Preliminary investigation of the hydrocarbon generation potential from the post-rift Abbas shale Formation (Pliocene) in the Tihamah Basin, south-eastern Yemeni Red Sea

Mohammed Hail Hakimi¹ · Abbas F. Gharib² · Nor Syazwani Z. Abidin³ · Madyan M. A. Yahya^{1,4}

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Abstract

Pliocene shales included in the post-rift Abbas Formation were recovered from an exploratory well (Kathib-01) in the Tihamah Basin and geochemically analyzed. A preliminary evaluation of the organic facies of the Abbas shales and their petroleum generation potential was conducted based on basic organic geochemical results. Most Abbas shale samples had total organic carbon (TOC) contents < 1% and a fair source potential, while the remaining samples, with TOC contents > 1%, had a relatively good potential. Overall, the Rock–Eval hydrogen index values of the shales analyzed were between 96 and 234 mg of hydrocarbon per gram of TOC (mg HC/g TOC), indicating two dominant organic facies: types III and II/III kerosene, which indicate the presence of mainly gas- and oil-prone source rocks. We conclude that the Pliocene Abbas shales in the Tihamah Basin are still in a very early-mature stage (with respect to the oil window) and, hence, have not generated petroleum yet.

Keywords Pliocene shale · Abbas Formation · Petroleum generation potential · Tihamah Basin · Yemeni Red Sea

Introduction

The hydrocarbon exploration history of the Tihamah Basin, which is located in the south-eastern Yemeni Red Sea (Fig 1a), began many years ago. In 1960, around 12 exploration wells were drilled in the onshore and offshore portions of the Tihamah Basin, Yemen (Fig 1b). These wells are operated by multiple petroleum-operating companies, such as Mecom, Hunt, Total, and Shell. Moreover, the presence of oil seeps in the As-Salif peninsula, its onshore migration, and the presence of oil and gas in several onshore

and offshore wells in the Tihamah Basin (e.g., SPT 1994), suggested the presence of several proven source rocks and encouraged further petroleum geochemistry studies. Several geochemistry works have been conducted on shale rocks contained in the corresponding (syn- and post-rift) sedimentary successions. A recent study by Hakimi et al. (2016) indicated that the syn-rift Salif Formation contains organic-rich shales, which are considered the main source rocks in the Tihamah Basin. The Salif organic-rich shales are characterized by a relatively high total organic carbon (TOC) content (> 3%) and mainly type II and mixed II–III kerogens, with a minor contribution of type III kerogen, indicating that they are mainly oil- and gas-prone source rocks (Hakimi et al. 2016). The current study focused on the overlain shales of the post-rift Abbas Formation and compared the results with those of recent studies on the organic-rich interval of the syn-rift Salif Formation. In this way, we expected to obtain a big picture of the petroleum resources in the Shabwah sub-basin, useful for future explorations. This study aimed to provide information on the source rock characteristics of the Abbas shale Formation, particularly with respect to their quantity, quality, level of thermal maturity, and potential for hydrocarbon generation. A total of 10 cutting shale samples were collected from an exploratory well located offshore in

✉ Mohammed Hail Hakimi
ibnalhakimi@yahoo.com

¹ Geology Department, Faculty of Applied Science, Taiz University, 6803 Taiz, Yemen

² Oil and Gas Economics, Imam Jaafar Al-Sadiq University, Kirkuk, Iraq

³ Geosciences Department, Faculty of Science and Information Technology, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia

⁴ Department of Petroleum Geology and Sedimentation, Faculty of Earth Sciences, University of King Abdulaziz, Jeddah, Saudi Arabia

Fig. 1 a Main sedimentary basins in the Republic of Yemen (modified after Beydoun et al. 1998) and b location map of exploration wells in the Tihamah Basin (south-eastern Yemeni Red Sea), including the studied well (i.e., Kathib-01)

the Tihamah Basin (i.e., Kathib-01; see Fig 1b) and were subjected to basic organic geochemical analyses.

Geological setting

The Tihamah Basin extends in the south-eastern part of the Yemeni Red Sea (Fig 1a), from the onshore to offshore. This sea was initially formed owing to early Oligocene and Tertiary rifting and then by recent tectonic movements (Redfern and Jones 1995; As-Saruri et al. 2010). The Tihamah Basin is structurally part of a tectonic zone of the Red Sea rifting,

which resulted from the detachment of the Arabian Peninsula from the African Plate (Fig 2; Redfern and Jones 1995). The tectonic rifting is manifested by parallel normal faults and several related structural elements, such as horsts and tilted fault blocks (Tari et al. 2014; Bawazer et al. 2018). The Tihamah Basin is filled with a thick sedimentary succession, belonging to the Early Miocene–Pleistocene (Fig 3), and represented by the Tihamah Group (Beydoun et al. 1998; As-Saruri et al. 2010). The Tihamah sediments were related mainly to the tectono-stratigraphic (i.e., syn- and post-rift) conditions: They accumulated in marine, transitional, and continental depositional environments (As-Saruri et al.

Fig. 2 Main offshore sedimentary basins in the Republic of Yemen, including the Tihamah Basin. The figure shows the formation of the offshore Aden-Abyan, Hawarh, Mukalla-Sayhut, and Tihamah Basins during the Oligocene–Miocene rifting (modified after SPT 1994)

2010). Prior to the first period of sedimentation, Tertiary volcanic rocks formed in the Tihamah Basin during the late Oligocene (Fig 3), and their formation accelerated during the late Pliocene (Mattash 1994; Al-Kadasi 1994; Nasher 2010). These Tertiary volcanic rocks are related to the evolution of the Red Sea and the Gulf of Aden (Mattash 1994; Al-Kadasi 1994; Redfern and Jones 1995; Nasher 2010).

The syn-rift sequences of the Zaydiyah, Maqna, and Salif formations were deposited during the early–late Miocene. Notably, they include mainly clastic sediments and evaporites and lie unconformably on volcanic rocks (Fig 3). The Zaydiyah Formation includes predominantly clastic sediments overlain conformably by marine sediments of the Maqna Formation (Fig 3). This latter formation mainly consists of shale with interbedded sandstones and is conformably overlain by the middle–late Miocene Salif Formation (Fig 3). The Salif Formation is composed of mixed marine evaporites with subordinate shales and sandstones (Fig 3). Among them, organic-rich shales were deposited in a marine anoxic environment under highly reducing conditions: They contain large amounts of algal and microbial organic matter and a lower amount of terrigenous organic matter (Hakimi et al. 2016).

The mixed clastic-carbonate sediments of the post-rift sequence conformably cover the Salif Formation (Fig 3).

The post-rift sequence is represented by Pliocene–Pleistocene Abbas clastics and Kamaran carbonates. The Abbas Formation is composed mainly of sandstone and mudstone; moreover, it presents vertical variations of thickness and lateral facies changes (from clastics to carbonate facies). These variations and changes were created along the shore of the Yemeni Red Sea during the deposition of organic reef limestone in the Pleistocene and are included in the Kamaran Member (Fig 3).

Materials and methods

The data used in this study include conventional organic geochemical results obtained from 10 cutting samples collected from an exploratory well (i.e., Kathib-01) in the Tihamah Basin, south-eastern Yemeni Red Sea (Fig 1b and Table 1). These samples were extracted from a shale unit within the post-rift Abbas Formation (Fig 3). Prior to the geochemical analytical process, the drilling mud and other drilling additives were removed using cold freshwater. The standard organic geochemical analyses included measurements of the TOC content and Rock–Eval pyrolysis analyses (conducted at specialized geochemical laboratories).

Fig. 3 Generalized stratigraphic column of the Miocene–Pliocene sequences in the Tihamah Basin (modified after SPT 1994)

Table 1 Basic geochemical results of the analyzed shale samples in the post-rift Abbas Formation (Pliocene) in the Tihamah Basin, south-eastern Yemeni Red Sea, including TOC content and measured and calculated Rock–Eval pyrolysis parameters

Wells	Depths (m)	TOC Wt. %	Rock–Eval pyrolysis data					
			Measured parameters			Calculated parameters		
			S_1 (mg/g)	S_2 (mg/g)	T_{max} (°C)	PY (mg/g)	PI (mg/g)	HI (mg/g)
Kathib-01 Well	1070	0.50	0.04	0.89	430	0.93	0.04	178
	1080	0.57	0.08	0.96	444	1.04	0.08	168
	1110	0.88	0.10	1.73	429	1.83	0.06	197
	1140	0.62	0.04	0.87	431	0.91	0.05	140
	1190	0.56	0.05	0.54	435	0.59	0.08	96
	1407	1.01	0.33	2.35	434	2.68	0.12	233
	1419	1.03	0.34	2.41	433	2.75	0.12	234
	1428	0.81	0.31	1.85	435	2.16	0.14	228
	1440	0.59	0.24	0.95	434	1.19	0.20	161
	1566	0.53	0.33	0.89	431	1.22	0.27	168

TOC total organic carbon, wt%; S_1 volatile hydrocarbon (HC) content, mg HC/ g rock; S_2 remaining HC generative potential, mg HC/g rock; HI hydrogen index = $S_2 \times 100 / \text{TOC}$, mg HC/g TOC; PY potential yield = $S_1 + S_2$ (mg/g); MI: migration index = $S_1 * 100 / \text{TOC}$; PI: production index = $S_1 / (S_1 + S_2)$

The whole-rock samples were crushed to fine particles and subsequently analyzed to determine the TOC content using a LECO CS-125 equipment. Rock–Eval pyrolysis analyses were subsequently performed on the powdered samples using a Rock–Eval II instrument. The results of the latter analysis provided three important parameters: the total free petroleum (S_1 peak, mg/g), the hydrocarbon yield from kerogen cracking (S_2 peak, mg/g), and the highest temperature at which the maximum S_2 is generated during pyrolysis ($T_{\max}$). Based on the TOC content and the Rock–Eval yields (i.e., S_1 and S_2), we could mathematically calculate additional geochemical parameters: the hydrogen index ($HI = S_2 \times 100/\text{TOC}$), the petroleum yield ($PY = S_1 + S_2$), and the production index ($PI = S_1/S_1 + S_2$) (Table 1).

Results and discussion

Total organic carbon (TOC) content and generative potential

The TOC content of the source rocks and their generative potential can be used to identify the amount of organic matter and the petroleum generation potential on thermal maturity (Peters and Cassa 1994; Hunt 1996; Shah and Ahmed 2018). In this study, the generative potential of the shale samples analyzed was evaluated from the organic geochemical results: the TOC content and the yields of S_1 and S_2 (Peter and Casa 1994; Hunt 1996; Shah and Ahmed 2018). The TOC content is indicated commonly in terms of weight percent (Peter and Casa 1994; Hunt 1996); notably, the minimum TOC content value associated with shale source rocks is ≥ 0.5 wt% (Tissot and Welte 1984). Here, the source rocks with TOC content < 1 wt% and up to 1 wt% were classified as “fair potential” and “good–excellent” source rocks, respectively (Peters and Cassa 1994). Most of the Abbas shale samples analyzed showed TOC values between 0.50 and 1.03 wt% (Table 1) and were, hence, considered as fair source rocks (Fig 4a). Only two samples showed TOC values slightly $> 1\%$, indicating their higher potential (i.e., good potential) as source rocks (Fig 4a). However, knowing the TOC content alone is not sufficient to determine the generative potential of source rocks: It must be considered in parallel with the Rock–Eval S_2 yield (Peters 1986; Peters and Cassa 1994; Hunt 1996; Dembicki 2009). Based on the S_2 and TOC data, we can conclude that most of the samples analyzed had a fair–good generative potential (Fig 4b).

Types of organic matter

The types of kerogen contained in the Abbas shale Formation were evaluated considering the basic geochemical

results. The Rock–Eval hydrogen (HI) and oxygen (OI) indices can be used to describe the bulk kerogen types present in source rocks (Peters and Cassa 1994; Hunt 1996). In this study, the Rock–Eval instrument did not measure the carbon oxide content (i.e., the S_3 peak); hence, no information on the oxygen content was obtained, and the kerogen type present in the samples analyzed was identified based on the HI. The potential of a source rock to generate hydrocarbons is usually determined from the HI rather than from the OI: The latter index is not accurate, because the oxygen released from the organic matter combines with that released from carbonates or the oxidation of kerogen (Tissot and Welte 1984; Espitalié et al. 1985; Mukhopadhyay et al. 1995). The HI pyrolysis parameter of the samples analyzed was in the range of 96–234 mg of hydrocarbon per gram of TOC (mg HC/g TOC) (Table 1). According to the modified van Krevelen diagram obtained by combining the Rock–Eval HI and $T_{\max}$ results, the organic matter in the samples analyzed was represented predominantly by types III and III/II kerogen (Fig 5a). These types of kerogen were further determined from a cross-plot of S_2 versus TOC (first proposed by Langford and Blanc-Valleron 1990). In fact, the HI values were calculated mathematically based on the TOC content and the Rock–Eval S_2 values: $HI = S_2 \times 100/\text{TOC}$ (Peters and Cassa 1994). The analysis of the cross-plot confirmed that the samples from the Kathib-01 well contained mainly types III and II/III kerogen (Fig 5b). These results are in good agreement with the interpretation based on the modified van Krevelen diagram.

Thermal maturation of organic matter

The degree of thermal alteration of the organic matter (due to heating) was defined as “maturation” (Peters and Cassa 1994). Geochemical data (i.e., $T_{\max}$ and PI values) can be used to estimate the maturation of organic matter in source rocks (Peters and Cassa 1994). The maximum temperature ($T_{\max}$) of the S_2 peak was measured during the pyrolysis analysis: It varied between 429 °C and 444 °C, indicating that the source rocks were in the early stage of maturity with respect to the oil-generation window (Peters and Cassa 1994). In the case of abnormally low $T_{\max}$ values, PI values are used as geochemical maturity indicators for source rocks (Peters and Cassa 1994). In this study, the samples analyzed had PI values between 0.04 and 0.27 (Table 1), further indicating a source rock in the early stage of maturity with respect to the oil-generation window (Fig 6). Furthermore, the S_1 yields (representing the free hydrocarbons, including gas and oil) were lower than the S_2 yields (Table 1), indicating that the organic matter had a low level of maturity and had not yet generated commercial petroleum. This low maturity level can be attributed to the

Fig. 4 **a** Distribution of the TOC content within adjacent depths of the Abbas shales in the studied well; **b** geochemical correlation between the TOC content and the potential petroleum yield ($S_1 + S_2$), indicating the presence of favorable source rocks (fair–good petroleum generation potential)

shallow burial depth of the Abbas Formation (< 1600 m) (Table 1).

Hydrocarbon generation potential

The kerogen facies dispersed in the source rocks greatly influence the type of hydrocarbons generated during their thermal maturation (Tissot and Welte 1984; Peters and Cassa 1994). This kerogen facies can be evaluated using geochemical and petrological parameters (Tissot and Welte 1984; Hunt 1996). Here, the organic matter quality (or the type of kerogen) and its relevance with respect to the hydrocarbon generation potential were determined primarily from the bulk pyrolysis data, examining them from a geochemical point of view. These analyses indicated that the samples analyzed contained mainly types III and II/III kerogen (Fig 5). This was also suggested by the corresponding HI values, which were between 96 and 234 mg HC/g TOC (Table 1). Considering these results, it can be inferred that the post-rift Abbas shale Formation in the Tihamah Basin can generate mainly gas and oil (Fig 7). Overall, our results indicate that the Abbas shale samples from the Kathib-01 well generally represent source rocks with an early level of thermal maturity with respect to the oil-generation window, and they should not yet have generated commercial amounts of petroleum. Despite being low in maturity, it is possible

that these shales have not yet reached a sufficient level of burial maturity and that, hence, they cannot generate commercial petroleum. The source rock characteristics of the Abbas shale Formation in the deeper parts of the basin are promising for future oil and gas explorations, suggesting new targets.

Conclusions

A basic organic geochemical investigation was performed on 10 shale samples of the Pliocene Abbas Formation collected from an exploratory well (i.e., Kathib-01) in the Tihamah Basin. This study aimed to characterize the source rocks and their hydrocarbon generation potential. Our conclusions, which can be used to evaluate future prospects and exploration targets in the area, are as follows:

- (1) The Abbas shale Formation has TOC contents ranging between 0.50% and 1.03%, indicating that it is a fair–good source rock.
- (2) The chemical Rock–Eval results revealed that the bulk kerogen in the Abbas shale Formation is mainly of type III and a mixture of type II/III kerogens. This shale can generate both oil and gas, with a high proportion of gas of a sufficiently mature level.
- (3) The chemical maturity parameters (i.e., T_{max} and PI) indicated that the Abbas shale Formation is located at a shallow depth (< 1600 m) and is currently in the early-mature stage with respect to the oil-generation window: Commercial oil should not have been generated yet.

Fig. 5 Geochemical correlations between the HI, $T_{\max}$, TOC content, OI, and S_2 : The shale samples analyzed were dominated by type III and mixed type II/III kerogens

Fig. 6 Geochemical cross-plots of the pyrolysis parameter $T_{\max}$ vs. the PI, indicating the maturity level and nature of the hydrocarbon products in the shale samples analyzed

Fig. 7 Geochemical correlations between the TOC content and the Rock–Eval HI data: The shale intervals in the Abbas Formation represented good source rocks, generating mainly gas and low amounts of oil in the Tihamah Basin

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