Islamic Azad University
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# Organic Geochemical Evaluation of Madbi Source Rock, Al-Jawf Basin, NE Central Yemen

**Abdulwahab S. Alaug*[1], Khaled A. Al-Wosabi[1]**

*1. Department of Geology-Faculty of Applied Sciences-Taiz University, Yemen*

Received 10 February 2014; accepted 11 December 2014

**Abstract**

Organic geochemical evaluation of the Madbi Formation as the main source rock of the Al-Jawf Basin, NE Central Yemen was the main objective of this study. The organic geochemical methods used in the study include: rock-eval pyrolysis, total organic carbon, and optical measurements as the vitrinite reflectance and thermal alteration index. In this study, 67 well core and side-well core samples of the H-1 and K-1 exploratory wells of the Al-Jawf Basin were analyzed to calculate the several organic geochemical and optical parameters. The obtained results show the presence of strong source rock probabilities within the Madbi Formation in this basin. The results are classified into three categories: poor, fair, and good source rocks, with a mixed marine Kerogen type II/III and continental Kerogen type III. The maturation of source rocks was affected by heating and re-cycling of heat events during the Cretaceous and Tertiary periods. This interpretation is strongly related to the breakup of the southern Gondwanaland and the opening of the Red Sea and Gulf of Aden. Based on the evaluation of the source rocks, the shale, calcareous shale, and claystones of the Madbi Formation are considered the main source rocks in this basin. According to the present study, the hydrocarbon potentiality is good to fair grade in the Al-Jawf Basin.

***Keywords:*** *Madbi Formation, organic geochemical, source rock, Al-Jawf Basin, Yemen*

## 1. Introduction and geological setting

The Mesozoic rift basins of Yemen have various orientations and ages. The Mesozoic interior or intra– The Mesozoic rift basins of Yemen have various orientations and ages. The Mesozoic interior or intra-continent rift basins of Yemen include the Al-Jawf, Marib, Shabwah, and Belhaf basins within the regional rift basin, which is commonly referred to as the Al-Sabatayn Basin [1 and 2]. These basins are oriented toward the NW–SE direction following the Precambrian Najd Fault System [3 and 4]. The Al-Jawf intra-cratonic rift basin was formed by multiple rifting phases due to reactivation of the Precambrian Najd Fault System. These tectonic activities were formed contemporaneously with the Gondwanaland fragmentation and separation of India and Madagascar during the Jurassic-Cretaceous Periods [1 and 4]. Al-Jawf Graben is located in northeastern Central Yemen (about 150 km NE of Sana'a City). It is 60 km in width, 140 km in length, and trends NW-SE. It is located within the Petroleum Province of Yemen and partly in the southern extension of the Petroleum Potential Province of Saudi Arabia. The basement rocks largely outcrop to the west and southwest of the basin. In the Al-Jawf Basin, which is recognized as Block-19 with a small part of Block-18 in the northeast central part of Yemen, the H-1 well is the first exploratory wildcat well in Block–19 and it was drilled by Yemen–Hunt Oil Company in the mid 1986s.

Al-Jawf Basin represents the half-graben structure of the major graben structure extending from the northeast to southeast central parts of Yemen including several sedimentary basins and covering a hundred square kilometers extending to the Arabian Sea along the NW-SE direction.

The subsurface sedimentary successions of Al-Jawf Basin consists of alternating transgressive and regressive depositional cycles (clastics and carbonates) as a result of different rift phases; these successions can be summarized from older to younger (in age) as follows (Table 1):

1-Wajid and/or Akbara Formations (Paleozoic)
2-Kuhlan Formation (Early-Middle Jurassic)
3-Shuqra Formation (Bathonian-Oxfordian)
4-Madbi Formation (Kimmeridgian)
5-Nayfa Formation (Berriasian-Hauterivian)
6-Undiferntied Tawilah Group (Cretaceous)
7-Quaternary Deposits

The Madbi Formation was considered as the main source rocks of the hydrocarbons in the different hydrocarbon production parts of the Republic of Yemen as pointed out by many authors [1,2,5,6,7,8 and 9]. In the H-1 well, the Madbi Formation forms the middle unit of the Amran Group in areas outside the

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*Corresponding author.
*E-mail address (es): wahabalaug@yahoo.com*

Sab'atayn Basin where the Sab'atayn Formation (principally evaporates including cyclical halite) is absent and the upper part of the Madbi Formation is coeval with the lower to middle Sab'atayn Formation and both are overlain by the Nayfa Formation [2]. In the K-1 well, the Madbi Formation is overlain by the Sab'atayn Formation and at both wells the Madbi Formation is underlain by the Shuqra Formation.

The Madbi Formation was subdivided [10] into two members: Meem (older) and Lam (younger). In the present study, the Meem member consists of mainly calcareous shales/mudstones with minor interbedded limestones especially in the lower part. It attains 680 m at the H-1 well and 1400 m at the K-1 well. The Lam member is predominantly composed of mudstones / shales with minor sandstones and carbonates and attains 450 m at the H-1 well and about 1380 m at the K-1 well (Figs. 2 and 3). The great thickness for the Madbi Formation at the K-1 well compared to the H-1 well may be attributed to the K-1 well that is sited within the fault plane and its vertical displacement.

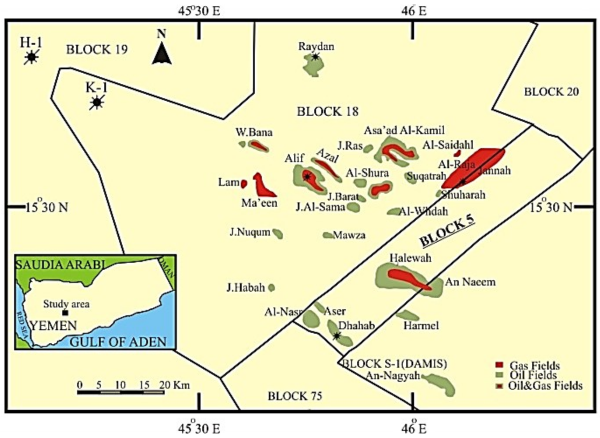


Fig 1. Location map of the studied area, Al-Jawf and Marib basins, NE Central Yemen.

## 2. Exploration history and previous study

Commercial discoveries to update are currently confined to Mesozoic-age rift basins of Yemen, within Marib, Shabwah, and Masilah-Sayun basins. The licensing of the tract of acreage adjacent to the Al-Jawf Basin, northeast central Yemen, is based on the hypothesis that the currently defined proven Play Fairways onshore Yemen extends into the Al-Jawf Basin. Should this prove to be correct, it will open up a new play area for the Republic of Yemen. Onshore, two major plays are proven: the Alif Play and the Qishn Play, as well as several minor plays: Yah, Seen, Safer (Sab'atayn Formation); Lam (Madbi Formation); Shuqra Formation; Kuhlan Formation and weathered, fractured basement rocks [2,4,11,12 and 13]. The reservoirs of both clastic and carbonate rocks of the previous lithostratigraphic units have been discovered in Mesozoic rift basins of Yemen. The Jurassic Play is confined to the Marib and Shabwah basins, where Yemen Hunt Oil Company (Block-18); Total Oil Company (Block-5) and Technoexport or Nimir Oil Company (Block-4) have also enjoyed success in both clastic and carbonate reservoirs (Amran Group).

The Lower Cretaceous Qishn main play within the Masilah-Sayun basins was discovered by Canadian Occidental Oil Company and Total Oil Company, respectively. Several minor plays within these basins include: the Kuhlan Formation, Sa'ar Formation and fractured basement rocks [14]. The major difference between the Masilah-Sayun and Marib and Shabwah basins is the absence of halite (Sab'atayn Formation) in the Masilah-Sayun Basin, although, the source rock is still the same Late Jurassic Madbi Formation [14].

Source rock consideration has rapidly assumed considerable importance, given the Yemeni's government recent decision to open Al-Jawf Basin (Block-19) again to international bidding for exploration. No unequivocal organic geochemical correlation between Jurassic succession of this basin and petroleum recovered from neighboring oil and/or gas fields of the Marib and Shabwah basins has been published.

Table 1 Simplified lithostratigraphic succession of the Al-Jawf Basin, NE Central Yemen.

| Lithostratigraphic Unit | | Lithology | Avg.Thick. (m.) | Rift phase | Age |
|---|---|---|---|---|---|
| Quaternary Deposits | | Gravel, Sands ,Clay | 0-20 | Post-Rift | Quaternary |
| Tawilah Group | | Sandstones | 30-300 | Post-Rift | Cretaceous |
| Amran Group | Nayfa Fm. | Limestone, Shale, Calc.shale | 40-300 | Late-Rift | Berriasian-Hauterivian |
| | Madbi Fm. | Shale, Calc. shale, Limestone | 200-600 | Syn-Rift | Kimmeridgian-Tithonian |
| | Shuqra Fm. | Limestone's, Dolomites | 150-550 | Early- Rift | Bathonian-Oxfordian |
| Kuhlan Formation | | Sandstone | 20-120 | Pre- Rift | Early-Middle Jurassic |
| Paleozoic rock units | | Argilaceous, Sandstone | 30-90 | Pre- Rift | Permian or older |
| Basement Rocks | | Granite, Gneiss, etc. | - | - | Precambrian |

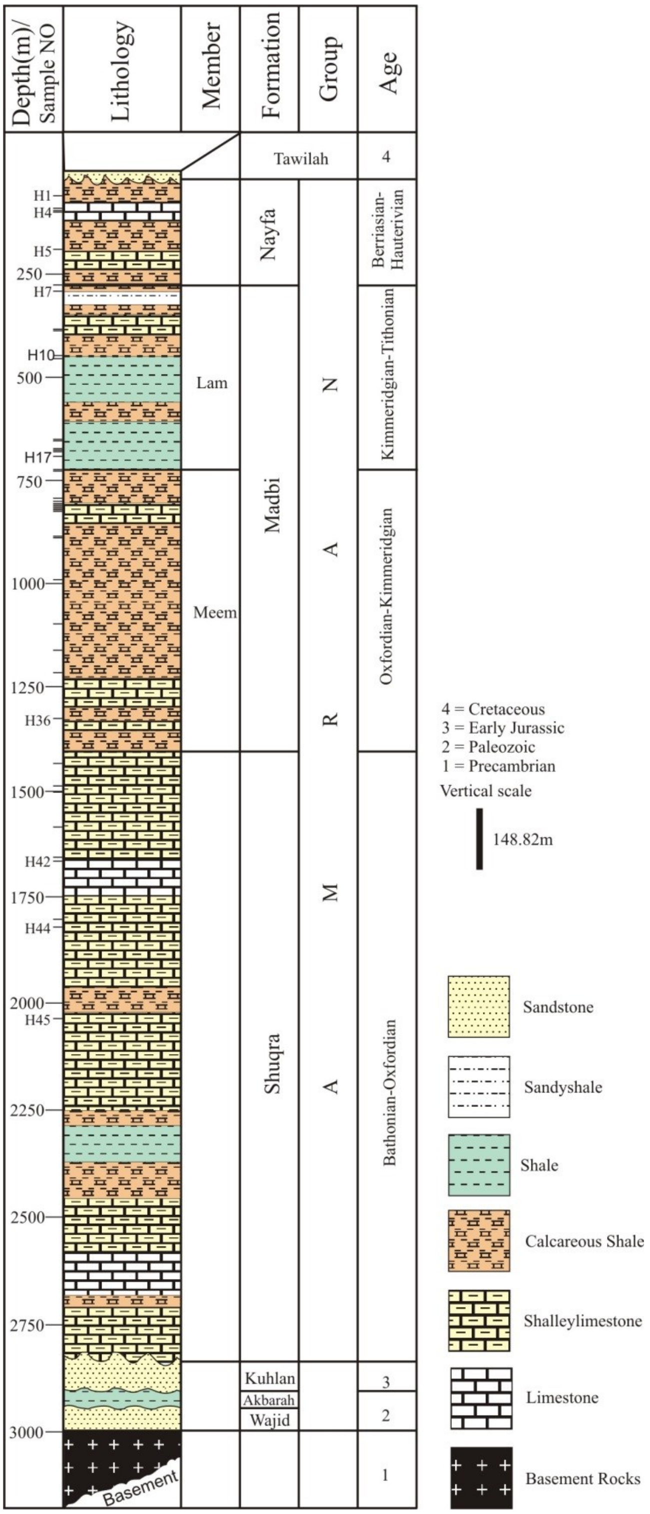


Fig 2. Lithostratigraphic section of the H-1 well, Al-Jawf Basin, NE Central Yemen.

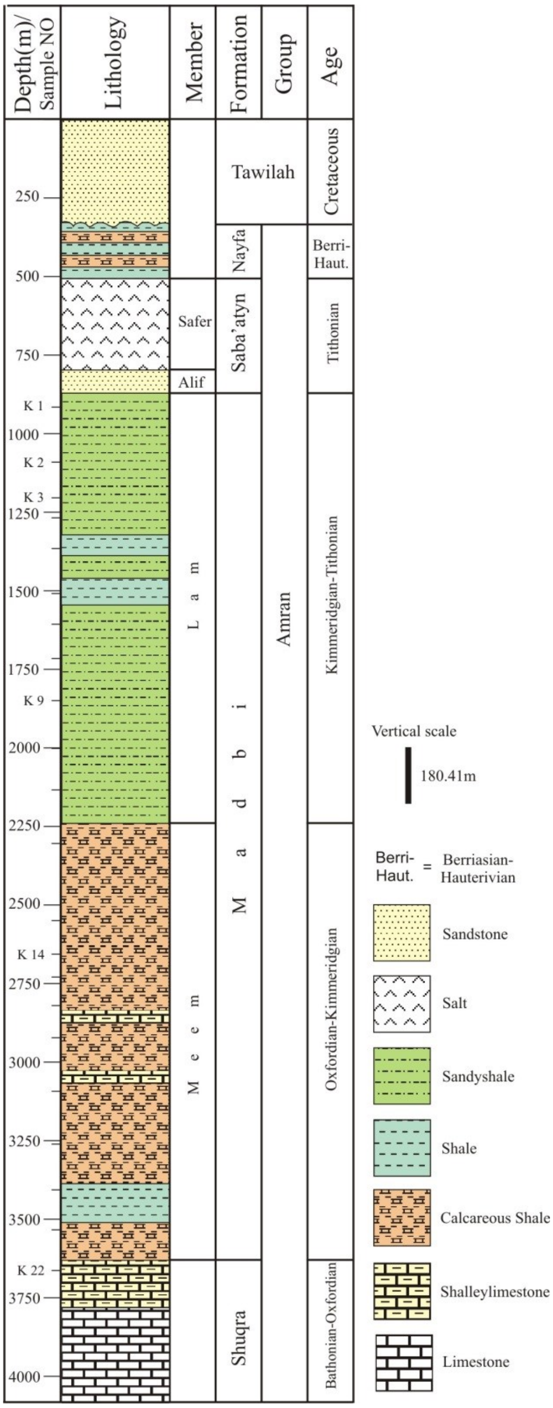


Fig.3 Lithostratigraphic section of the K-1 well, Al-Jawf Basin, NE Central Yemen.

The source potential of these successions remains uncertain, although various oil investigation companies have worked in this basin during the last century (e.g., Yemen-Hunt Oil Company, Exxon Oil Company and Phillips Oil Company). The poor published data of potential source rocks for each of the Marib and

Shabwah basins have been a barrier to comprehensive correlation studies with petroleum from the Al-Jawf Basin. Although several organic geochemical and sedimentlogical studies have been done by oil companies, unfortunately, their linings are not available -some of them remaining still confidential to research. More than 26 oil and/or gas fields have been discovered in Marib Basin and about 19 oil and/or gas fields also have been discovered in Shabwah Basin. All major hydrocarbon accumulations are structurally trapped due to extensional tectonics; some minor stratigraphic traps of hydrocarbon accumulations are associated with the major structural traps [5 and 14].

## 3. Objectives

This study aims to determine the evaluation of source rocks' impact on the maturation and hydrocarbon potentiality in Al-Jawf Basin NE Central Yemen. The majority of the hydrocarbon potentiality of the source rocks and their nature of sedimentary organic matter (SOM) are based on optical and geochemical analyses. This includes using the microscopic study of dispersed soil organic matter (SOM) to predict the nature of hydrocarbon (il and/or gas), which can be produced from organic matter preserved in the source rocks of this succession. This study provides a primary organic geochemical and visual Kerogen database for reviewing the maturation, Kerogen type and generation of petroleum in this basin.

## 4. Material and Methods

A total of 45 core and side-well core samples of the H-1 exploratory well and 22 core and side-well core samples of the K-1 exploratory well were processed and analyzed by optical and geochemical methods. These methods include: the total organic carbon (TOC wet %), vitrinite reflectance (Ro), rock-eval pyrolysis (PY), thermal alteration index (TAI), and palynodebris quant and the interpreting of (SOM) and hydrocarbon products [15 and 16]. Each sample underwent maceration with HCl and HF palynological preparation and separation of sedimentary organic matter (SOM) as the standard palynolgical method to use in optical and organic geochemical analysis. Other pieces of samples were analyzed by LECO equipment to detect the weight percent of TOC wet %. Visual kerogen study and TAI were determined for the H-1 well samples alone. Vitrinite reflectance was used to measure some selected samples within rich intervals of SOM and vitrinite material (kerogen type II and III) to determine the maturation zones and identification of historical heating of source rocks. As a general guide vitrinite reflectance increases with maturity and the main phase of oil generation usually occurs in the range of 0.65-1.30 $R_0$ [17]. The method was applied in assessing thermal maturity in types II and III kerogen [17]. The last method was PY of selected samples of rich interval zone and good data of TOC to identify the following parameters: S1, S2, S3, HI, OI, Tmax, PI, and PP. The identification of the palynological assemblages of each studied sample was based on the different characteristics.

Some of geochemical analyses and data of this study have been collected and obtained from oil companies and the Yemen Ministry of Oil and Minerals in order to be used in this study. All palynological processing was carried out using standard preparation techniques similar to those described by [15,16,18 and 19], but without oxidation processing to measure the TAI.

Quantitative and qualitative palynological analysis of the SOM was carried out on sieved and non-sieved unoxidized palynological material. The standard number of counts per slide was 300 from different palynomorphs particles. The descriptive categories of organic matter for the H-1 well are found in Table 2.

Table 2. Organic matter types and maturation of the H-1 well. Organic matter description (A=Algal, H= Herbaceous, In=Inertinite, Am=Amorphous, Ph =phytoclasts, *=re-worked).

| Sample No. | Depth (m) | Thermal Alteration Index TAI | Preservation | | | | Organic Matter Description |
|---|---|---|---|---|---|---|---|
| | | | TOC% | No. ($R_0$) Measurements | $R_0$ Average | Preservation | |
| 1 | 59.7 | 1 | 0.21 | 23 | 0.43 | F | In, Ph, H, Am. |
| 2 | 91.4 | 1 | 0.59 | 13 | 0.61 | G | In, Ph, H, Am. |
| 3 | 97.5 | 1 | 0.42 | 15 | 0.64 | G | In, Ph, H, Am. |
| 4 | 100.5 | 1 | 0.32 | 9 | 0.61 | G | In, Ph, H, Am. |
| 5 | 192 | 1+ | 0.45 | 13 | 0.64 | G | In, Ph-H, Am. |
| 6 | 277.3 | 1+ | 0.39 | 17 | 0.7 | G | In, Ph-H, Am, A. |
| 7 | 295.6 | 1+ | 0.48 | 19 | 0.71 | F-G | In, Ph-H, Am, A. |
| 8 | 387 | 2- | 0.54 | 20 | 0.71 | G-VG | In, Ph, H, Am. |
| 9 | 390.1 | 2- | 0.47 | 15 | 0.86 | G | In, Ph, H, Am. |
| 10 | 451.1 | 2- | 0.49 | 21 | 0.85 | F-G | In, Ph, H, Am. |
| 11 | 566.9 | 2- | 0.31 | 3 | 0.6 | F-G | In, Am, Ph, H |
| 12 | 655.3 | 2- | 0.56 | 7 | 0.8 | F-G | Ph, In-H, Am. |
| 13 | 658.3 | 2- | 0.4 | 7 | 0.81 | F-G | Ph, In-H, Am. |

Table 2 . (Continued)

| Sample No. | Depth (m) | Thermal Alteration Index TAI | Preservation | | | | Organic Matter Description |
|---|---|---|---|---|---|---|---|
| | | | TOC% | No. ($R_0$) Measurements | $R_0$ Average | Preservation | |
| 14 | 679.7 | 2- | 0.5 | 6 | 0.79 | F-G | Am, In–Ph ,H - A |
| 15 | 682.7 | 2- | 0.7 | 12 | 0.81 | F-G | Am, In–Ph, H |
| 16 | 685.8 | 2- | 0.7 | 14 | 0.78 | F-G | Am, In–Ph, H |
| 17 | 697.9 | 2- | 0.65 | 13 | 0.75 | F-G | Am, In–Ph, H-A |
| 18 | 728.4 | 2- | 0.61 | 15 | 0.72 | F | Am, H–In, Ph |
| 19 | 731.5 | 2- | 0.55 | 7 | 0.74 | F-G | Am, H–In, Ph |
| 20 | 798.5 | 2- | 0.82 | 6 | 0.9 | G | H, Am, Ph |
| 21 | 807.72 | 2- | 0.75 | 8 | 0.8 | F-G | In, Ph-H, Am. |
| 22 | 813.8 | 2- | 0.61 | 11 | 0.81 | F-G | In, H-Ph, Am. |
| 23 | 816.8 | 2- | 0.55 | 14 | 0.85 | F-G | In, Ph-H, Am |
| 24 | 820.5 | 2- | 0.54 | 9 | 1.06 | F-G | In, H-Ph, Am |
| 25 | 822.9 | 3 | 0.51 | 8 | 0.91 | G | Am, In–H, Ph |
| 26 | 826.6 | 2 | 0.47 | 12 | 1.1 | F-G | Am, In–H, Ph |
| 27 | 832.1 | 2 | 0.47 | 9 | 0.81 | F-G | Am, In–H, Ph |
| 28 | 890 | 2 | 0.51 | 13 | 0.82 | F-G | Am, In–Ph, H-A |
| 29 | 893 | 2 | 0.59 | 9 | 0.85 | F-G | In, Am, Ph-A |
| 30 | 999.7 | 2+ | 0.52 | 16 | 0.9 | F | H, Ph, Am |
| 31 | 1106.4 | 2+ | 0.51 | 27 | 1.21 | F | * H, Am, Ph-In |
| 32 | 1170.4 | 2+ | 1.3 | 25 | 1.1 | F-G | * H, Am, Ph-In |
| 33 | 1225.2 | 3- | 0.91 | 18 | 1.3 | G | * H, Am, Ph-In |
| 34 | 1335 | 3- | 0.42 | 17 | 0.75 | F-G | Am*, H, Ph-In |
| 35 | 1444.7 | 3- | 0.85 | 10 | 1.2 | F | H*, Am, Ph |
| 36 | 1499.6 | 3- | 0.92 | 15 | 1.08 | F | Am*, Ph-In , A-H |
| 37 | 1514.8 | 3- | 1.1 | 20 | 1 | F | Am*, Ph-A, In-H |
| 38 | 1600.2 | 3- | 0.82 | 9 | 0.95 | F | Am*, In-A, Ph-H |
| 39 | 1673.3 | 2+ | 0.81 | 15 | 0.78 | F | Am, In-A, Ph-H |
| 40 | 1682.4 | 2+ | 1.1 | 12 | 0.86 | F | Am, In-A, Ph-H |
| 41 | 1687.9 | 2+ | 1.2 | 16 | 0.94 | F | Am, In-A, Ph-H |
| 42 | 1825.7 | 2+ | 0.91 | 24 | 0.81 | F-G | Am, A-In, Ph-H |
| 43 | 1844 | 2+ | 1.1 | 27 | 0.74 | F-G | Am, A-In, Ph-H |
| 44 | 2035.1 | 2+ | 1.2 | 25 | 0.75 | G | Am, A-In, Ph-H |
| 45 | 2066.5 | 2+ | 1.1 | 15 | 0.7 | F-G | Am, A-In, Ph-H |

## 5. Results and discussion

### 5.1. Source rock and hydrocarbon potentiality

Rock-eval pyrolysis is the most widely used method for screening the petroleum generation potential, the level of organic maturation, and the type of kerogen [20]. Parameter S1 is a measure of the amount of free hydrocarbon liberated at 300C°. Peak S2 is the amount of hydrocarbon released during the temperature programmed pyrolysis (300-600C°). The TOC is determined by the Leco method or by oxidizing the pyrolysis residue in a second oven (600C° in air). Tmax values are obtained also from the measurement. Some parameters can be calculated as HI, OI, PP, PI (organic geochemical logs). Results of organic geochemical analyses of the Late Jurassic Madbi Formation are listed in Tables 3 and 4. Peters (1986) presented a scale for assessment of source rocks used in a wide scale and it has been applied in this work as such: a content of less 0.5 wt % TOC as a poor source, 0.5–1.0 wt % as a fair source, 1.0– 2.0 wt % as a good source, and more than 2.0 wt % TOC as excellent source rock. Usually the typical minimum acceptable TOC values for various types of petroleum source rocks are 0.5% for shale, 0.3% for carbonates and, 1.0% for siltstone source rocks [17 and 22]. Several good source rock intervals are found in the Madbi Formation succession. The kerogen type controls the quality and the amount of hydrocarbon generated from a potential source rock. In the study area, the location of the Madbi Formation samples on the Van Krevelen diagrams indicate kerogen types that involve kerogen type II/III and kerogen type III (Fig. 4).

The boundary between kerogen type II/III and type III is at a value of HI=200, but perhaps the rock matrix adsorbs some of the hydrocarbon liberated by pyrolysis; clay is the main agent of absorption and more hydrocarbon should be released from carbonate source rocks than argillaceous [20 and 23]. The organic geochemical logs of the two exploratory wells (K-1 and H-1) are shown in Figures 5 and 6. The TOC% of these samples varies from 0.21 % to 1.3 %.

Table 3. Rock-Eval Pyrolysis data of the H-1 well.

| Sample No. | Depth (m) | TOC% | $T_{max}$ | $S_1$ | $S_2$ | $S_3$ | PP | HI | OI | PI |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 59.7 | 0.21 | 420 | 0.025 | 0.31 | 0.18 | 0.335 | 147.6 | 85.7 | 0.075 |
| 2 | 91.4 | 0.59 | 430 | 0.031 | 0.32 | 0.17 | 0.351 | 54.2 | 28.8 | 0.088 |
| 3 | 97.5 | 0.42 | 425 | 0.045 | 0.25 | 0.19 | 0.295 | 59.5 | 45.2 | 0.153 |
| 4 | 100.5 | 0.32 | 425 | 0.081 | 0.41 | 0.21 | 0.491 | 128.1 | 65.6 | 0.165 |
| 5 | 192 | 0.45 | 415 | 0.091 | 0.45 | 0.15 | 0.541 | 100.0 | 33.3 | 0.168 |
| 6 | 277.3 | 0.39 | 421 | 0.15 | 0.41 | 0.17 | 0.56 | 105.1 | 43.6 | 0.268 |
| 7 | 295.6 | 0.48 | 430 | 0.095 | 0.38 | 0.21 | 0.475 | 79.2 | 43.8 | 0.200 |
| 8 | 387 | 0.54 | 430 | 0.11 | 0.54 | 0.13 | 0.65 | 100.0 | 24.1 | 0.169 |
| 9 | 390.1 | 0.47 | 420 | 0.12 | 0.71 | 0.14 | 0.83 | 151.1 | 29.8 | 0.145 |
| 10 | 451.1 | 0.49 | 425 | 0.091 | 0.85 | 0.18 | 0.941 | 173.5 | 36.7 | 0.097 |
| 11 | 566.9 | 0.31 | 430 | 0.071 | 1.1 | 0.31 | 1.171 | 354.8 | 100.0 | 0.061 |
| 12 | 655.3 | 0.56 | 427 | 0.081 | 0.97 | 0.3 | 1.051 | 173.2 | 53.6 | 0.077 |
| 13 | 658.3 | 0.4 | 418 | 0.091 | 0.93 | 0.25 | 1.021 | 232.5 | 62.5 | 0.089 |
| 14 | 679.7 | 0.5 | 422 | 0.094 | 0.74 | 0.31 | 0.834 | 148.0 | 62.0 | 0.113 |
| 15 | 682.7 | 0.7 | 427 | 0.14 | 0.85 | 0.27 | 0.99 | 121.4 | 38.6 | 0.141 |
| 16 | 685.8 | 0.7 | 428 | 0.13 | 0.91 | 0.28 | 1.04 | 130.0 | 40.0 | 0.125 |
| 17 | 697.9 | 0.65 | 420 | 0.11 | 1.4 | 0.34 | 1.51 | 215.4 | 52.3 | 0.073 |
| 18 | 728.4 | 0.61 | 431 | 0.12 | 0.95 | 0.18 | 1.07 | 155.7 | 29.5 | 0.112 |
| 19 | 731.5 | 0.55 | 415 | 0.13 | 1.7 | 0.21 | 1.83 | 309.1 | 38.2 | 0.071 |
| 20 | 798.5 | 0.82 | 424 | 0.098 | 0.97 | 0.25 | 1.068 | 118.3 | 30.5 | 0.092 |
| 21 | 807.72 | 0.75 | 428 | 0.091 | 1.8 | 0.31 | 1.891 | 240.0 | 41.3 | 0.048 |
| 22 | 813.8 | 0.61 | 428 | 0.091 | 1.2 | 0.23 | 1.291 | 196.7 | 37.7 | 0.070 |
| 23 | 816.8 | 0.55 | 415 | 0.094 | 1.1 | 0.15 | 1.194 | 200.0 | 27.3 | 0.079 |
| 24 | 820.5 | 0.54 | 413 | 0.14 | 1.3 | 0.28 | 1.44 | 240.7 | 51.9 | 0.097 |
| 25 | 822.9 | 0.51 | 424 | 0.11 | 1.4 | 0.21 | 1.51 | 274.5 | 41.2 | 0.073 |
| 26 | 826.6 | 0.47 | 430 | 0.1 | 0.93 | 0.31 | 1.03 | 197.9 | 66.0 | 0.097 |
| 27 | 832.1 | 0.47 | 432 | 0.094 | 0.82 | 0.19 | 0.914 | 174.5 | 40.4 | 0.103 |
| 28 | 890 | 0.51 | 437 | 0.081 | 0.85 | 0.18 | 0.931 | 166.7 | 35.3 | 0.087 |
| 29 | 893 | 0.59 | 424 | 0.12 | 0.81 | 0.21 | 0.93 | 137.3 | 35.6 | 0.129 |
| 30 | 999.7 | 0.52 | 420 | 0.14 | 0.92 | 0.32 | 1.06 | 176.9 | 61.5 | 0.132 |
| 31 | 1106.4 | 0.51 | 425 | 0.27 | 1.7 | 0.31 | 1.97 | 333.3 | 60.8 | 0.137 |
| 32 | 1170.4 | 1.3 | 441 | 0.29 | 1.5 | 0.35 | 1.79 | 115.4 | 26.9 | 0.162 |
| 33 | 1225.2 | 0.91 | 429 | 0.38 | 0.91 | 0.48 | 1.29 | 100.0 | 52.7 | 0.295 |
| 34 | 1335 | 0.42 | 420 | 0.31 | 1.2 | 0.28 | 1.51 | 285.7 | 66.7 | 0.205 |
| 35 | 1444.7 | 0.85 | 435 | 0.36 | 1.5 | 0.22 | 1.86 | 176.5 | 25.9 | 0.194 |
| 36 | 1499.6 | 0.92 | 440 | 0.34 | 1.4 | 0.24 | 1.74 | 152.2 | 26.1 | 0.195 |
| 37 | 1514.8 | 1.1 | 450 | 0.29 | 0.94 | 0.31 | 1.23 | 85.5 | 28.2 | 0.236 |
| 38 | 1600.2 | 0.82 | 445 | 0.24 | 0.45 | 0.37 | 0.69 | 54.9 | 45.1 | 0.348 |
| 39 | 1673.3 | 0.81 | 448 | 0.23 | 0.75 | 0.19 | 0.98 | 92.6 | 23.5 | 0.235 |
| 40 | 1682.4 | 1.1 | 440 | 0.25 | 0.89 | 0.25 | 1.14 | 80.9 | 22.7 | 0.219 |
| 41 | 1687.9 | 1.2 | 445 | 0.28 | 0.95 | 0.18 | 1.23 | 79.2 | 15.0 | 0.228 |
| 42 | 1825.7 | 0.91 | 449 | 0.22 | 0.92 | 0.22 | 1.14 | 101.1 | 24.2 | 0.193 |
| 43 | 1844 | 1.1 | 442 | 0.21 | 1.1 | 0.31 | 1.31 | 100.0 | 28.2 | 0.160 |
| 44 | 2035.1 | 1.2 | 439 | 0.28 | 0.8 | 0.24 | 1.08 | 66.7 | 20.0 | 0.259 |
| 45 | 2066.5 | 1.1 | 438 | 0.24 | 0.81 | 0.31 | 1.05 | 73.6 | 28.2 | 0.229 |

These values indicate that the basin can be classified into three categories such as poor, fair and good source rocks. The hydrocarbon content in several source rock intervals indicates the generative potential. Free oil contents (S1) vary between 0.025 and 0.34 mg HC/g rock in H-1 well samples and from 0.13 to 0.47 mg HC/g rock in K-1 well samples, while the while the hydrocarbon generating potential (S2) differentiate

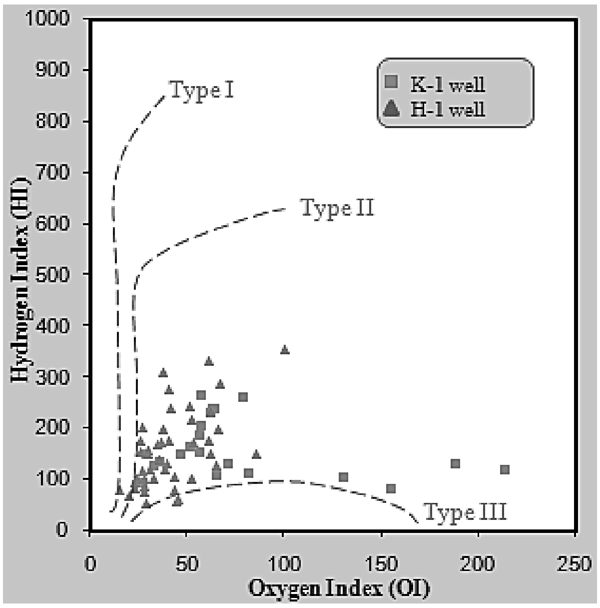


Fig.4 Van Krevelen Diagram, showing kerogen type of the Madbi Formation, Al-Jawf Basin.

Table 4: Rock-Eval Pyrolysis data of the K-1 well.

| Sample No. | Depth (m) | No. of Meas.(Ro) | Average (Ro) | $T_{max}$ | TAI | HI | OI | $S_1$ | $S_2$ | $S_3$ | PI | PP | TOC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 920.4 | 41 | 0.49 | 433 | 2 | 131 | 188 | 0.3 | 1.69 | 2.43 | 0.15 | 1.99 | 1.29 |
| 2 | 1103.3 | 37 | 0.61 | 434 | 2 | 150 | 40 | 0.3 | 1.6 | 2.4 | 0.84 | 1.9 | 0.4 |
| 3 | 1213.1 | 46 | 0.61 | 429 | 2 | 119 | 214 | 0.25 | 0.76 | 1.37 | 0.25 | 1.01 | 0.64 |
| 4 | 1277.1 | 24 | 0.58 | 432 | 2 | 132 | 71 | 0.23 | 1.02 | 0.55 | 0.18 | 1.25 | 0.77 |
| 5 | 1377.6 | 37 | 0.65 | 431 | 2 | 106 | 131 | 0.23 | 0.72 | 0.89 | 0.24 | 0.95 | 0.68 |
| 6 | 1517.9 | 46 | 0.76 | 436 | 2+ | 113 | 82 | 0.22 | 0.77 | 0.56 | 0.22 | 0.99 | 0.68 |
| 7 | 1618.4 | 27 | 0.8 | 437 | 2+ | 84 | 155 | 0.22 | 0.62 | 1.15 | 0.26 | 0.84 | 0.74 |
| 8 | 1728.2 | 34 | 0.83 | 440 | 2+ | 154 | 56 | 0.29 | 1.08 | 0.39 | 0.21 | 1.37 | 0.7 |
| 9 | 1865.3 | 34 | 0.83 | 439 | 2+ | 92 | 27 | 0.27 | 0.72 | 0.21 | 0.27 | 0.99 | 0.78 |
| 10 | 2002.5 | - | - | 444 | - | 149 | 29 | 0.47 | 1.3 | 0.25 | 0.27 | 1.77 | 0.87 |
| 11 | 2148.8 | - | - | 447 | - | 127 | 33 | 0.39 | 1.05 | 0.27 | 0.27 | 1.44 | 0.83 |
| 12 | 2322.5 | - | - | 436 | - | 108 | 65 | 0.38 | 0.68 | 0.41 | 0.36 | 1.06 | 0.63 |
| 13 | 2569.4 | - | - | 474 | - | 134 | 36 | 0.21 | 0.21 | 0.26 | 0.5 | 0.42 | 0.73 |
| 14 | 2679.1 | - | - | 444 | - | 206 | 57 | 0.14 | 0.15 | 0.3 | 0.48 | 0.29 | 0.53 |
| 15 | 2743.2 | - | - | 435 | - | 266 | 57 | 0.13 | 0.14 | 0.3 | 0.48 | 0.27 | 0.53 |
| 16 | 2843.7 | - | - | 432 | - | 230 | 62 | 0.19 | 0.16 | 0.37 | 0.54 | 0.35 | 0.6 |
| 17 | 2944.3 | - | - | 459 | - | 260 | 79 | 0.25 | 0.24 | 0.55 | 0.51 | 0.49 | 0.7 |
| 18 | 3118.1 | - | - | 422 | - | 165 | 51 | 0.22 | 0.1 | 0.35 | 0.69 | 0.32 | 0.68 |
| 19 | 3264.4 | - | - | 454 | - | 240 | 63 | 0.25 | 0.17 | 0.48 | 0.6 | 0.42 | 0.76 |
| 20 | 3429 | - | - | 410 | - | 150 | 47 | 0.19 | 0.11 | 0.33 | 0.63 | 0.3 | 0.7 |
| 21 | 3560 | - | - | 467 | - | 240 | 64 | 0.23 | 0.18 | 0.48 | 0.56 | 0.41 | 0.75 |
| 22 | 3691.1 | - | - | 477 | - | 187 | 56 | 0.25 | 0.14 | 0.41 | 0.64 | 0.39 | 0.73 |

between 0.25 to 1.7 mg HC/g rock in the H-1 well and from 0.1 to 1.69 mg HC/g rock in K-1. Likewise, the production index (PI) of the H-1 well samples varies from 0.65 to .95 mg HC/g rock and from 0.15 to 0.69 mg HC/g rock in K-1 well. The results of the H-1 well posse hydrogen index (HI) range from 54 to 354 mg HC/g TOC and range from 84 to 266 mg HC/g TOC of the K-1 well samples (Tables 3 and 4). These values of HI define the late immature to mature stages.

The H-1 well samples show Petroleum Potential (PP) values range between 0.29 and 1.97 mg HC/g of rock and in the K-1 well the values range between 0.27 and 1.99 97mg HC/g of rock. These values emphasize that the studied sections have a good hydrocarbon potentiality. Total Organic Carbon (TOC wt%) values range between 0.21 and 1.3% and between 0.4% and

1.29% of the H-1 and K-1 wells, respectively. These values indicate that the source rocks in the study area vary from poor to good source rocks. The plots of HI versus Tmax and HI versus TOC (wet %) (Figs. 7 and 8) indicate mature and hydrocarbon potentiality of the Al-Jawf Basin. Likewise, the plots of HI versus OI as well as HI versus Tmax indicated two types of kerogen, continental kerogen III, and small amounts of marine kerogen II (Figs.4 and 7).

## 5.2. Visual Kerogen

The identification of SOM with relative proportions is quantified for all preparing samples through a use of palynological methods (Table 2).

The optical observation studies of SOM indicate anoxic deposition and moderate thermal maturation. The SOM is predominantly of mixed marine organic matter with load and influx of wood bearing materials, land plants and miospores. Maybe this situation is related to the intra-cratonic rift valley, which was covered by the opening of the "Neo-Tethys" Ocean and connected with this basin from the northeast and northwest during the Late Jurassic Period [24 and 25].

## 5.3. Thermal Alternation Index (TAI)

The TAI were measured by using a transmitted light microscope according to standard methods as shown in Table 5. These values for the H-1 well are listed in Table 2. The gymnosperm pollen of Classopollis genera were used to measure the TAI in the current study. The TAI values indicated a mature stage (Catagenesis) especially in the Madbi Formation.

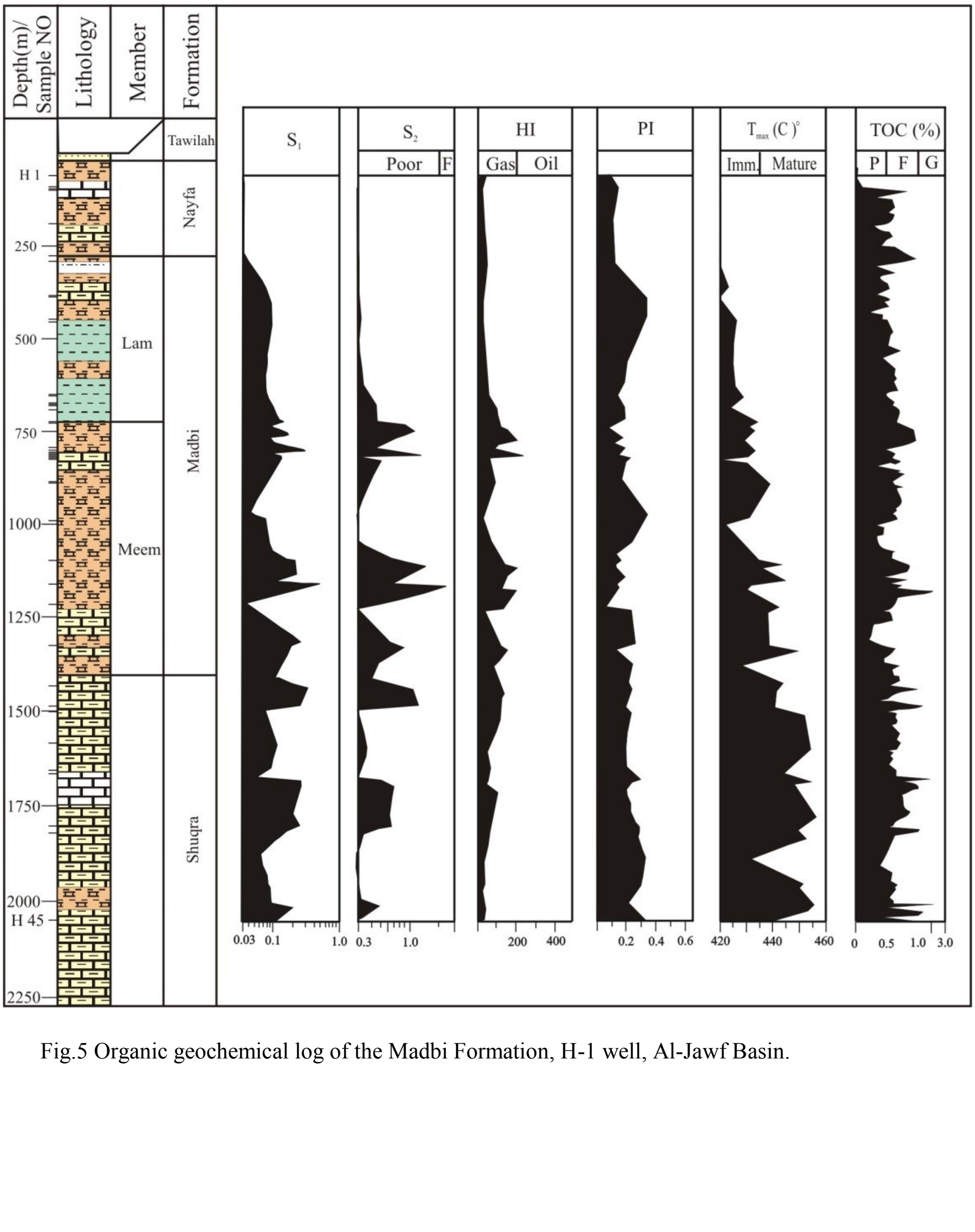


Fig.5 Organic geochemical log of the Madbi Formation, H-1 well, Al-Jawf Basin.

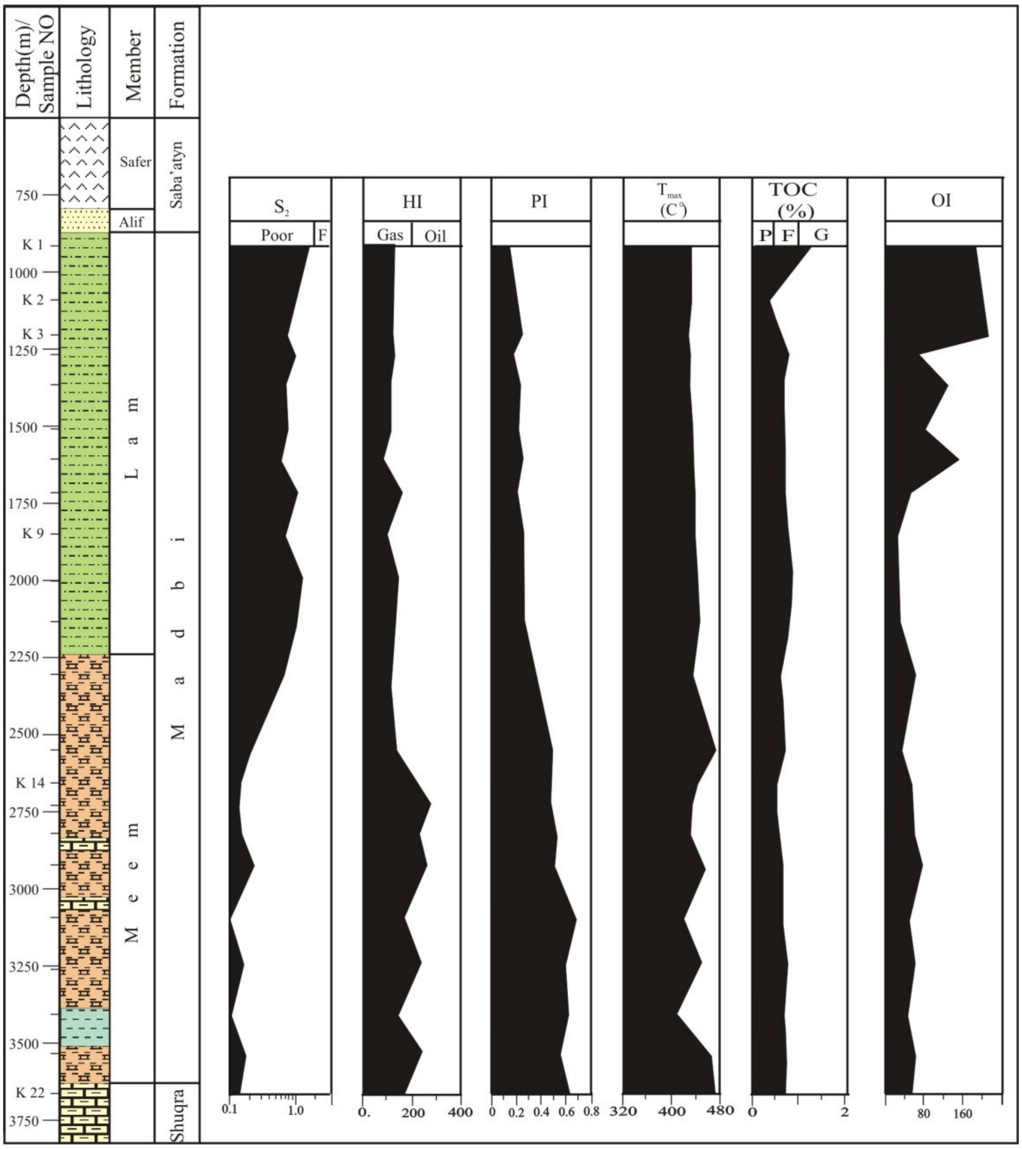


Fig.6 Organic geochemical log of the Madbi Formation, K-1 well, Al-Jawf Basin.

## 5.4. Vitrinite Reflectance ($R_o$)

Vitrinite reflectance data of the H-1 well samples (Table 3 and Fig. 9) and the upper nine samples (Lam member) of the K-1 well (Table 4) indicated that most samples relate to immature to mature stages with respect to oil and gas generation. Two optical measurements ($R_o$ and TAI) were conducted determining the early mature to mature stage of the Madbi Formation source rocks (Tables 2 and 3). Core and side-well core samples usually are accurate, because of non-contamination and the caving effect, but may be used as an indicator with other organic geochemical measurements such as Tmax of the pyrolysis data. The gradual increasing of paleothermal indicators (TAI, Ro and Tmax) with depth indicated increase of maturation and burial depth. Vitrinite reflectance's values of the H-1 and K-1 wells indicate a slightly immature to early mature stages of the Lam member succession; however, early mature to moderate mature stages within the Meem member succession.

## 5.5. Thermal Maturation

Maximum of temperature (Tmax) in which the amount of organic S2 hydrocarbons are generated in the rock-vval pyrolysis method. It is a rough measurement of the thermal maturity of the organic matter, in which its dependency is based on the type of organic matter. In general terms, the beginning of a mature stage is located between 430ºC and 465ºC, while the values that exceed 465ºC reflect the overmature stage. In turn, the value of Tmax less than 430ºC represents an immature stage [28].

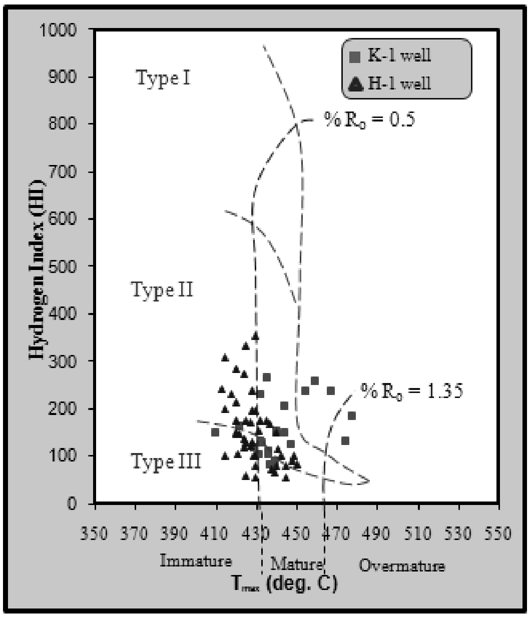


Fig. 7 The plot of the hydrogen index (HI) versus maximum temperature (Tmax) for the Madbi

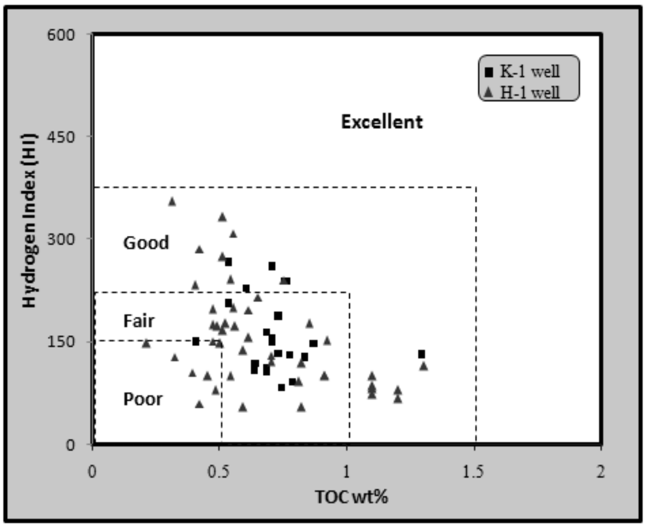


Fig. 8 The plot of the hydrogen index (HI) versus the total organic composite (TOC) for the Madbi

Table 5 Scale of the thermal alteration index and comparison between different schemes of the thermal alternation index standards.

| [26] | [27] | [19] | This study | | |
|---|---|---|---|---|---|
| | | | Scale | color | Organic maturity |
| 1 | 1 | 1-2. | 1 | Colorless | Immature |
| 1+ | 1+ | 2 | 1+ | Light yellow | |
| 2- | 2- | 2-3. | 2- | Moderate to dark yellow | |
| 2 | 2 | 3 | 2 | Dark yellow to orange | Early mature |
| 2+ | 2+ to 3- | 3-4. | 2+ | Orange to light brown | |
| 3- | 3- to 3 | 4 | 3- | Yellow brown | Mature |
| 3 | 3 to 3+ | 4-5. | 3 | Brown | |
| 3+ | 3+ to 4- | 5 | 3+ | Dark brown | |
| 4- | 4- to 4 | 5-6. | 4 | Brownish black | |
| 4 | >4 | 6 | 5 | Black | Over mature |
| 5 | | 7 | | Black and deformed | |

On the other hand, the low value of the Production Index (<0.1) is indicative of immature organic matter (Diagenesis), while the intermediate values of the production index (0.1 to 0.4) reflect mature organic matter (Catagenesis) and the high value of the production index (>0.4) reflects overmature organic matter (Metagenesis) [28 and 29].

According to [29] the zone of oil generation ranges between Tmax temperatures of 435 and 460ºC and between production index (PI) values of 0.1 and 0.4 [30]. Usually the values less than 435ºC indicate immature organic matter, while at the maximum value (about 460 ºC) the bottom of the oil window and at the beginning of the condensate and wet gas zone [31]. In the study area, Tmax values vary between 410ºC and 477ºC in the K-1 well indicates immature to overmature stages. On other hand, the Tmax values of the H-1 well range between 413ºC and 450ºC and reflect immature to mature stages. The PI of the K-1 well ranges between 0.15 and 0.69, which indicatethe mature to overmature stage. In the H-1 well these values vary between 0.65 and 0.95 and reflect an overmature stage. The level of thermal maturation of organic matter was estimated from the vitrinite reflectance , Temperature of maximum pyrolitic hydrocarbon generation (Tmax), production index and thermal alteration index (Fig. 9). Thus, any conclusion regarding thermal maturity should be carried out by other geochemical and optical measurements as the vitrinite reflectance and thermal alteration index.

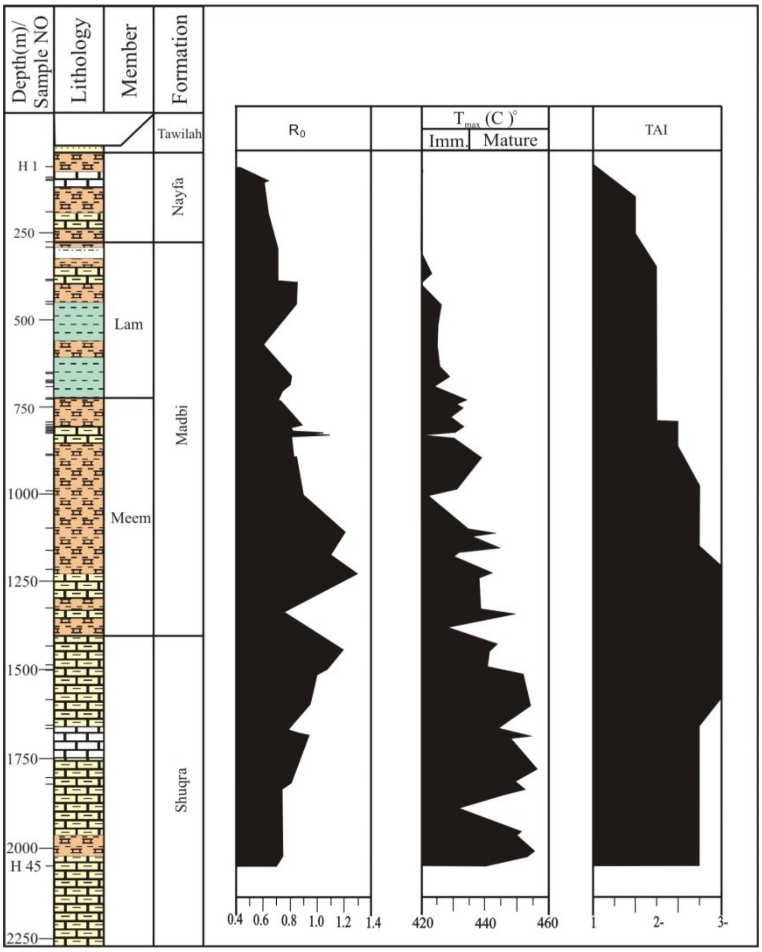


Fig. 9 Palaeothermal indicators [vitrinite reflectance (Ro), thermal alternation index (TAI), maximum temperature (Tmax)] of the H-1 well, Al-Jawf Basin.

## 6. Conclusions

Organic geochemical analyses of the Madbi Formation indicate that it the total organic carbon varies between poor and good, but mostly towards good and are potentially enough to produce indigenous hydrocarbon. Moreover, most of the studied samples have kerogen type II and III that indicate they are able to generate oil and gas. The level of thermal maturation of organic matter was determined based on the vitrinite reflection ($R_0$), temperature of maximum pyrolitic hydrocarbon generation (Tmax), production index (PI), and thermal alteration index (TAI). These parameters indicate that the samples of the Madbi Formation range from immature to overmature, but most of them are mature. So, the shale and claystones of the Madbi Formation are considered the main source rocks in this basin.

## Acknowledgement

The authors wish to express their thanks to the Petroleum Exploration and Production Board – Republic of Yemen (PEPA), Safer Oil Company, and Iraqi Petroleum Exploration Company (IPEC) for providing the samples and assistance in this analysis.

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