CrossRef DOI of original article:

Upper Jurassic Source Rock Evaluation and Thermal Maturity Evolution of the NW Sab'atayn Basin, Yemen

Mohammed Al-Baroot[1], Nabeel A. S. Al-Azazi[2] and A. S. A. E. Alsrory[3]

[1] Saba University, Ma?rib-Yemen

Received: 1 January 1970 Accepted: 1 January 1970 Published: 1 January 1970

Abstract

Abstract-The Sab?atayn Basin has the greatest oil and gas exploration potential in the Mesozoic basins of Yemen. The quantity and quality of the organic matter of sediments is a core focus of source rocks evaluation in exploration of hydrocarbon. Organic-rich sediments within the Meem (Lower) and Lam (Upper) members from four wells in the NW Sab?atayn basin were analyzed using organic geochemistry and total organic carbon content.

Index terms— upper jurassic source rocks, thermal maturity, hydrocarbon generation potential, sab?atayn basin, yemen.

1 Introduction

emen 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 affect 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, resource reassessment must carry out in parts of sedimentary basins previously little explored especially in northwestern part of the petroliferous Sab'atayn basin Fig. 1. The Sab'atayn basin, which conserved Mesozoic succession in its stratigraphy, favored petroleum accumulation because it contains the whole petroleum system element (Source, Reservoirs and Seal rocks). The upper Lam member is the first target of source rock assessment and hydrocarbon exploration because of organic matter richness and greater proli fic oil prone source rock across Yemen (Brannin et al., 1999; Albaroot et al., 2016). The Lower Meem member made up of argillaceous limestone (Alaug et al., 2011; Al-Areeq, 2011; Al-Azazi, 2010 and Al-Areeq, 2004), consider the second target of source rock assessment. In the past decades, several wells have been drilled in northwestern (NW) part of Sab'atayn basin but unfortunately the results became frustrated. 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. Therefore, it is necessary to evaluate systematically the characteristic of the source rocks and their maturity evaluation within this part of the basin. This evaluation can improve our understanding of Lam and Meem source unit evolution and maturation. The characteristics of source rock evaluation include the kerogen type, organic matter abundance and source rock maturity. The source rocks thermal maturity investigation primarily includes vitrinite reflectance (% Ro) and temperature maximum (Tmax) from the Rock-Eval pyrolysis. The quantity of organic matter is commonly assessed by a measuring total organic carbon (TOC) contained 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, drilling wells and samples are short in the NW part of the basin, because this area has not been subjected to extensive conventional oil and gas targets. 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 (SPT, 1994) reports.

Challenges and breakthroughs in recent research in hydrocarbon generation, expulsion, migration and accumulation led to more understanding 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. Along with the development of petroleum geology theory and the wide application of computing technology, quantitative research on the thermal maturity evolution of source rocks in the geological period is of great significance.

2 II.

3 Geological Setting

Yemen, situated at the southern end of the Arabian Peninsula, both are geographically and geologically has the same geological signature between the Arabian and African plate. (Redfern and Jones, 1995). During the Late Jurassic commencing in the Kimmeridgian, syn-rift sediments of the Madbi Formation were deposited . The Madbi Formation is composed of porous limestone to argillaceous lime mudstone. This Formation is divided into two members, the lower member (Meem Member) consists of source rock-quality shales, and sandy turbidites in the border of the basin and may form the reservoir rocks in some Volume XXII Issue IV Version I oilfields of the northwestern Sab'atayn Basin. The Upper Lam Member is mostly composed of laminated organic rich shales and considered to be the most prolific oilprone source rock in the basin (Brannan et al., 1999 andCsato et al., 2001). During Tithonian time, late stages of the syn-rift phase, ocean circulation in the Sab'atayn Basin became restricted, and an evaporitic succession (Safir Member) with an estimated original thickness of about 731 m was deposited (Albaroot, 2017). Massive halite occurs in the basin center, whereas anhydrite and clastic rocks rare along the basin margins (Seaborne, 1996), or totally absent. Interbedded thin shales within Safir member are rich in organic matter (Brannan et al., 1999). The Sab'atayn Formation is divided into four members named as Safir, Alif, Seen and Yah Member. Yah Member is dominated by fluvio-deltaic sandstone, mudstone and evaporate, followed by Seen Member, which is the second clastic sequence. Alif Member is composed of sandstone with shale, which form main reservoir in Sab'atayn Basin. Safir Member consists predominantly of halite with subordinate anhydrite divisible into several bodies separated by interbedded organic-rich shale and sandstone with minor argillaceous, dolomite and limestone. 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 constitute an excellent seal to the underling Alif Member reservoir and contain within them some potential good local reservoir seal pairs in the intra evaporate clastics and the evaporates . 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.

4 III.

Methology provide information on the quantity, quality and maturity of organic matter contained within the Lam and Meem rock units (Table 1). A total of 148 rock samples were collected from shales of the Lam and Meem Members in the studied wells. Initially, the studied shale samples were cleaned of contaminants from drilling mud additives by washing the samples with water several times until no mud was visible on their surface. Parameters measured include Total organic carbon (TOC), free hydrocarbons (S1) in the rock, remaining hydrocarbon generative potential, mgHC/g rock (S2), and temperature of maximum pyrolysis yield (Tmax). Hydrogen (HI), production yield (PY), and production (PI) indexes were mathematically calculated (Table 1). The temperature at which the maximum generation of the products of pyrolysis occurs was used to calculate IV.

5 Results & Discussions

The capability of any prospective reservoir depends on an effective source rock. Petroleum geochemistry is proving its value in helping petroleum geologists to evaluate source rocks and quantify the elements and processes that control the generation of oil and gas. Geochemistry is also an important tool for reducing uncertainty inherent in exploration and production of frontier basins. This section will explore basic geochemical methods used to evaluate new prospects.

6 a) Quality and quantity of organic matter

The impact of quality and quantity of the organic matter (TOC) in the sediments are very important for hydrocarbon generation. The quality term of organic matter is refer to whether the source rock organic matter is oil prone or gas prone, since different types of organic matter have different hydrocarbon generating potential or quality. However, the amount of organic matter in source rocks is the results of a wide variety of environmental influences. **??**issot and Welte (1984), Peters and Cassa (1994) and Peters (1986) presented a scale for the assessment of source rocks potentiality, based on the TOC weight % and Rock-Eval Source rock evaluation within the study area depends on the determination of organic matter content, which is usually expressed as total organic carbon (TOC). The hydrocarbon potentiality depends on the type and quantity of organic matter (kerogen) preserved in the petroleum source rock, thermal maturity and finally the generation potential of kerogen. The geochemical data such as total organic carbon (TOC), Rock-eval pyrolysis data, and vitrinite reflectance are presented and discussed for the proposed Upper Jurassic rock units in Northwestern part of Sab'atayn Basin (Dahamr Ali-01, Himyar-01, Kamaran-01 and Saba-01 wells). TOC determination and Rock-Eval pyrolysis analysis were performed on 100 mg crushed whole rock samples, heated to 600°C in a helium atmosphere, using a Rock-Eval II unit with a total organic carbon module. The Rock-Eval pyrolysis data pyrolysis data, such as S 1 and S 2 . The obtained data in (Table 1) show that the total organic carbon content (TOC) values for the Meem source rocks are between 0.2 and 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 1) reveal that most of the samples consist of reworked organic matter with no interesting source rocks potential. On the other hand, the plot of Tmax versus production index (PI) Fig. 2B provides an indication of source rock maturity and hydrocarbon genesis. Thermal maturity is influenced by source rock organic matter type and the presence of excess free hydrocarbon together with the other factors like mineral matter, content, depth of burial and age **??**Tissot and Welte, 1984). The degree of thermal evolution of the sedimentary organic matter was deduced from Tmax (°C) Production Index (PI) and Vitrinite Reflectance (% Ro). The increase of maturity level of organic matter corresponds to an increase in Tmax. This phenomenon is related to the nature of chemical reactions that occur through thermal cracking. The weaker bonds breakup in the early stages while, the stronger bonds survive until higher temperatures in the late stages (Whelan and Thompson, 1993). Combining and finding relations between the essential Rock-Eval parameter, Tmax, and calculated Rock-Eval parameter, PI, is a valuable method for indicating the maturity of organic matter. The following relations between Tmax and PI are observed: In well Dahamr Ali-01, most of the samples of Meem source rocks especially in the lower part have Tmax more than 445 °C and PI of 0.34 -0.73. This indicate that the lower part in mature stage, while the upper part are in early mature and immature stages. Most of the samples are non-indegenous hydrocarbon except for few samples which fall within the hydrocarbon generation zone. Most of the samples in Himyar-01, Kamaran-01 and Saba-01 wells have Tmax less than 445 °C, accordingly ranging from immature to early mature stage. Some samples have elevated Tmax more than 445 °C making them peak mature. Samples from aforesaid wells except four samples from Kamaran-01 well are in main stages of hydrocarbon generation. The reset samples are non-indigenous hydrocarbons (Fig. 3). Most of the samples from the Lam source rocks in Dahamr Ali-01, Himyar-01, Kamaran-01 and Saba-01 wells are have Tmax less than 435 °C, accordingly plotted in immature zone.

7 b) Generating potentialities

The generating potential of source rocks is used to evaluate their capacity for hydrocarbon generation and can be determined by using the results of pyrolysis analysis. Tissot and Welte, (1984) 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 nongenerative rocks. Furthermore those source rocks with exceptionally high GP values in order of more than 10 mg HC/g rock may provide either 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 rocks. 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 worthy to mention that both of the source rocks are located in shallow depth in the study area even more exposed on the surface for some wells location.

8 c) Genetic type of organic matter

The initial genetic type of organic matter of a particular source rock is essential for the prediction of oil and gas potential. Waples, (1985) used the hydrogen index values (HI) to differentiate between the types of organic matter. 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 are 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 Tmax (modified ven Krevelen diagram, Fig. 4 and TOC vs S2 (Fig. 2A) which are probably resulted from deposition of more terrigenous type III organic matters sourced from land. Type III kerogen is Volume XXII Issue IV Version I 4 ( ) 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 do Type II kerogen and, unless they have small inclusions of Type II material, 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 is prevailed. This type of kerogen is characterized by small amount of Hydrogen is present; However this type of kerogen can generate gas only.

9 d) Thermal Maturation

Thermal maturity is the extent of heat-driven reactions that alter the composition of organic matter. The concentration and distribution of hydrocarbons contained in a particular source depend on both the type of the organic matter and its degree of thermal alteration (Longford et al, 1990). 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 "Tmax", Hydrogen index "HI' Fig. 4. Combining and finding relations between the essential Rock-Eval parameter, Tmax, and calculated Rock-Eval parameter, HI, is a valuable method for indicating the thermal maturity of organic matter. Based on pyrolysis data kerogen classification diagrams were constructed using the HI versus Tmax plot as carried out by previous workers (Espitalie et al, 1985) which is used to determine the kerogen type and maturity Fig. 4. The results show that the analysed Meem source rocks are generally plotted in the mature zone of type III kerogen. Some 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 wide variation in maturity level of Meem source rocks attributed to overburden rocks and depth. Results of Lam source rocks samples show that the source rocks are still immature. Marginally mature in Dahamr Ali-01 and Saba-01 wells. These results have led to classify the Meem member as fully mature source rocks, while the Lam member is immature source rocks in the study area, because the structural setting shows the deepening of Meem member and shallowing of Lam member.

10 V. 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 argued this kerogen derived from land derived organic matter. The Rock-Eval pyrolysis data is reveal that most of the samples consist of reworked organic matter with no interesting source rocks potential. 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 is located in study area. Results of TOC for the studied wells show that the quantity of source rocks are fair to good, some samples are graded to excellent. Most of the studied samples of Meem and Lam source rocks have Tmax less than 440 °C, which place them in immature to marginally mature. Majority of samples in main stages of hydrocarbon generation Based on generative potential of Meem source rocks, it shows non-generative rocks. Kerogen type for Lam and Meem source units is dominated by type III organic matters sourced from land.

Volume XXII Issue IV Version I [1]

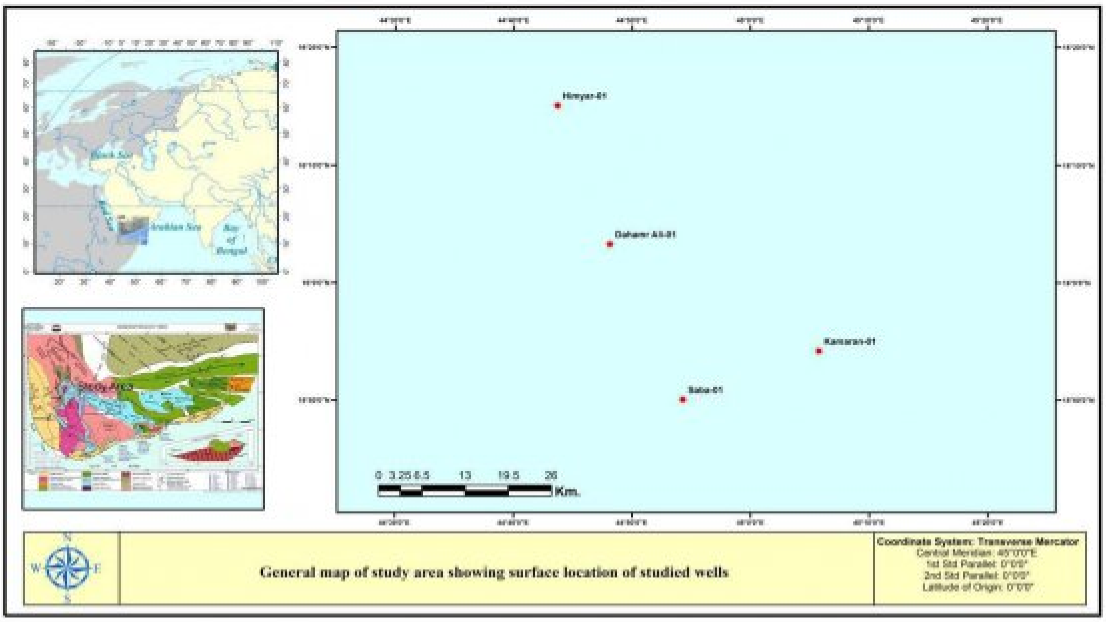


Figure 1:

[1] BUpper Jurassic Source Rock Evaluation and Thermal Maturity Evolution of the NW Sab'atayn Basin, Yemen

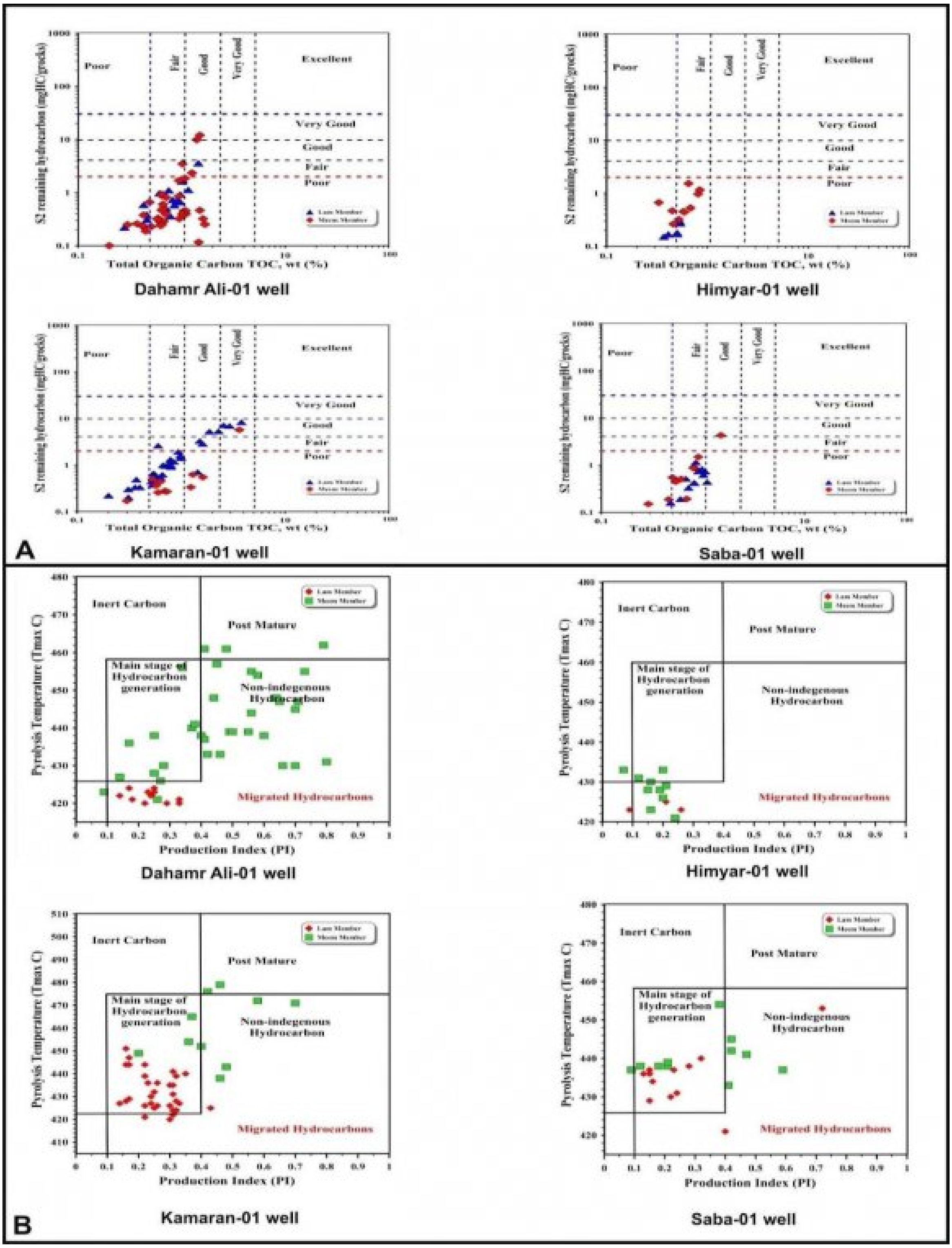
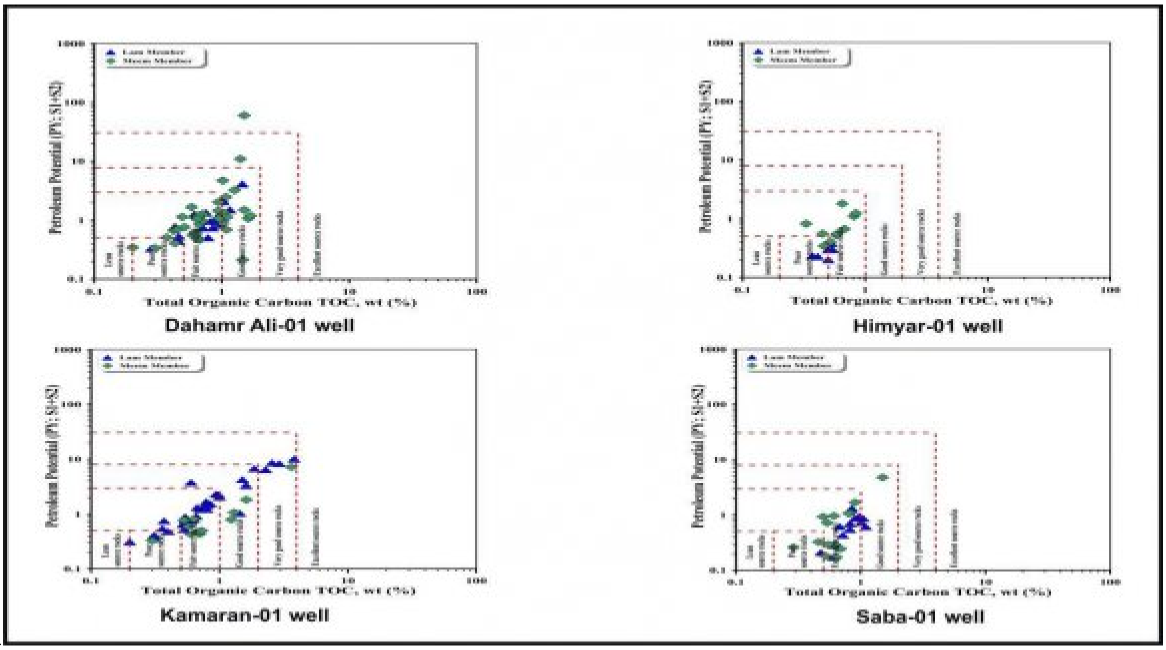

Poor
Fair
Good
Very Good
Excellent
S2 remaining hydrocarbon (mgHC/grocks)
Total Organic Carbon TOC, wt (%)
Dahamr Ali-01 well
Himyar-01 well
Kamaran-01 well
Saba-01 well
A
Inert Carbon
Post Mature
Main stage of Hydrocarbon generation
Non-indegenous Hydrocarbon
Migrated Hydrocarbons
Pyrolysis Temperature (Tmax C)
Production Index (PI)
Dahamr Ali-01 well
Himyar-01 well
Kamaran-01 well
Saba-01 well
B

Figure 2: B



1

Figure 3: Figure 1 :

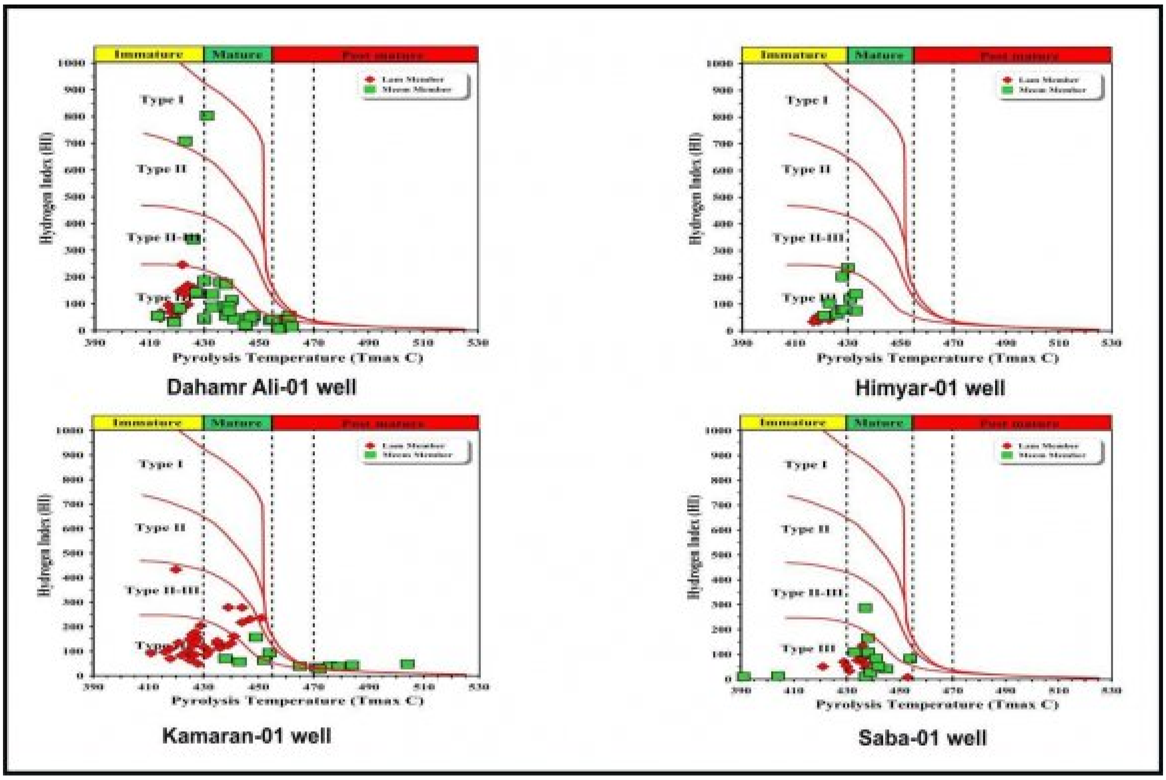


Figure 4:

Figure 5:

1

Wells Name	Members	Depth (m)	TOC "wt%"	S1	S2	S1+S2	Tmax	HI	PI

Figure 6: Table 1 :

.1 Acknowledgement

The authors thank the Ministry of Oil and Minerals and Petroleum Exploration and Production Authority (PEPA), Yemen for supplying the raw and approval and permission to use the material for studied area. The authors also would like to sincerely thank the editors and all of the anonymous reviewers for their careful and useful comments that improved the revised manuscript.

[Beydoun et al. ()] , Z R Beydoun , M L As-Saruri , H El-Nakhal , I N Al-Ganad , R S Baraba , A O Nani , M H Al-Aawah . *International Lexicon of Stratigraphy* 1998. III p. 245. ASIA, Fasc. 1012, Republic of Yemen

[Arabian Journal Geosciences ()] , *Arabian Journal Geosciences* 2011. 4 p. .

[Albaroot et al. ()] M Albaroot , A H M Ahmad , N , & M Sultan . *Tectonostratigraphy of Yemen And Geological Evolution: A New Prospective"; (IJNTR)*, 2016. p. .

[Whelan and Thompson-Rizer ()] 'Chemical methods for assessing kerogen and protokerogen types and maturity: Organic geochemistry principles and applications'. J K Whelan , & C Thompson-Rizer . *New York Plenum 130*, M H Engle, S A Macko (ed.) 1993. p. .

[Espitalié et al. ()] J Espitalié , F Marquis , I Barsony . *Geochemical logging, In: Voorhees KJ (ed) Analytical pyrolysis: techniques and applications*, (Butterworth, London) 1984. p. .

[Al-Areeq ()] 'Formation Evaluation and Petrophysical Characteristics of Some Upper Jurassic Rock Unit (Tithonian) in Alif Field'. N M Al-Areeq . *National Research Center* 2011. 10 (2) p. . (Cairo, J. Appl. Geophys)

[Waples ()] *Geochemistry in Petroleum Exploration*, W Waples . 1985. Boston. p. 232.

[Brannan et al. ()] 'Geological evolution of the central Marib-Shabwa basin'. J Brannan , Sahota , K D Gurdip , J A L Gerdes , Berry . *GeoArabia* 1999. 4 p. .

[Peters ()] 'Guidelines for evaluating petroleum source rock using programmed pyrolysis'. K E Peters . *Am. Assoc. Pet. Geol. Bull* 1986. 70 p. .

[Beydoun et al. ()] 'International Union of Geological Sciences and Ministry of Oil and Mineral Resources'. Z R Beydoun , M Al-Saruri , M El-Nakhal , H Al-Ganad , I N Baraba , R S Nani , AS O , M H Al-Aawah . *Publication* 1998. III p. 245. (International Lexicon of Stratigraphy)

[Longford and Blanc-Valleron ()] 'Interpreting Rock-Eval pyrolysis data using graphs of pyrolyzable hydrocarbons vs. total organic carbon'. F Longford , Blanc-Valleron . *AAPG Bull* 1990. 74 p. .

[Ziegler ()] 'Late Permian to Holocene paleofacies evolution of the Arabian Plate and its hydrocarbon occurrences'. M A Ziegler . *GeoArabia* 2001. 6 (3) p. .

[Al-Wosabi and Wasel] *Lithostratigraphic subdivision of the Kuhlan Formation in Yemen*, M Al-Wosabi , & S Wasel .

[Tissot and Welte] *Petroleum Formation and Occurrence*, P Tissot , D H Welte . New York: Springer. (second ed. 1984)

[Csato et al. ()] *Play concepts*, A Csato , K Habib , I Kiss , V Kocz , K Kovacs , K Lorincz , Milota . 2001.

[Albaroot ()] *Reservoir Characterization and Basin Modelling of Marib-Shabwa basin*, M Albaroot . 2017. India. Aligarh Muslim University (Un unpublished Phd Thesis)

[Espitalie et al. ()] 'Rock-Eval pyrolysis and its application'. J Espitalie , G Deroo , F Marquis . *Inst. Fr. Petrol* 1985. p. 72.

[Al-Areeq ()] *Sedimentary and Reservoir Study of Clastic Members from Sabatyn Formation in Alif Oil Field (Marib-Shabwa Basin) Republic of Yemen*, N M Al-Areeq . 2004. Iraq. Baghdad University (Unpublished master thesis)

[Alaug et al. ()] 'Source rock evaluation, maturation, and reservoir characterization'. S Alaug , Leythäeuser , A F Bruns , Ahmed . *Iran. J. Earth Sci* 2011. 3 p. . (Source and reservoir rocks of the Block 18 oilfields)

[Stephenson and Al-Mashaikie ()] 'Stratigraphic note: Update on the palynology of the Akbarah and Kuhlan formations, northwest Yemen'. M H Stephenson , & S Z A Al-Mashaikie . *GeoArabia* 2011. 16 p. .

[Al-Azazi ()] *Subsurface geological studies and hydrocarbon potentialities of the Sab'atayn Formation (Upper Jurassic) in Alif oil field, Marib-Shabwa basin, Republic of Yemen*, N A Al-Azazi . 2010. Egypt. p. 236. Menoufiya Univ. (Unpublished M. Sc. Thesis)

[Seaborne ()] 'The influence of the Sabatayn Evaporites on the hydrocarbon prospectivity of the Eastern Shabwa Basin, Onshore Yemen'. T R Seaborne . *Marine and Petroleum Geology* 1996. 13 p. .

[Redfern and Jones ()] 'The interior basins of Yemen-analysis of basin structure and stratigraphy in a regional plate tectonic context'. P Redfern , J A Jones . *Basin Res* 1995. 7 p. .

[The Petroleum Geology of the Sedimentary Basins of the Republic of Yemen Non exclusive report ()] 'The Petroleum Geology of the Sedimentary Basins of the Republic of Yemen'. *Non exclusive report* 1994. SPT (Simon Petroleum Technology

[Bacon et al. ()] 'The petroleum potential of onshore Tasmania: a review. Mineral Resources Tasmania'. A Bacon , C R Calver , C J Boreham , D E Leaman , K C Morrison , A T Revill , & J K Volkman . *Geological Survey Bulletin* 2000. p. .

[Peters and Cassa (ed.) ()] *The petroleum system -from source to trap*, K E Peters , & M R Cassa . Magoon, L.B., and Dow, W.G., (ed.) 1994. American Association of Petroleum Geologists. 60 p. . (Applied source rock geochemistry)

[Bott et al. ()] 'The tectonic framework and regional hydrocarbon prospectivity of the Gulf of Aden'. W F Bott , B A Smith , G Oakes , A H Sikander , A I Ibrahim . *J Petrol Geol* 1992. 15 p. .