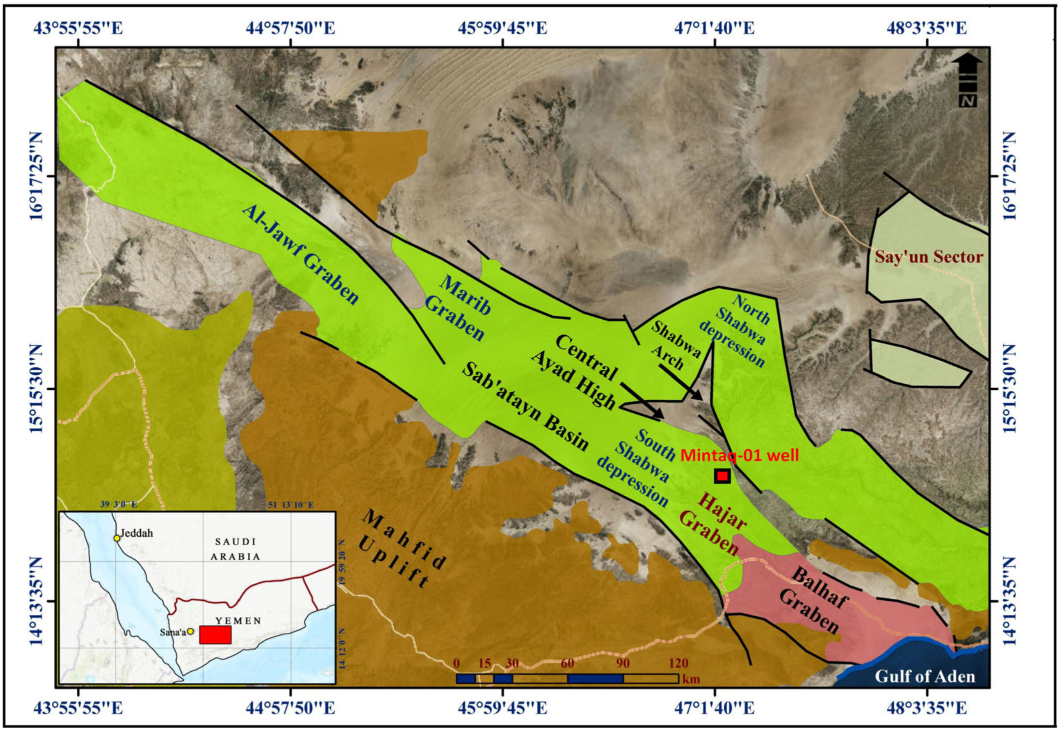

Figure 1. The main grabens (e.g., Al-Jawf, Marib, and Hajar) and the Shabwah depression in the Sabatayn basin, Yemen (modified after Al-Areeq et al. 2018), including location map of the studied well (Mintaq-01) in the Wadi Hajar graben.

previously been documented (SPT 1994). However, there are needs for them to be investigated further, particularly with respect to the types of organic matter and their relation to petroleum generation potential with thermal burial. The current study intends to analyze, interpret and document the characteristics of the shales and coals of the Mukalla and Harshiyat Formations in the Wadi Hajar graben using conventional geochemical results (e.g., Total organic matter (TOC) content and Rock-Eval pyrolysis data) from Mintaq-01 well.

2. Geological setting

The Sabatayn onshore basin is initially formed during the rifting event of the Late Jurassic and continues to the early Cretaceous (Redfern and Jones 1995; Beydoun et al. 1998; As-Saruri, Sorkhabi, and Baraba 2010). Stratigraphic succession includes thick sedimentary rocks and is represented by the pre, syn-, and post-rift strata (Figure 2).

Compared with other grabens of the Sabatayn Basin, the Wadi Hajar composed of both marine and non-marine deposits, ringing from Middle Jurassic to Eocene age (Figure 2). These deposits are punctuated by several unconformities and related mainly to tectono-stratigraphic phases (pre-, syn-, and post-rifts) (As-Saruri, Sorkhabi, and Baraba 2010).

The pre-rift sequence is unconformable resting in the Pre-Cambrian basement rocks, and is represented by the Kuhlan clastics and the marine Shuqra carbonates (Figure 2). Here, the syn-rift package (Late Jurassic to Early Cretaceous) includes the whole Madbi and Sabatayn formations and the lower part of Naifa Formation (Figure 2). The Madbi Formation contains mainly shale and sandstones (Figure 2), where the shales are rich in organic matter and represent the main oil-source rocks in the Sabatayn Basin (Alaug et al. 2011; Hakimi et al. 2014; Hakimi and

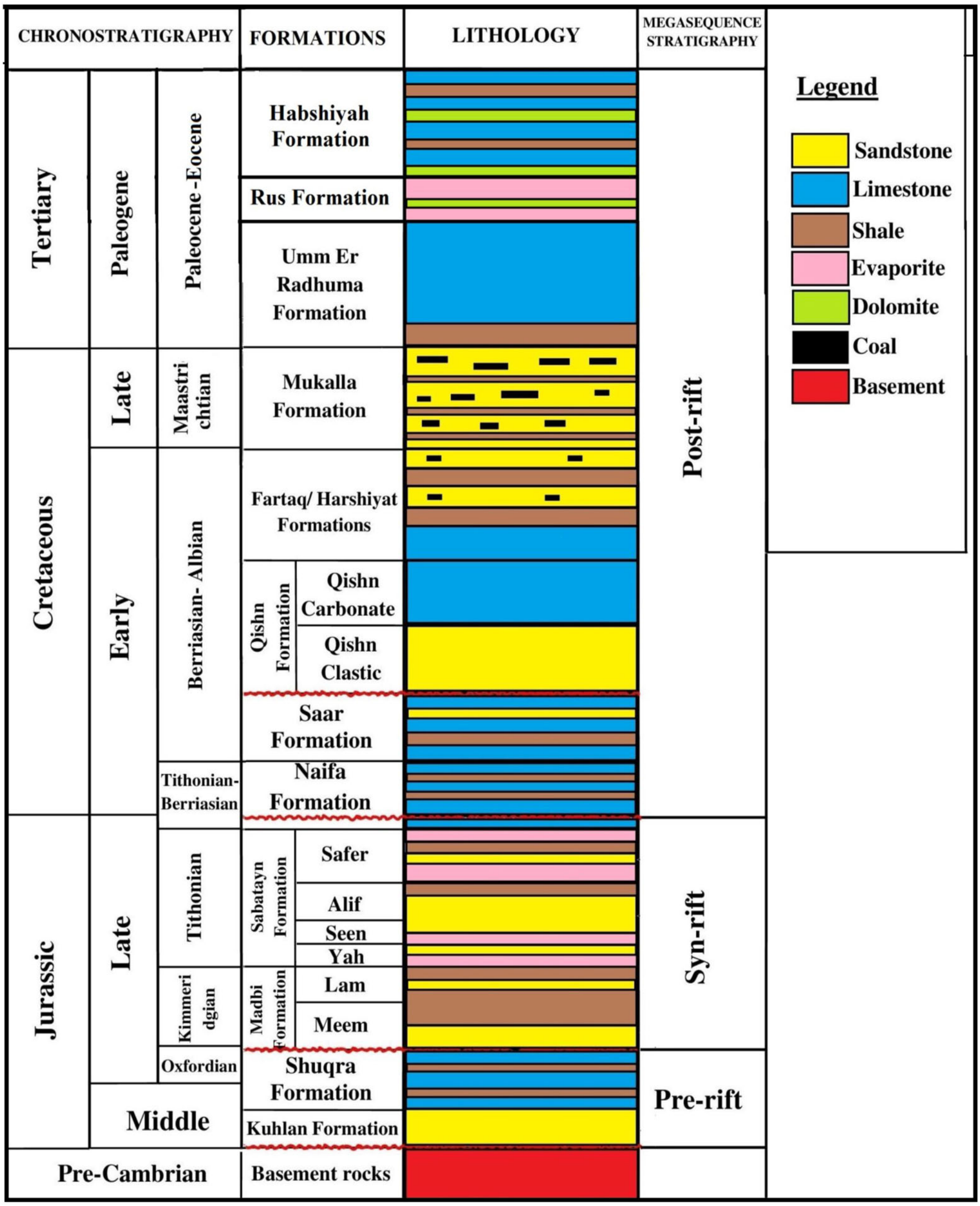

Figure 2. Generalized stratigraphic column represented exploration Mintaq-01 well (modified after SPT 1994).

Ahmed 2016; Al-Areeq et al. 2018; Hakimi, Al-Matary, and Hersi 2018). The Sabatayn Formation lies on Madbi Formation with a conformable contact, and composed of clastic and evaporite sediemnts (Figure 2).

The Early Cretaceous to Tertiary sequence were accumulated during the post-rift and representing by mixed carbonate-clastic sequence of the Saar, Qishn, Fartaq, and Harshiyat formations and followed by fluvio-marine sediments of the Mukalla Formation (Figure 2). The Mukalla Formation overlies the Paleocene marine sediments of the Umm Er Radhuma Formation (Figure 2). These Early Paleogene sediments consist of carbonate rocks and were subsequently followed by deposits of mixed clastic and evaporites of the Rus and Habshiyah formations (Figure 2).

3. Samples and methods

In total, 25 representative cutting samples were collected from the exploration well (Mintaq-01 well) in the Wadi Hajar (Figure 1). The cutting samples are represented by shale and coal intervals within the Mid-Late Cretaceous Mukalla and Harshiyat Formations (Figure 2 and Table 1). The samples were analyzed using geochemical method, including TOC content and Rock-Eval pyrolysis analysis. The TOC analysis was carried out on crushed samples of less than 200 mesh size and then was measured using a LECO CS-125 equipment. The bulk pyrolysis was performed using a Rock Eval-II. Several parameters such as free hydrocarbon (S_1, mg/g), total hydrocarbon yield from cracking of kerogen (S_2, mg/g), and oven temperature at maximum S_2 generation (T_{max}) were measured during the pyrolysis process. Based on the TOC and Rock-Eval results, hydrogen index (HI $= S_2 \times 100$/TOC), petroleum yield (PY $= S_1 + S_2$), and production index (PI $= S_1/S_1 + S_2$) were subsequently calculated as shown in Table 1.

4. Results and discussion

4.1. Organic matter content and source generative potential

The organic geochemical results of the analyzed samples from the studied well are presented in Table 1. The organic richness and source generative potential of the source rocks were primary evaluated based on TOC content and Rock-Eval S_1 and S_2 parameters as described by Peters and Cassa (1994) and Mccarthy et al. (2011). The TOC content of the analyzed samples exhibited a moderate to high range of values from 0.50 to 53.13 wt% (Table 1), suggesting favorable source

Table 1. Rock Eval pyrolysis data and TOC content and additional calculated parameters for the shale and coal samples of the Mid-Late Cretaceous Mukalla and Harshiyat Formations from Mintaq-01 well in the Wadi Hajar of Southern Sabatayn Basin, Yemen.

				Rock-Eval pyrolysis					
Formation	Lithology	Depth (MD)	TOC wt%	S_1 (mg/g)	S_2 (mg/g)	T_{max} (°C)	HI (mg/g)	PY (mg/g)	PI (mg/g)
Mukalla Formation	Shale	460	0.9	0.12	3.46	422	384	3.58	0.03
	Shale	460	3.0	0.45	13.89	426	463	14.34	0.03
	Shale	628	0.5	0.02	0.45	437	90	0.47	0.04
	Shale	636	1.62	0.12	1.85	436	114	1.97	0.06
	Shale	856	1.03	0.06	1.25	426	121	1.31	0.05
	Shale	860	2.91	0.13	3.90	416	134	4.03	0.03
	Coal	860	53.13	5.78	228.46	404	430	234.24	0.02
	Shale	868	1.07	0.06	1.07	437	100	1.13	0.05
	Shale	945	1.63	0.80	8.66	432	531	9.46	0.08
	Shale	1,046	0.56	0.03	3.16	422	564	3.19	0.01
Harshiyat Formation	Shale	1,168	2.53	0.08	8.05	416	318	8.13	0.01
	Coaly shale	1,172	8.45	0.18	31.01	415	367	31.19	0.01
	Shale	1,176	1.69	0.09	2.32	430	137	2.41	0.04
	Shale	1,180	0.73	0.05	0.95	434	130	1.00	0.05
	Shale	1,184	1.53	0.03	3.75	429	245	3.78	0.01
	Shale	1,188	1.84	0.13	2.54	436	138	2.67	0.05
	Shale	1,192	1.03	0.06	1.07	436	104	1.13	0.05
	Shale	1,196	3.10	0.09	12.93	421	417	13.02	0.01
	Shale	1,204	0.82	0.07	1.33	432	162	1.40	0.05
	Shale	1,208	1.26	0.09	1.42	435	113	1.51	0.06
	Shale	1,212	2.76	0.10	6.90	418	250	7.00	0.01
	Shale	1,220	1.59	0.08	9.81	415	617	9.89	0.01
	Shale	1,224	1.61	0.06	2.48	429	154	2.54	0.02
	Shale	1,228	0.79	0.04	1.40	436	177	1.44	0.03
	Shale	1,236	1.00	0.10	6.76	416	676	6.86	0.01

S_1: Volatile hydrocarbon (HC) content, mg HC/ g rock; TOC: Total organic carbon, wt%; S_2: Remaining HC generative potential, mg HC/ g rock; PI: Production index $= S_1/(S_1 + S_2)$; T_{max}: Temperature at maximum of S_2 peak; PY: Potential yield $= S_1 + S_2$ (mg/g); HI: Hydrogen index $= S_2 \times 100$/TOC, mg HC/g TOC.

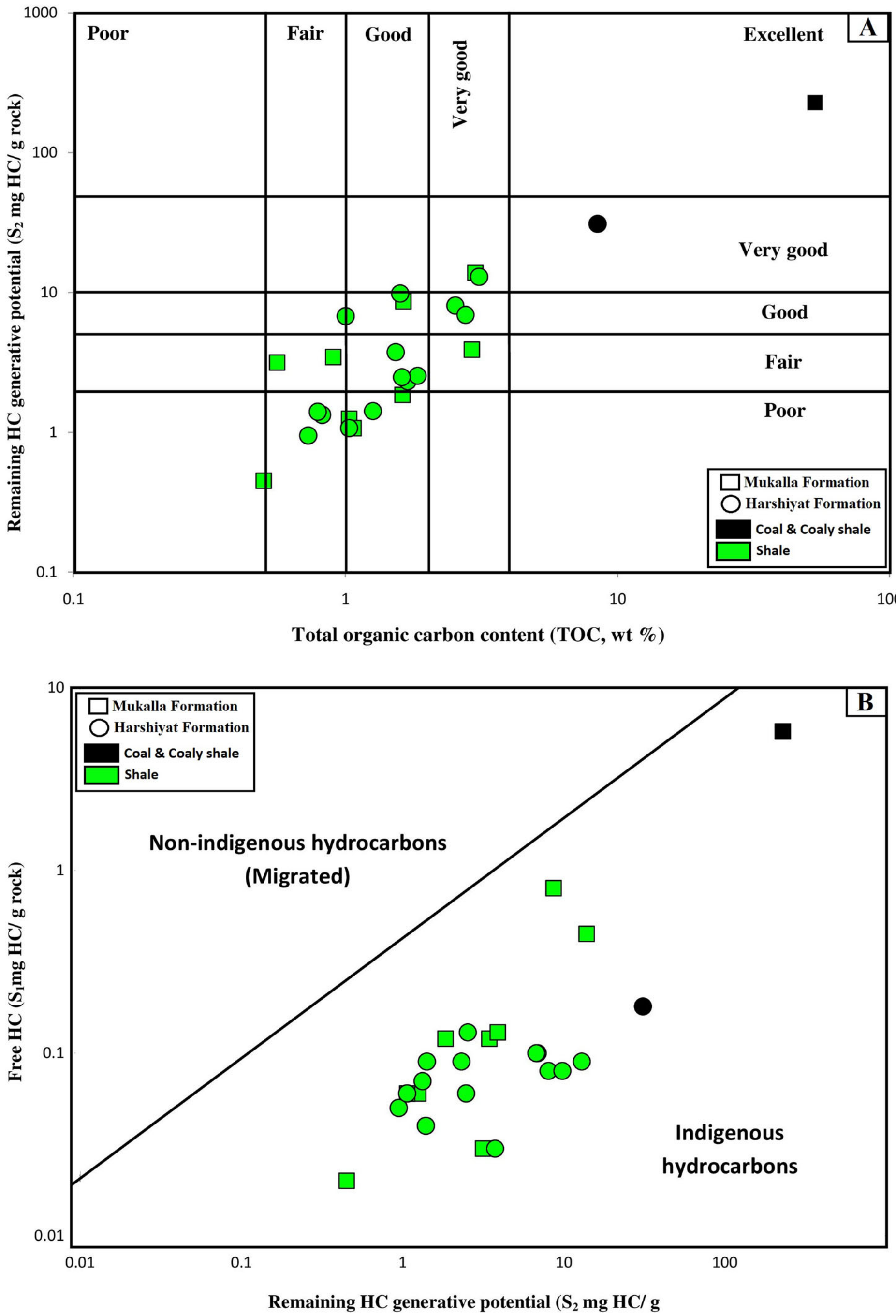

Figure 3. Geochemical cross-plot of relationship between the TOC content and remaining petroleum yield of S2 (A) and free petroleum yield of S1 (B) of the analyzed Mukalla and Harshiyat samples.

rocks. The analyzed samples have S_2 yields between 0.45 and 228.46 mg HC/g rock, which indicates fair to excellent source generative potential in collaboration with TOC results (Figure 3a). The coal and coaly shale samples have relatively higher generative potential than the shale samples, with high values of TOC content and Rock-Eval S_2 yield (Figure 3a). The source generative potential was also inferred from the S_2 together with the S_1 yields (PY $= S_1 + S_2$). The range of the PY values is between 0.47 and 234.24 (Table 1), which further indicates that the analyzed samples exhibit good source rocks potential for hydrocarbon generation. The relationship between the two yields of S_1 and S_2 as demonstrated in Figure 3b further indicates that most of the hydrocarbons in the analyzed samples are indigenous in origin.

4.2. Quality of organic matter input (kerogen typing)

Interpretation of the quality of the kerogen input in a source rock can be provided from geochemical results such as Rock-Eval hydrogen index (HI) and oxygen index (OI) (Peters and Cassa 1994; Hunt 1996). The Rock-Eval-II instrument in this study does not measure S_3 peak, hence, information on oxygen content and the available pyrolysis hydrogen index (HI) are generally used as kerogen type indicator in the analyzed samples. HIs were calculated from the equation provided in Espitalie et al. (1977) as follows: HI $= S_2 \times 100$/TOC.

The HI pyrolysis values were found to be in the range of 90–676 mg HC/g TOC (Table 1). Typically, HI values between 700 and 300 mg HC/g TOC reflect types I/II kerogen and HI values in the range of 200–300 mg HC/g TOC indicate mixed type II/III kerogen (Peters and Cassa

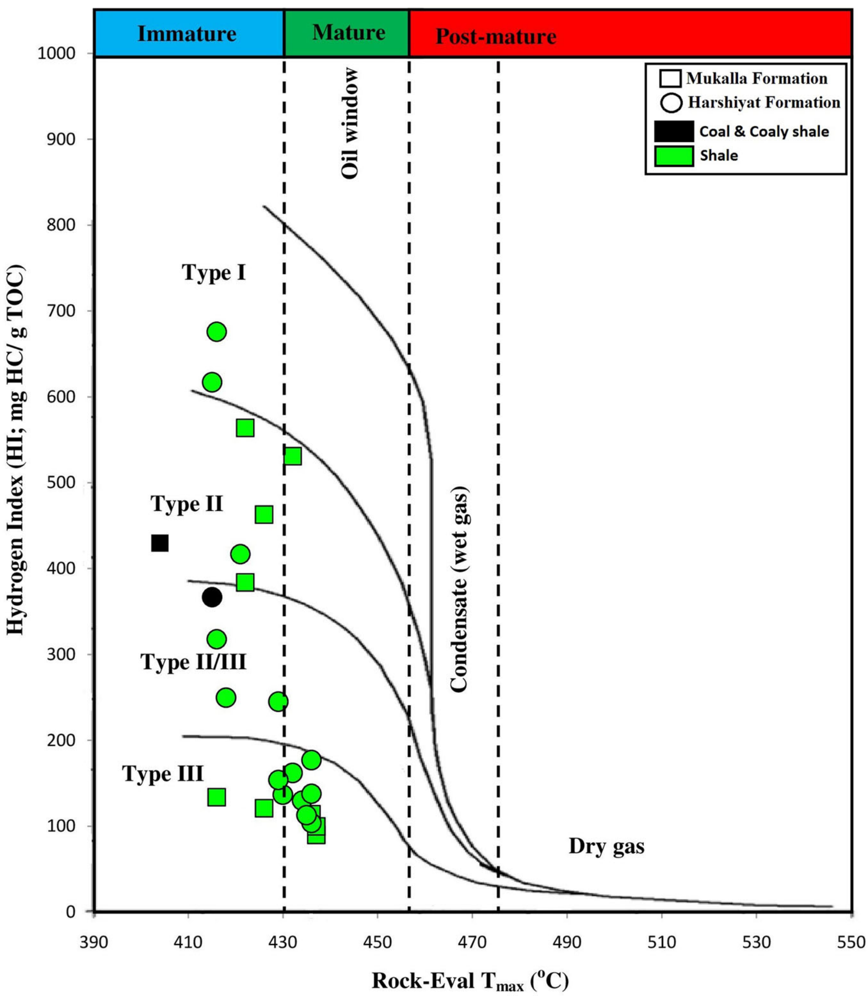

Figure 4. Pseudo-van Krevelen diagrams of pyrolysis HI versus Tmax, showing types of kerogen in the analyzed Mid-Late Cretaceous Mukalla and Harshiyat samples.

1994; Hunt 1996). Based on the HI values in this study, the types I/II and III kerogen were found to be the major kerogen component in the analyzed samples, with a minor contribution of the mixed type II/III kerogen as illustrated in the modified Van Krevelen diagram of HI and T_{max} plot of Figure 4.

4.3. Maturity level of organic matter

The estimation of maturity level is a very important criterion to predict the petroleum generation (oil and/or gas) from the organic matter in a source rock and further hydrocarbon exploration (Tissot and Welte 1984; Espitalie and Bordenave 1993; Hunt 1996). In this study, the maturity of organic matter was estimated using geochemical maturity indicators such as T_{max} and production index (PI $= S_1/S_1 + S_2$). The measured T_{max} values were recorded between 404 and 437 °C (Table 1). This indicate that the entire Mid-Late Cretaceous Mukalla and Harshiyat Formations contains immature to early-mature organic matter. This is clearly reflected by the modified Van Krevelen diagram of HI and T_{max} values (Figure 4). The measured T_{max} values also agree with the calculated PI values, which further indicate that the analyzed samples are immature to early-mature for oil-generation (Figure 5). This implies that the analyzed formations have not been buried to a sufficient depth to generate liquid hydrocarbons of less than 1,300 m (Table 1).

4.4. Petroleum resource potentially

Understanding of the petroleum generation potential (oil and/or gas) during maturation depends on the organofacies characterization and typifying of kerogen in the source rocks (Tissot and Welte 1984; Peters and Cassa 1994; Hunt 1996; Ardakani et al. 2017). This study provides a preliminary investigation of the petroleum potentiality for the Mid-Late Cretaceous source rocks in the Mintaq-01 well in the Wadi Hajar graben of Southern Sabatayn Basin. This has been assessed based on the geochemical results as presented in the above subsections.

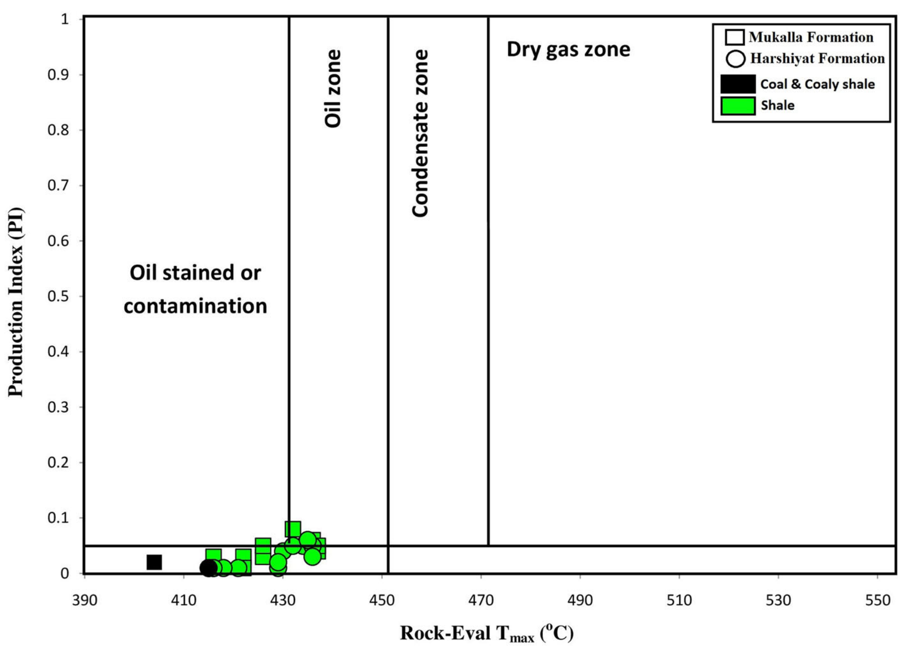

Figure 5. Cross-plot of the relationship between the pyrolysis Tmax versus PI values of the analyzed Mukalla and Harshiyat samples, indicating that the analyzed samples are immature to very early-mature.

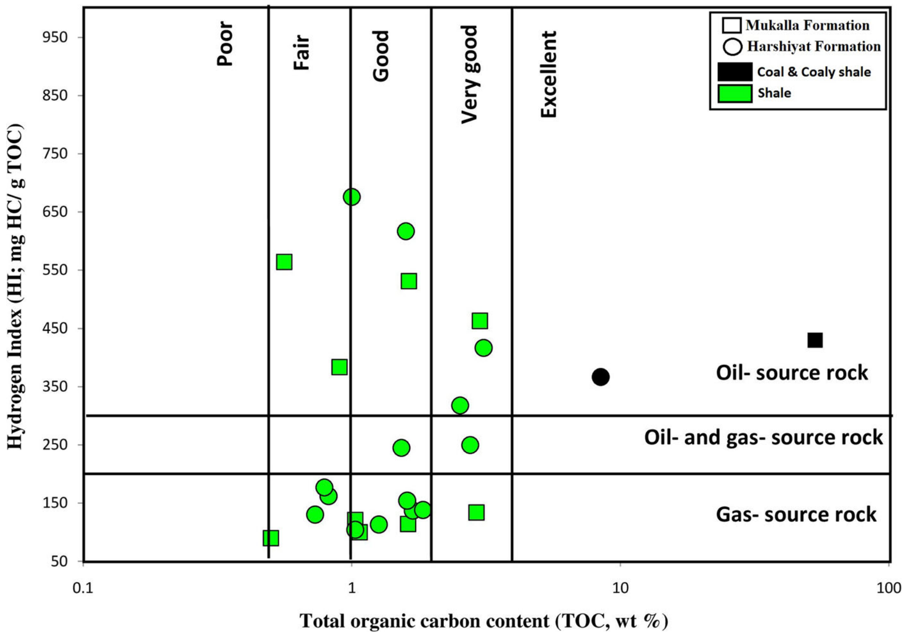

Figure 6. Relationship between TOC content and Rock-Eval HI values, showing both oil and gas generation potential for the analyzed Mukalla and Harshiyat samples.

Based on the geochemical results, the analyzed shale and coal samples were shown to contain moderate to high concentrations of organic matter and are characterized by a dominance of types I/II and III kerogen (Figure 4). These findings reveal that the analyzed shale and coal intervals in the Mid-Late Cretaceous Mukalla and Harshiyat formations possess important potential both oil- and gas-generation (Figure 6). Besides the indicated kerogen type, the maturity indicators underscore that the identified type of organic matter (I/II and II/III) are in low maturity level i.e., immature to very early-mature oil window (Figures 4 and 5). This suggests that the thermal alteration was not enough to generate oil or gas for the analyzed Mukalla and Harshiyat source rocks in the shallower part of the Wadi Hajar graben. However, oil and gas generation can be expected in the deeper parts of the Wadi Hajar graben, where these formations could be reached a sufficient maturity level and act as significant source rocks.

5. Conclusions

Conventional geochemical methods such as TOC and Rock-Eval pyrolysis have been used to investigate the abundance and type of organic matter and it's potentially for petroleum generation. The investigated samples of shales and coals within the Mid-Late Cretaceous Mukalla and Harshiyat formations in the Mintaq-01 well in the Wadi Hajar, Southern Sabatayn Basin were revealed to possess high amount of organic matter, with TOC content of more than 1%, indicating a favorable source rocks. The hydrogen indices (HI) of 99–676 mg HC/g rock and petroleum generation potential yields ($S_1 + S_2$) of 0.47–234.24 mg HC/g rock in collaboration with TOC results, thus indicate that the analyzed samples are generally good potential source rocks for both oil and gas-prone. The Rock-Eval parameters such as low T_{max} and production index (PI) values suggest that the shale and coal intervals within the Mukalla and Harshiyat formations throughout the Mintaq-01 well section are in low level of thermal maturity i.e., immature to very early-mature oil window range, and therefore, no commercially viable oil or gas has been generated from this studied Cretaceous interval.

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