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Petroleum generation modeling of the organic-rich shales of Late Jurassic-Early Cretaceous succession from Mintaq-01 well in the Wadi Hajar sub-basin, Yemen

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Abstract

Late Jurassic-Early Cretaceous shales of the Naifa, Safer and Madbi formations were studied to evaluate source rock characterisation. The results of the source rock were then incorporated into basin modeling to understand the timing of hydrocarbon generation and expulsion. The Late Jurassic-Early Cretaceous shales have low to high organic matter, with TOC values in the range of 0.50%–28.01%, indicating fair to excellent source rock potential. Main oil and gas are anticipated to be generated from the Naifa, Safer and Lam shale samples with Type I/II and Type II-III kerogens. In contrast, the Meem samples are dominated by Type III kerogen ($HI < 200$ mg HC/g TOC), and are thus considered to be gas-prone. The Late Jurassic-Early Cretaceous shale samples have pyrolysis T_{max} in the range of 337–515°C, consistent with immature to post-mature stages. The T_{max} data also indicate that the Safer and Madbi shale samples have sufficient thermal maturity i.e., peak-mature of oil and gas window.

The basin models indicate that the Naifa Formation is early mature and the onset oil-generation began during the Early Miocene. The models also indicate that the main phase of oil-generation in the Safer source rock began during the Late Eocene. In contrast, the Madbi source rock units are passed the peak oil-generation window and the oil was converted to gas during the Late Cretaceous to Late Eocene. The modeled hydrocarbon expulsion history reveals that most of oils are contributed by both Madbi units, with significant amounts of gas originating from the Meem unit.

Keywords: Late Jurassic-Early Cretaceous; Organic-rich shale; Rock-Eval pyrolysis; petroleum generation modeling; Wadi Hajar sub-basin; Yemen

1. Introduction

The area of interest of this study is the Wadi Hajar sub-basin, forming the east-south part of the Sabatayn Basin (Fig. 1). The Sabatayn Basin is known by a variety of names, such as Sabatayn Basin, Marib-Shabowah-Hajar Basin (Beydoun et al. 1998) and Marib-Shabowah Basin (Brannin et al. 1999; Csato et al. 2001). The Sabatayn Basin is a Mesozoic sedimentary basin across the western Yemen (Fig. 1) that was formed as a result of rifting basin linked to the Mesozoic breakup of Gondwanaland (Redfern and Jones 1995).

The Sabatayn Basin contains proven commercial quantities of HCs (i.e., oil and gas), and has attracted the interest of numerous researchers, authors and oil companies (e.g., Brannin et al. 1999; Csato et al. 2001; Alaug et al. 2011; Hakimi and Abdullah 2013a, b; Hakimi et al. 2014; Hakimi and Abdullah 2015). All these publications have been done in north part of the Sabatayn Basin (i.e., Marib sub-basin). However, the Wadi Hajar sub-basin is one of the hydrocarbon exploration frontier regions in western Yemen where very few data are available for the adequate assessment of the hydrocarbon generation potential. The first drilled well in Wadi Hajar sub-basin is Mintaq-01 well, which was drilled by the Total Oil Company in early 1989. The Mintaq-01 well was reached the Precambrian basement rocks with total depth 3750 m (unpublished report). The oil and condensate shows are also discovered within the Madbi sandstone reservoir rock in the Mintaq-01 well (unpublished report). However, the Mintaq-01 well was chosen because the well are drilled to depths that penetrated a significant part of the Late Jurassic-Early

Cretaceous source rock units of interest, and have organic geochemical results. In this respect, the present study focuses on the evaluation of organic matter type, richness, thermal maturity and hydrocarbon generation potential of the thick Late Jurassic-Early Cretaceous organic-rich sedimentary rocks in this sub-basin. In addition, the results of source rock characterisation are incorporated into basin models in order to know and determine the timing of hydrocarbon generation and expulsion of the Late Jurassic-Early Cretaceous source rocks. This study is expected to provide further insight into the source rocks in the Wadi Hajar sub-basin, and responsible for further exploration success and resource assessment in the whole Sabatayn Basin.

2. Geologic setting

The Sabatayn Basin, onshore sedimentary basins, is situated in western Yemen (Fig. 1), which is developed as a rift-basin during the Late Jurassic–Early Cretaceous during the Mesozoic breakup of Gondwanaland and the evolution of the Indian Ocean (Redfern and Jones 1995). The main stratigraphy section of the Sabatayn Basin contains more than 4km of Jurassic to Tertiary in thickness (As-Saruri et al. 2010). Based on subsurface exploration wells and previous studies (e.g., As-Saruri et al. 2010), the Wadi Hajar sub-basin contains sedimentary rocks range from Jurassic to Tertiary time (Fig. 2). On top of the Precambrian basement rests the Kuhlan and Shuqra formations, which were deposited during Middle to Early Jurassic time (Fig. 2). The Kuhlan Formation includes fluvial and arkosic red beds that grade upward into the shallow-marine facies of Shuqra Formation, the latter represents the early transgressive sediments of the Late Jurassic (Beydoun et al. 1998). The sediments of the overlying Madbi Formation were deposited during the Kimmeridgian time (Beydoun et al. 1998). In the Sabatayn sub-basins, the

Madbi Formation has been divided into two members: Meem and Lam members (Oldest to youngest) (Fig.2). The Meem member consists of turbidite sandstones, shales and claystones (Fig.2). The upper Lam member is mostly organic-rich shale sediments (Fig.2). The sediments of Madbi Formation reflect a marine environment setting (Beydoun et al. 1998; Hakimi et al. 2012a, 2014). The Tithonian Sabatayn Formation is overlying the Madbi Formation, which was deposited during ocean circulation in the western part of Yemen (Beydoun et al. 1998). The Sabatayn Formation consists of thick sequence of clastic and evaporite sediments with interbedded shales (Fig. 2). The Alif Member is considered as the main reservoir for Jurassic petroleum system in the Marib-Shabowah sub-basin (JNOC, 2000 “personal communication”). The Safer Member constitutes an excellent seal to the underling Alif Member reservoir and contains interbedded organic-rich shales. The interbedded organic-rich shales are considered to be oil-source rock in the Marib sub-basin (Hakimi and Abdullah 2013a). The rifting system of the Sabatayn Basin continued during latest Jurassic to Early Cretaceous, but the subsidence showed down. This causes the deposition of shallow water carbonates, the Naifa Formation, lying conformably on top of the Sabatayn Formation (Fig. 2). During Early to Late Cretaceous, post-rift sediments accumulated in the basin forming the Saar, Qishn, Harshiyat/Fartaq, Mukalla, and Sharwyn formations. The earliest Cretaceous Saar Formation is composed mainly of limestone and dolomitic limestone with some mudstone and sandstone intercalations (Fig. 2). The Qishn Formation overlies the Saar Formation unconformably and can be divided into two members: (1) Qishn clastic member and (2) Qishn carbonate member (Beydoun et al. 1998). The Qishn clastic member is considered to be the main reservoir rock in the Masila Basin (King et al. 2003;

Hakimi et al. 2012b). The Late Cretaceous Harshiyat Formation is composed of mainly sandstones and interbedded shales, which were deposited in fluvial-deltaic to shallow marine setting (Beydoun et al. 1998), with vertical variations of thickness and lateral facies to the Fartaq Formation (Fig. 2). The Late Cretaceous Mukalla Formation is underlain conformably by Harshiyat/ Fartaq sediments, which is composed of sandstones and intercalated with shales and coal beds (Fig. 2). The Sharwyn Formation is composed of shallow marine limestones and marls (Fig. 2). In the Late Paleocene, sea level rose and resulted in the formation of transgressive shale deposits at the base of the Umm Er Radhuma carbonate Formation. The Umm Er Radhuma Formation continued to the Early Eocene and followed by anhydrite of the Jiza , Rus and Habshiyah formations (Fig. 2).

3. Samples and methods

A total of 260 cuttings samples of organic-rich shale intervals within the Late Jurassic-Early Cretaceous formations (40 samples from Naifa Formation, 16 samples from Safer Formation and 204 samples from Madbi Formation) were collected from Mintaq-01 well in the Wadi Hajar sub-basin of the Sabatayn Basin (Table 1). The drilling mud contaminated samples were water washed prior to geochemical analysis.

3.1. Organic geochemical analysis

Basic organic geochemical analysis (i.e., total organic carbon (TOC) content and Rock-Eval pyrolysis) is presented in this study. Organic geochemical analysis was conducted at Simon Petroleum Technology Limited Laboratories, United Kingdom, and the results provided by Petroleum Exploration and Production Authority (PEPA), Republic of Yemen (Personal communication).

The whole rock samples were crushed to powder and analysed by a LECO CS125 instrument that can provide measurements of the total organic carbon (TOC) content. The samples were subsequently screened by Rock Eval-II instrument, which were heated to 600°C in a helium atmosphere and several parameters such as free hydrocarbons (S_1) in the rock, remaining hydrocarbon generative potential, mg HC/g rock (S_2), and temperature of maximum pyrolysis yield (T_{max}) were measured. Hydrogen index (HI), production index (PI) and petroleum potential yield (PY) were subsequently calculated (Table 1).

Vitrinite reflectance measurements were also performed on polished block for some shale samples. Mean vitrinite reflectance (Ro%) was conducted on particles of vitrinite maceral that are not associated with strong bitumen staining using a microscope with white light source and oil immersion objectives. Typically, 20 measurements were made for each sample, but the low organic matter content limited the number of points counted in some samples.

3.2. Basin modeling procedure

In this study, Mintaq-01 well was chosen as a representative site to reconstruct the burial and thermal histories and to simulate the petroleum generation and expulsion of the Late Jurassic-Early Cretaceous source rocks in the Wadi Hajar sub-basin.

PetroMod 1-D (version 10.0 SP1) software developed by Schlumberger was used to reconstruct the burial and thermal history of the studied well. Subsequently, the maturity of the source rocks and the timing of HC generation and expulsion could be modelled. Good knowledge of the lithologies of the sedimentary section, their ages and periods of deposition and erosion are necessary for the evaluation of basin evolution (Lerche 1990).

The geologic model consisting of the depositional, non-depositional in absolute ages (Table 2), was compiled using stratigraphic data from well report and previous stratigraphy studies (e.g., Beydoun et al. 1998). In addition, the erosional events is also estimated and used to reconstruct the burial history. Based on the pervious works (e.g., Beydoun et al. 1998; As-Saruri et al. 2010) of the ideal stratigraphic section of the sedimentary basins of Yemen, there are three missing formations in the Mintaq-01 well (i.e., Saar, Sharwayn and Jiza formations). These formations were deposited during 140.2-136.4 Ma, 71.0-65.5 Ma and 58.7-43.2 Ma, respectively (Table 2). These three missing formations were considered as erosion events in the model (Table 2). However, the erosional thicknesses were estimated by the average depositional thicknesses of these missing formations from subsurface well data described by previous published works studies (Hakimi et al. 2010; Hakimi and Abdullah 2015). A total amount 500 m erosional thickness was considered in the model (Table 2).

The heat flow history is also needed as a basic input parameter, which was reconstructed based on the general tectonic evolution of the area of interest and finally fine-tuned to match the calibration data such as vitrinite reflectance and temperature data. Maturity of vitrinite was simulated using the EASY%Ro model by Sweeney and Burnham (1990).

4. Results and discussion

4.1. Source rock characteristics

Source rock characteristics were conducted by TOC content and Rock Eval-pyrolysis results (Fig. 3) to investigate the quantity and quality of organic matter, thermal maturity, and hydrocarbon generation potential of the Late Jurassic-Early Cretaceous organic-rich

shales in the Mintaq-01, Wadi Hajar sub-basin. The source rock properties i.e., total organic carbon (TOC) content and type of organic matter (kerogen) were used in basin modeling to simulate the hydrocarbon generation and expulsion history.

4.1.1. Source rock generative potential

The source rock generative potential of the Late Jurassic-Early Cretaceous shales was evaluated using total organic carbon (TOC) content and pyrolysis S_1 and S_2 yields (Table 1). The S_1 and S_2 yields together make up the petroleum potential yield; thus, the sum of these two parameters is referred to as PYs. However, the TOC values is usually used to estimate the organic richness of a sedimentary rock (Peters and Cassa 1994; Hunt 1995). The Late Jurassic-Early Cretaceous shale samples have low to high TOC content values (0.50–28.01 Wt. %), revealing fair to excellent source rocks (Fig. 4). The organic source rock generative potential was also evaluated from the amount of hydrocarbon yield (S_2) generated during pyrolysis process (Peters 1986; Bordenave 1993). The S_2 yields for the Late Jurassic-Early Cretaceous shale samples range from 0.15 to 158.86 mg HC/g rock (Table 1), thus are in agreement with TOC contents and considered to be a fair to excellent source generative potential (Fig. 5a). The Safer, Naifa and Lam source rock samples are higher generative potential than Meem source rock samples (Fig. 5a). In addition, the relationship between genetic petroleum potential yield (S_1+S_2) and total organic carbon (TOC) content also confirms that the majority samples of the Late Jurassic-Early Cretaceous have good genetic petroleum potential, with PY values more than 2.5 mg HC/g rock (Fig. 5b). The source rock characteristics of the Upper Jurassic Safer and Lam in this study are consistent with those of the Sabatayn and Lam source

rocks in the Tagina South-1 (Sachsenhofer et al. 2012), which is very close in location to the studied well.

4.1.2. Type of organic matter and petroleum generation potential

The organic matter type (kerogen) was characterized based on Rock Eval pyrolysis data, such as Hydrogen Index (HI). The Late Jurassic-Early Cretaceous source rock samples have HI values range between 8 and 738 mg HC/g TOC (Table 1). Based on kerogen classification HI versus $T_{\max}$ plot (Fig. 6), the Meem shale samples contain kerogen Type-III (Fig. 6), with HI values less than 200 mg HC/g TOC. In contrast, the Safer, Naifa and Lam shale samples contain Type I and II kerogens through Type II and III kerogens (Fig. 6), with HI values range from 76 to 738 mg HC/g TOC. Therefore, the Safer, Naifa and Lam shale samples would be expected to generate mainly oil and gas, consistent with kerogen Types I/II and II-III. The Meem shale samples with a dominant contribution of Type III kerogen would generate mainly gas, if mature.

4.1.3. Maturity of organic matter

The level of thermal maturity of organic matter in the Late Jurassic-Early Cretaceous source rock samples were evaluated based on Rock Eval pyrolysis $T_{\max}$ and production index (PI) data (Table 1). The Late Jurassic-Early Cretaceous source rock samples have Rock Eval pyrolysis $T_{\max}$ values between 337 and (Table 1). The Safer and Madbi units (Lam and Meem) samples have $T_{\max}$ values more than 430°C, and thus they are higher thermally mature than Naifa samples, and consistent with early mature to post mature stages (Fig. 6). However, the samples of Safer and Madbi source rock with lower $T_{\max}$ values (< 430 °C) may probably be due to the presence of migrated hydrocarbons (e.g., Peters 1986; Shalaby et al. 2012) or contamination of oil base mud (e.g., Peters 1986;

Issler et al. 2012). The migrated hydrocarbons are confirmed by high production index (PI) values (Fig. 7). Furthermore, the relationship between production index (PI) and $T_{\max}$ thermal maturity indicators reflects the same maturity levels of the organic matter. The Naifa samples are immature to early mature source rocks, while the Safer and Madbi units are thermally mature and generally within the petroleum generation stage (Fig. 7).

4.2. Basin modeling concept

4.2.1. Burial history modeling

The main parts of the 1D modeling results are burial and tectonic subsidence histories. The burial (subsidence) and thermal histories are necessary in order to predict timing of hydrocarbon generation and expulsion. The burial history was reconstructed based on stratigraphic descriptions taken from well report. Together with lithological information, which reveal the compaction behavior, back stirring can be performed to receive a burial history including decompacting (Table 2). The subsidence curves and basin history filling of the studied well are represented in Figure 8. The burial history illustrates that the pre-rift section associated with thin sediments while the syn-rift and post rift exhibit a thick sediments (Fig. 8).

The burial history demonstrates that there was an initial phase of slow subsidence in the pre-rift sedimentary rocks (163–155.7 Ma). The pre-rift phase includes Kuhlan and Shuqra formations and was characterized by low subsidence rates of about ~9m per million years leading to a present thickness of about 64m (Table 2). This period was followed by syn-rift phase with rapid subsidence during Late Jurassic to Early Cretaceous constituting the main rift phase (Table 2). The subsidence and sedimentation during the Late Jurassic to Early Cretaceous (~155.7 – ~145 Ma) are much higher (~201m per

million years), leading to a total thickness of ~2148 m. The overlying post-rift phase during Early Cretaceous to Tertiary (~145–24.9 Ma) were also characterized by relatively high sedimentation rates, resulted in deposition of thick sedimentary successions with a total thickness of 1489m. However, the overburden rocks of Early Cretaceous to Tertiary have an influence on syn-rift Madbi and Safer source rocks maturation and the petroleum generation can be expected around this time.

4.2.2. Heat flow and thermal history

The heat flow is crucial in the basin modeling and used to help reconstruction thermal maturity modeling. The heat flow of sedimentary basins can be evaluated based on the tectonic evolution and rifting phase (Lachenbruch 1970; Allen and Allen 1990). The rifting history influences heat flow. A higher heat flow is incorporated into episodes during the rifting phase and an exponential reduction in heat flow is considered during the post-rift phase (Mckenzie 1978). The palaeo-heat flow models are usually calibrated with thermal maturity data such as vitrinite reflectance measurements (e.g., Welte and Yukler 1981, 1987; Poelchau et al. 1997; He and Middleton 2002; Li et al. 2010; Hakimi et al. 2010; Shalaby et al. 2011, 2013). Moreover, the present-day heat flow can also be estimated from thermal conductivities of the rock units and subsurface geothermal gradients, which are determined from corrected bottom hole temperatures (BHT) (e.g., Abdalla et al. 1999).

In this study, the heat flow is estimated using the regional heat flow in the north part of the Sabatayn Basin (Marib sub-basin) as indicated by earlier works of Hakimi and Abdullah (2015). Hakimi and Abdullah (2015) were estimated the heat flow is in the range of 60-95+ mW/m². The present day heat flow was inferred from fair to good

matching between corrected bottom hole temperature and modeled (calculated) temperature curves (Fig. 9). The present-day geothermal suggests heat flow may currently be (60 mW/m²) at Mintaq-01 well (Fig. 10c). The paleo-heat flow was the result of the fit between measured and modeled vitrinite reflectance profile. A very good correlation between measured and calculated % Ro values implies that the thermal model is valid for this study area (Fig. 10b) and indicate that the heat flow increased from background values (60 mW/m²) during the initial phase (155.7 Ma) of syn-rifting stage in the basin and reached peak heat-flow values of approximately 97.0 mW/m² at 150 Ma (Fig. 10c). This peak is related to the initial rifting event starting the basin development (Late Jurassic time; Redfern and Jones 1995). These heat flow values (60-97 mW/m²) were applied and considered for the maturity modeling of the source rocks in this study (Fig. 10a).

4.2.3. Maturity history modeling of the source rocks

The maturation history was used to determine the time when the source rocks passed through the oil window maturity. The modeled maturity history of the Late Jurassic-Early Cretaceous source rocks reflects that the hydrocarbon generation history of the source rocks are different because of variation in their thermal and burial histories (Fig. 10a).

The Naifa source rock is still in the early-mature stage of oil generation (0.55 %Ro), which was reached during the Miocene time at 21 Ma (million years ago) (Fig. 10a). The Safer source rock has entered the early-mature of oil window during the Late Eocene (41 Ma) and the peak oil-generation was reached during the Late Oligocene at 27 Ma (Fig. 10a). In contrast, the oil generation stages of the Madbi source rock units (Meem and Lam) began during earlier time due to the high levels of thermal maturity

(Fig. 10a). These higher levels of maturity of the Madbi source rock were probably attribute to the buried histories (Fig. 10a).

In the Lam unit, the source rock was reached the early-mature stage of oil generation during the Cretaceous (140-90 Ma) (Fig. 10a). The peak oil-generation of the Lam source rock unit was started during the Eocene (53 Ma), with computed vitrinite reflectance values of 0.70 %Ro (Fig. 10a). Furthermore, the late oil generation was also occurred during the Eocene at 30 Ma and continued to the present-day, with vitrinite reflectance values between 1.0 and 1.13 Ro% (Fig. 10a). Compared with Lam unit, the peak and late oil generation window of the Meem source rock have reached earlier time during the Late Cretaceous (98Ma) and the Early Eocene (50 Ma), respectively (Fig. 10a). These higher levels of maturity of the Meem source rock were probably due to the thermal and buried histories. Moreover, the gas window of the Meem source rock was also reached during the Late Eocene (37 Ma), and continued to present-day (Fig. 10a).

4.2.4. Timing of hydrocarbon generation and expulsion from source rocks

The timing of hydrocarbon generation and expulsion from Late Jurassic-Early Cretaceous source rocks were analysed based on maturation history using an assumed 10% transformation ratio (Figs. 11 and 12). The hydrocarbon generation and expulsion stages were also calculated using difference reaction kinetics data based on source rock parameters (i.e., HI and TOC). The modeled hydrocarbon generation and expulsion history of the Late Jurassic-Early Cretaceous source rocks in the studied well shows difference of HC (i.e., oil and gas) products because of variation in transformation ratios (TR) and reaction kinetic data (Figs. 11 and 12).

The Naifa Formation is still a very early-mature source rocks, therefore, the oil has not yet generated (Fig. 11a). This is due to its lower thermal maturity with transformation ratio (TR) less than 10% (Fig. 11b).

The kerogen type in the Safer source rock is Type II-S kerogen as indicated from: (1) very low Pr/Ph ratios (Hakimi and Abdullah 2013a), (2) high sulfur contents; (3) low maturity level of generated oil (Hakimi and Abdullah 2013b), (4) association Safer shale source rock with evaporite deposits (Fig. 2). Therefore, the hydrocarbon generation history of the Safer source require a special kinetic model (i.e., Type II-S kerogen reaction kinetic data). Based on the maturity and reaction kinetic data of the Safer source rock, the hydrocarbon generation and expulsion history model can be divided into two stages (Fig. 11). The first stage of hydrocarbon generation was occurred during the Late Eocene (approximately 38-35 Ma). This stage is the early phase of oil-generation, with TR between 10% and 25% (Fig. 11b). The second stage (approximately 35-5 Ma) is the main phase of oil-generation. In this stage, the TR ranges from 25% to 50% (Fig. 11b), with computed VR in the range of 0.63-0.73 %Ro. Therefore, the Safer oil is an early generated product from a high S- kerogen. The limited oil also expelled during this stage because of significant amounts of oil-generation, with TR more than 50%. (Fig. 11b). This is supported by the presence of expelled and migrated hydrocarbon within the Safer source rock samples as indicated by high PI values (Fig. 7).

In the Madbi source rock units (i.e., Meem and Lam), hydrocarbon generated and expelled in the earlier time due to their deeper burial depth (2329-3647m). However, the hydrocarbon generation history of the Madbi source rock units was modelled based on a

Type II kerogen gradient to type II-III kerogen kinetic model (i.e., IES Kimmeridge Clay kinetic model).

The hydrocarbon generation and expulsion history from Meem source rock unit began earlier compared to Lam source rock unit because the higher maturity levels of the Meem unit compared to Lam unit. The hydrocarbon generation and expulsion history were modeled as four main stages (Fig. 12). The first stage (approximately 98-61 Ma) is the early phase of oil generation without any expulsion (Fig. 12a). The TR of this stage ranges between 10% and 25% (Fig. 12b). The second stage was occurred at 61-42 Ma, which represents the main phase of oil generation and significant amount of gas was generated (Fig. 12a), with calculated TR and VR values in the range of 25% to 50% and 0.85-1.09 % Ro, respectively (Fig. 12b). The oil was also expelled during this stage, with TR more than 50%. The main stage of oil expulsion was reached between 42 and 30 Ma, with increased TR from 50% to 81% (Fig. 12b). The last stage was started during the Oligocene time (30 Ma) and continued to present day (Fig. 12a). The significant gas was expelled from the Meem source rock unit during this stage, with TR ratio of the range 81%-95% (Fig. 12b). In contrast, the oil generation and expulsion model of the Lam source rock unit were modeled in three main phases (Fig. 12). The Lam source rock starts generating oil during the Eocene (approximately 55-37 Ma) (Fig. 12a), with TR of the range 10%-25% (Fig. 12b). The main phase of oil generation was reached at approximately 37-26 Ma, with TR values between 25% and 50% (Fig. 12b). The gas generation can also be expected in this stage from reaching the maximum transformation ratio (TR > 40%) and calculated VR of the range 0.86-1.10 % Ro. In the last phase, the significant oil was expelled from Lam source rock during the Late Oligocene (26 Ma) to

present-day with TR value more than 50% (Fig. 12b). Looking at the amount and phase of expelled hydrocarbons from the Madbi source rock units reveal quickly that significant oil and gas were expelled so that a successful charge of any nearby prospect is likely. This is in agreement with the presence of oil and condensate shows exist along the Madbi reservoir rocks as confirmed by the drilling activity in the Mintaq-01 well (unpublished report). The hydrocarbon generation modeling in this study is also compared to the previous study (i.e., Sachsenhofer et al. 2012). Sachsenhofer et al. (2012) have modeled the hydrocarbon generation history of the Upper Jurassic source rocks in the Tagina South-1 well, Sabatayn Basin. The Tagina South-1 well is very close in location to the studied Mintaq-01 well. They suggested that the major hydrocarbon generation of the Upper Jurassic source rocks (i.e., Safer and Lam) occurred during both, Late Cretaceous and Eocene–Oligocene times. These results are similar with the modeling results in this study, which are indicated that the Upper Jurassic source rocks (i.e., Safer and Lam) began generated hydrocarbons during Late Cretaceous to Late Eocene.

5. Conclusions

Late Jurassic-Early Cretaceous organic-rich shales of the Naifa, Safer and Madbi formations from Mintaq-01 well in the Wadi Hajar sub-basin were analysed for organic geochemistry of whole rock (i.e., total organic carbon content and Rock-Eval pyrolysis) and the results were then incorporated into basin modeling. The results obtained in this study give a strong indication as follows:

- 1- The Late Jurassic-Early Cretaceous organic-rich shales are potentially important petroleum source rocks. . They have low to high organic matter with TOC values in the range of 0.50-28.01 wt. %, indicating fair to excellent source rock potential.

However, the Late Jurassic Safer and Madbi source rocks are relatively higher in genetic petroleum potential.

- 2- The shale samples of the Naifa, Safer and Lam contain Type I/II and II-III kerogens with HI values in the range of 76 -738 mg HC/g TOC, which can be expected to generate mainly oil and gas HCs. In contrast, the Meem source rock contains Type III kerogen with HI values less than 200 mg HC/g TOC and considered to generate gas.
- 3- Maturity data such as Rock Eval pyrolysis T_{max} and PI show that the Naifa source rock samples are thermally immature to early-mature, while the Safer and Madbi (i.e., Lam and Meem units) samples are early-mature to post-mature source rocks.
- 4- The basin models indicate that the Safer and Madbi formations are an effective oil-source rocks in the Wadi Hajar sub-basin. The oil was early generated from Safer source rock during the Late Eocene time (35 Ma). In contrast, the peak of oil-generation of the Madbi units (Meem and Lam) was passed in the earlier time (Early Eocene and Early Oligocene, respectively), and the oil was converted to gas from Meem unit during the Late Eocene time.
- 5- The modeled hydrocarbon expulsion suggests that the timing of hydrocarbon expulsion from the Madbi units began in the Late Eocene and persisted to present-day, with mainly oil contributed by both Madbi units and significant amounts of gas from the Meem unit. Therefore, the hydrocarbon exploration processes should be focused on the known kitchen area location of the Late Jurassic Safer, Lam and Meem stratigraphic successions.

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Figure captions

Figure 1. Location map of the main sedimentary basins in Republic of Yemen (modified after Beydoun et al., 1998;), showing location of the Wadi Hajar sub-basin including studied well.

Figure 2. Stratigraphic column for the Wadi Hajar sub-basin based on subsurface exploration wells and pervious published by As-Saruri et al. (2010).

Figure 3. Organic geochemical log of the Late Jurassic-Early Cretaceous source rock samples in the studied well (Mitaq-01) according to Rock-Eval pyrolysis and TOC content results.

Figure 4. Distribution of total organic carbon (TOC) versus depth (meter) for Late Jurassic-Early Cretaceous formations, showing most of the samples plot in fair to excellent source rocks.

Figure 5. Relationship between (a) total organic matter (TOC) content versus remaining hydrocarbon potential (S_2) and (b) petroleum potential yield (PY) for the analysed Late Jurassic-Early Cretaceous formations.

Figure 6. Plot of hydrogen index (HI) versus pyrolysis $T_{\max}$, showing kerogen quality of the samples from Late Jurassic-Early Cretaceous formations in the Wadi Hajar sub-basin.

Figure 7. Cross-plot of pyrolysis $T_{\max}$ versus production index (PI), showing the maturation and nature of the hydrocarbon products of the samples from Late Jurassic-Early Cretaceous formations in the investigated well (Mintaq-01), Wadi Hajar sub-basin.

Figure 8. Burial history for 1-D model reconstructed for the Mintaq-01 well location in the Wadi Hajar sub-basin

Figure 9. (A) Burial and temperature histories reconstructed for the Mintaq-01 well location calibrated to present day corrected bottom-hole temperature data (B).

Figure 10. (A) Burial and thermal maturity histories reconstructed for the Mintaq-01 well location calibrated to vitrinite reflectance data (B) using site specific heat flow histories (C).

Figure 11. (a) 1-D model extraction of cumulative hydrocarbon generation and expulsion from the Naifa and Safer source rocks in the Mintaq-01 well. (b) Evolution of the transformation ratio through time for the Naifa and Safer source rocks of the same 1-D model.

Figure 12. (a) 1-D model extraction of cumulative hydrocarbon generation and expulsion from the Madbi source rock units (Lam and Meem) in the Mintaq-01well. (b) Evolution of the transformation ratio through time for the Madbi source rock units of the same 1-D model.

Draft

290x169mm (300 x 300 DPI)

207x256mm (300 x 300 DPI)

429x258mm (300 x 300 DPI)

198x137mm (300 x 300 DPI)

204x285mm (300 x 300 DPI)

169x191mm (300 x 300 DPI)

178x134mm (300 x 300 DPI)

457x223mm (300 x 300 DPI)

598x224mm (300 x 300 DPI)

Draft

489x285mm (300 x 300 DPI)

554x353mm (300 x 300 DPI)

558x348mm (300 x 300 DPI)

Table 1

Rock-Eval pyrolysis and TOC content results with calculated parameters of the Late Jurassic-Early Cretaceous source rocks in the Mintaq-01 well of the Wadi Hajar sub-basin, Yemen.

Wells	Age	Formations	Depth (m)	TOC Wt. %	Rock-Eval pyrolysis						
					S ₁ (mg/g)	S ₂ (mg/g)	T _{max} (°C)	HI (mg/g)	PY (mg/g)	PI (mg/g)	
Mintaq -01	Early Cretacouse-Late Jurassic	Late Tithonian–Berriasian	Naifa Formation	1340	2.25	0.19	9.68	410	430	9.87	0.02
				1352	4.59	1.25	31.17	421	679	32.42	0.04
				1353	18.22	16.72	128.63	426	706	145.35	0.13
				1356	3.13	0.80	20.00	420	639	20.80	0.04
				1360	2.34	0.40	13.48	422	576	13.88	0.03
				1364	1.18	0.17	5.75	420	487	5.92	0.03
				1368	0.77	0.13	2.54	424	330	2.67	0.05
				1376	1.33	0.15	7.38	425	555	7.53	0.02
				1384	1.28	0.14	7.07	426	552	7.21	0.02
				1388	2.33	0.30	14.80	423	635	15.10	0.02
				1392	2.90	0.43	21.40	423	738	21.83	0.02
				1396	1.30	0.16	7.76	424	597	7.92	0.02
				1399	1.47	0.14	4.72	439	321	4.86	0.03
				1400	1.15	0.14	6.87	424	597	7.01	0.02
				1404	1.90	0.25	12.29	425	647	12.54	0.02
				1408	1.56	0.19	9.39	426	602	9.58	0.02
				1412	0.68	0.07	3.25	432	478	3.32	0.02
				1416	1.13	0.14	6.81	424	603	6.95	0.02
				1420	1.69	0.20	10.12	422	599	10.32	0.02
				1424	0.85	0.07	3.55	432	418	3.62	0.02
				1432	1.27	0.15	7.26	428	572	7.41	0.02
				1434	2.50	0.58	14.50	432	580	15.08	0.04
				1436	0.66	0.05	2.44	432	370	2.49	0.02
				1440	0.95	0.10	4.77	426	502	4.87	0.02
				1448	0.55	0.08	2.55	433	464	2.63	0.03
				1452	1.15	0.21	6.93	429	603	7.14	0.03
				1456	0.58	0.11	2.69	429	464	2.80	0.04
				1460	0.62	0.13	3.26	432	526	3.39	0.04
				1464	0.50	0.16	2.31	432	461	2.47	0.07
				1470	0.73	0.28	3.98	432	545	4.26	0.07
				1476	0.52	0.18	2.64	432	508	2.82	0.07
				1486	0.50	0.21	2.09	418	418	2.30	0.10
				1496	1.60	0.79	6.58	430	411	7.37	0.12
				1522	0.63	0.30	3.35	434	531	3.65	0.09
				1526	1.06	0.38	5.46	435	515	5.84	0.07
				1530	1.23	0.40	6.73	432	547	7.13	0.06
				1533	2.50	0.53	3.75	432	150	4.28	0.14
				1534	1.06	0.47	5.83	435	550	6.30	0.08
				1538	1.44	0.57	6.35	434	441	6.92	0.09
				1541	1.07	0.63	4.84	433	452	5.47	0.13

Wells	Age		Formations	Depth (m)	TOC Wt. %	Rock-Eval pyrolysis						
						S ₁ (mg/g)	S ₂ (mg/g)	T _{max} (°C)	HI (mg/g)	PY (mg/g)	PI (mg/g)	
Mintaq -01	Late Jurassic	Tithonian	Safer Formation	1546	1.05	0.74	4.62	440	440	5.36	0.16	
				1550	1.11	0.68	3.79	435	341	4.47	0.18	
				1566	0.82	0.14	1.80	436	219	1.94	0.08	
				1699	4.32	3.97	9.03	433	209	13.00	0.44	
				1705	1.53	1.20	2.45	439	160	3.65	0.49	
				2168	2.80	2.51	13.92	439	497	16.43	0.18	
				2172	2.13	2.17	9.05	435	425	11.22	0.24	
				2174	1.66	1.94	7.17	438	432	9.11	0.27	
				2178	0.51	0.41	1.36	438	267	1.77	0.30	
				2190	0.63	0.58	1.39	433	221	1.97	0.42	
				2195	0.60	0.35	0.76	434	127	1.11	0.46	
				2332	2.10	1.04	9.43	434	449	10.47	0.11	
				2334	4.58	2.53	23.04	430	503	25.57	0.11	
				2336	2.41	1.28	10.63	433	441	11.91	0.12	
				2338	2.69	1.19	14.85	434	552	16.04	0.08	
				2340	0.95	0.40	2.64	439	278	3.04	0.15	
	Late Jurassic	Kimmeridgian	Madbi Formation	Lam unit	2342	3.05	1.37	13.73	431	450	15.10	0.10
					2344	3.57	1.72	19.14	430	536	20.86	0.09
					2346	1.48	0.76	5.83	438	394	6.59	0.13
					2348	1.06	0.45	4.54	437	428	4.99	0.10
					2350	1.31	0.50	4.17	435	318	4.67	0.12
					2352	1.14	0.40	4.43	430	389	4.83	0.09
					2354	0.86	0.33	1.96	438	228	2.29	0.17
					2356	1.04	0.32	3.50	432	337	3.82	0.09
					2358	1.13	0.40	2.85	438	252	3.25	0.14
					2360	13.36	11.98	57.05	437	427	69.03	0.21
					2362	1.56	0.25	2.46	445	158	2.71	0.10
					2364	0.73	0.21	1.91	437	262	2.12	0.11
					2365	9.29	5.22	32.61	436	351	37.83	0.16
					2368	6.23	3.58	21.06	436	338	24.64	0.17
					2370	0.94	0.55	4.22	440	449	4.77	0.13
					2371	0.94	0.57	4.08	442	434	4.65	0.14
					2372	4.61	1.50	16.64	435	361	18.14	0.09
					2376	2.72	0.42	13.93	437	512	14.35	0.03
					2380	1.97	0.39	7.78	436	395	8.17	0.05
					2385	0.58	0.91	1.65	430	284	2.56	0.55
2387	7.47	2.48	35.41	434	474	37.89	0.07					
2387	28.01	9.41	156.86	445	560	166.27	0.06					
2388	10.34	3.71	61.83	434	598	65.54	0.06					
2388.5	1.16	2.10	4.03	432	347	6.13	0.52					
2389	2.26	1.08	12.02	440	532	13.10	0.09					

Wells	Age	Formations	Depth (m)	TOC Wt. %	Rock-Eval pyrolysis							
					S ₁ (mg/g)	S ₂ (mg/g)	T _{max} (°C)	HI (mg/g)	PY (mg/g)	PI (mg/g)		
Mintaq -01	Late Jurassic	Kimmeridgian	Madbi Formation	Lam unit	2390	0.74	0.34	2.85	441	385	3.19	0.12
					2396	0.82	0.18	1.64	439	200	1.82	0.11
					2400	1.16	0.37	3.71	442	320	4.08	0.10
					2404	1.14	0.34	3.41	440	299	3.75	0.10
					2408	1.56	0.42	5.30	439	340	5.72	0.08
					2416	1.12	0.47	3.60	442	321	4.07	0.13
					2420	2.01	1.09	7.78	443	387	8.87	0.14
					2424	0.96	0.41	2.91	443	303	3.32	0.14
					2432	1.90	0.61	7.62	441	401	8.23	0.08
					2436	1.19	0.39	4.30	440	361	4.69	0.09
					2440	0.92	0.30	3.35	441	364	3.65	0.09
					2444	1.49	0.52	5.80	442	389	6.32	0.09
					2448	1.56	0.62	6.22	443	399	6.84	0.10
					2456	1.27	0.62	3.85	444	303	4.47	0.16
					2458	1.52	0.49	6.13	442	403	6.62	0.08
					2476	1.04	0.32	2.70	441	260	3.02	0.12
					2488	1.23	0.46	4.17	440	339	4.63	0.11
					2492	2.18	0.34	5.60	438	257	5.94	0.06
					2496	1.25	0.24	4.08	445	326	4.32	0.06
					2516	1.39	0.38	3.16	441	227	3.54	0.12
					2522	13.31	7.64	84.92	428	638	92.56	0.09
					2526	1.40	0.29	2.44	430	174	2.73	0.12
					2546	0.75	0.25	2.50	440	333	2.75	0.10
					2550	1.42	0.57	4.77	443	336	5.34	0.12
					2554	2.32	0.87	7.93	438	342	8.80	0.11
					2574	0.59	0.17	0.45	434	76	0.62	0.37
					2578	0.53	0.26	0.65	444	122	0.91	0.40
					2587	0.52	0.75	1.49	400	286	2.24	0.50
					2589	0.57	0.93	2.07	407	363	3.00	0.45
					2594	5.03	8.51	21.28	418	423	29.79	0.40
					2595	0.69	0.10	2.05	442	297	2.15	0.05
					2596	2.02	0.38	7.62	430	377	8.00	0.05
					2599	3.74	1.20	20.08	441	537	21.28	0.06
					2603	1.43	0.39	2.43	443	170	2.82	0.16
					2608	1.13	0.16	2.71	444	240	2.87	0.06
					2620	3.12	0.97	10.76	439	345	11.73	0.09
					2624	0.87	0.15	1.85	441	213	2.00	0.08
					2628	1.51	0.26	4.35	439	288	4.61	0.06
					2640	1.78	0.55	6.89	440	387	7.44	0.08
					2644	1.10	0.28	2.77	445	252	3.05	0.10
					2664	1.30	0.45	3.71	442	285	4.16	0.12
					2676	3.47	1.24	10.31	441	297	11.55	0.12
					2680	1.95	0.73	4.29	446	220	5.02	0.17

Wells	Age		Formations		Depth (m)	TOC Wt. %	Rock-Eval pyrolysis					
							S ₁ (mg/g)	S ₂ (mg/g)	T _{max} (°C)	HI (mg/g)	PY (mg/g)	PI (mg/g)
Mintaq -01	Late Jurassic	Kimmeridgian	Madbi Formation	Lam unit	2684	1.89	0.82	5.10	446	270	5.92	0.16
					2686	2.02	0.94	5.23	446	259	6.17	0.18
					2692	1.70	0.71	3.93	449	231	4.64	0.18
					2696	2.22	0.93	6.66	447	300	7.59	0.14
					2700	3.81	1.23	15.32	439	402	16.55	0.08
					2708	1.65	0.56	5.59	441	339	6.15	0.10
					2712	1.99	0.59	5.35	443	269	5.94	0.11
					2716	2.49	1.05	7.52	448	302	8.57	0.14
					2742	3.89	1.32	11.01	441	283	12.33	0.12
					2746	0.90	0.34	1.89	449	210	2.23	0.18
					2750	1.28	0.44	4.43	446	346	4.87	0.10
					2758	1.37	0.62	3.26	447	238	3.88	0.19
					2762	1.64	0.72	3.77	447	230	4.49	0.19
					2766	1.23	0.49	2.87	448	233	3.36	0.17
					2778	2.66	1.26	6.30	448	237	7.56	0.20
					2782	2.68	1.18	7.85	445	293	9.03	0.15
					2786	3.07	1.23	9.49	446	309	10.72	0.13
					2806	2.05	0.73	5.60	446	273	6.33	0.13
					2810	2.62	0.86	7.81	445	298	8.67	0.11
					2814	1.13	0.44	3.38	443	299	3.82	0.13
					2818	2.22	0.81	5.79	448	261	6.60	0.14
					2822	3.39	1.53	8.07	447	238	9.60	0.19
					2826	2.99	1.26	7.86	448	263	9.12	0.16
					2830	3.21	1.37	8.03	448	250	9.40	0.17
					2834	3.06	1.36	8.48	448	277	9.84	0.16
					2838	3.14	1.21	7.57	448	241	8.78	0.16
					2842	2.90	1.25	6.96	448	240	8.21	0.18
					2846	2.47	0.97	5.38	449	218	6.35	0.18
					2850	1.09	0.35	2.20	452	202	2.55	0.16
					2864	6.64	1.20	17.20	443	259	18.40	0.07
					2866	3.30	0.54	10.76	448	326	11.30	0.05
					2868	3.44	0.48	12.04	445	350	12.52	0.04
					2870	1.66	0.35	5.00	448	301	5.35	0.07
					2872	1.14	0.21	2.31	451	203	2.52	0.09
					2876	2.96	0.58	7.28	441	246	7.86	0.08
					2880	1.51	0.55	3.94	448	261	4.49	0.14
					2885	2.82	1.29	6.15	449	218	7.44	0.21
					2886	4.32	1.83	10.76	449	249	12.59	0.17
					2888	5.09	1.83	11.45	451	225	13.28	0.16
					2892	3.42	1.36	8.52	454	249	9.88	0.16
					2900	2.40	0.64	6.36	447	265	7.00	0.10
					2908	2.98	1.20	6.68	450	224	7.88	0.18
					2912	3.36	1.61	8.06	450	240	9.67	0.20
					2916	3.44	1.33	7.40	448	215	8.73	0.18
					2938	2.04	0.83	5.20	438	255	6.03	0.16
					2940	4.76	1.25	13.52	449	284	14.87	0.10
					2984	6.70	1.26	25.19	432	376	26.45	0.05

Wells	Age	Formations	Depth (m)	TOC Wt. %	Rock-Eval pyrolysis							
					S ₁ (mg/g)	S ₂ (mg/g)	T _{max} (°C)	HI (mg/g)	PY (mg/g)	PI (mg/g)		
Mintaq -01	Late Jurassic	Kimmeridgian	Madbi Formation	Mem unit	2992	1.04	0.27	1.09	461	105	1.36	0.25
					2996	3.20	0.98	3.26	461	102	4.24	0.30
					3000	2.92	0.91	2.60	462	89	3.51	0.35
					3004	2.86	0.80	2.17	452	76	2.97	0.37
					3008	1.76	0.42	1.20	466	68	1.62	0.35
					3010	2.32	0.40	1.32	454	57	1.72	0.30
					3016	1.88	0.22	0.64	492	34	0.86	0.34
					3020	1.04	0.10	0.26	502	25	0.36	0.40
					3024	1.86	0.20	0.61	495	33	0.81	0.33
					3028	1.76	0.11	0.18	515	10	0.29	0.60
					3032	2.14	0.46	3.06	433	143	3.52	0.15
					3052	1.29	0.40	0.85	464	66	1.25	0.47
					3060	1.43	0.64	1.10	445	77	1.74	0.58
					3108	1.42	0.52	0.77	459	54	1.29	0.67
					3112	1.23	0.28	0.62	483	50	0.90	0.45
					3116	1.17	0.34	0.96	462	82	1.30	0.35
					3120	1.96	0.47	1.00	445	51	1.47	0.47
					3124	2.43	0.26	0.39	337	16	0.65	0.67
					3128	2.14	0.15	0.32	406	15	0.47	0.48
					3132	1.83	0.09	0.15	444	8	0.24	0.61
					3136	2.43	0.24	0.39	490	16	0.63	0.61
					3142	1.83	0.30	0.59	476	32	0.89	0.50
					3146	2.49	0.51	0.92	475	37	1.43	0.55
					3148	1.74	0.39	0.77	478	44	1.16	0.50
					3152	1.86	0.37	0.71	478	38	1.08	0.52
					3156	2.70	0.54	1.19	480	44	1.73	0.45
					3160	2.30	0.38	0.71	472	31	1.09	0.53
					3164	2.14	0.25	0.43	487	20	0.68	0.59
					3168	2.31	0.28	0.49	485	21	0.77	0.57
					3172	1.33	0.14	0.23	469	17	0.37	0.63
					3180	1.47	0.34	0.82	465	56	1.16	0.41
					3184	2.04	0.35	0.84	475	41	1.19	0.42
					3188	1.04	0.25	0.61	478	59	0.86	0.41
					3196	1.15	0.19	0.44	472	38	0.63	0.44
					3204	2.07	0.46	0.79	365	38	1.25	0.58
					3208	2.14	0.44	0.75	350	35	1.19	0.59
					3212	2.86	0.65	1.09	358	38	1.74	0.60
					3216	4.09	1.28	2.41	467	59	3.69	0.53
					3220	4.43	1.84	4.08	463	92	5.92	0.45
					3224	4.36	2.22	5.28	449	121	7.50	0.42
					3228	3.53	1.76	4.09	447	116	5.85	0.43
					3232	3.59	1.84	4.60	449	128	6.44	0.40
					3236	3.26	1.78	4.69	447	144	6.47	0.38
					3240	2.25	1.18	2.88	448	128	4.06	0.41
					3244	3.23	1.73	4.65	449	144	6.37	0.37

Wells	Age		Formations		Depth (m)	TOC Wt. %	Rock-Eval pyrolysis					
							S_1 (mg/g)	S_2 (mg/g)	T_{max} (°C)	HI (mg/g)	PY (mg/g)	PI (mg/g)
Mintaq -01	Late Jurassic	Kimmeridgian	Madbi Formation	Mem unit	3248	2.97	1.75	4.99	448	168	6.74	0.35
					3252	3.01	1.58	4.79	450	159	6.37	0.33
					3256	2.67	1.44	4.01	451	150	5.45	0.36
					3260	2.40	1.36	4.25	453	177	5.61	0.32
					3260	2.02	1.12	2.87	450	142	3.99	0.39
					3270	1.79	0.97	2.86	451	160	3.83	0.34
					3274	1.92	0.91	2.59	450	135	3.50	0.35
					3276	2.36	0.99	3.66	455	155	4.65	0.27
					3282	1.98	0.79	2.81	451	142	3.60	0.28
					3286	2.85	1.06	4.08	454	143	5.14	0.26
					3290	2.69	0.95	3.66	453	136	4.61	0.26
					3454	1.10	0.34	1.16	459	105	1.50	0.29
					3462	1.12	0.44	1.20	456	107	1.64	0.37
					3466	1.47	0.50	1.68	459	114	2.18	0.30
					3472	1.49	0.50	1.56	460	105	2.06	0.32
					3474	1.66	0.60	2.01	459	121	2.61	0.30
					3480	1.36	0.46	1.48	457	109	1.94	0.31
					3484	2.04	0.79	2.73	461	134	3.52	0.29
					3488	2.17	0.85	2.73	459	126	3.58	0.31
					3492	2.06	0.81	2.37	459	115	3.18	0.34
					3496	2.18	0.81	2.79	455	128	3.18	0.35
					3500	2.37	0.98	3.03	455	128	3.77	0.33
					3504	2.30	1.00	2.81	456	122	4.03	0.34
					3508	2.34	0.96	2.48	459	106	3.77	0.36
					3512	2.53	0.89	2.68	454	106	3.37	0.35
					3516	2.50	0.94	2.83	456	113	3.62	0.36
					3520	2.59	1.02	2.90	455	112	3.85	0.36
					3524	2.64	1.04	2.82	449	107	3.94	0.21
					3528	3.16	0.59	3.60	456	114	3.41	0.35
					3532	2.81	1.26	2.84	456	101	4.86	0.34
					3540	2.44	0.97	2.39	457	98	3.81	0.31
					3544	1.60	0.74	1.62	454	101	3.13	0.34
					3548	1.73	0.55	1.78	456	103	2.17	0.32
					3552	1.56	0.57	1.15	460	74	2.35	0.38
					3556	1.52	0.44	1.28	459	84	1.59	0.37
					3562	1.76	0.47	1.55	410	88	1.75	0.34
					3566	1.20	0.53	1.24	443	103	2.08	0.34
					3570	1.10	0.42	1.02	445	93	1.66	0.34
					3574	1.49	0.35	1.27	441	85	1.37	0.37
					3576	2.40	0.47	1.75	444	73	1.74	0.49
					3578	1.67	0.86	1.74	461	104	2.61	0.37
					3586	1.29	0.64	1.23	456	95	2.38	0.35
					3590	1.03	0.43	0.56	460	54	1.66	0.46

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

T_{max} : Temperature at maximum of S_2 peak

HI: Hydrogen Index = $S_2 \times 100 / \text{TOC}$, mg HC/ g TOC

PI: Production Index = $S_1 / (S_1 + S_2)$

PY: Potential Yield = $S_1 + S_2$ (mg/g)

Table 2

Basin model input data used to reconstruct the burial history for studied well (Mintaq-01), Wadi Hajar sub-basin, Yemen.

Tectonic events	Formations	Deposition age		Erosion age		Erosion (m)	Calibration data		Lithology	Mintaq-01 well		
		From (Ma)	To (Ma)	From (Ma)	To (Ma)		VRo (%)	Temperature (°C)		Top (m)	Bottom (m)	Thickness (m)
Sediments surface		24.9	0						Recent sediments	0.0	10	10
Post-rift	Habshiyah	40.6	24.9						Limestone & Shale & Dolomite	10	43	33
	Rus	43.2	40.6						Evaporite & Dolomite	43	217	174
	Jiza			58.7	43.2	100			Evaporite & Shale	-----	-----	-----
	Umm Er Radhuma	65.5	58.7						Limestone and interbedded shale	217	453	236
	Sharwayn			71.0	65.5	150			Sandstones & Shale and carbonates	-----	-----	-----
	Mukalla	93.5	71.0				0.38-0.40 (R _o %)		Sandstone & Shale & Coal	453	1050	597
	Harshiyat/ Fartaq	112	93.5				0.48-0.53 (R _o %)	1190 m-55°C	Sandstones and shale interbedded	1050	1259	209
	Qishn	136.4	112				0.55-0.56 (R _o %)		Sandstones and carbonates	1259	1337	78
	Saar			140.2	136.4	250			Limestone & Shale & Dolomite & Sandstone	-----	-----	-----
	Naifa	146.3	140.2				-----		Limestone and shales	1337	1549	212
Syn-rift	Safer	148.0	146.3				-----		Sandstones, shales and evaporites	1549	2329	780
	Upper Madbi (Lam)	150.8	148.0				0.55-0.79 (R _o %)	2450 m-95°C	Organic-rich shales and sandstones	2329	2989	660
	Lower Madbi (Meem)	155.7	150.8				1.12 (R _o %)		Organic-rich shales and sandstones	2989	3647	658
	Shuqra	161.2	155.7				-----	3650 m-125°C	Massive Limestone and interbedded shale	3647	3682	35
Pre-rift	Kuhlan	163.0	161.2				-----		Sandstones	3682	3711	29
	Basement	<170.0	163.0						Granite and metamorphic rocks	3711	3759	48