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Research Article

Shale Gas Geochemistry of the Middle Jurassic Upper Safa Member, Amoun Field, Shushan Basin, Western Desert, Egypt

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ABSTRACT

Shale gas resources are known for their high organic content and maturity, which allows for gas generation. Accurate assessment of their productive potential requires evaluating the geochemical properties of shale gas reservoirs and subsequent basin modeling. In this study, the geochemical characteristics of the Middle Jurassic Upper Safa Shale in the Amoun field, Shushan Basin, Western Desert, Egypt were evaluated. The study assessed the Total Organic Carbon (TOC) content, kerogen type, and maturity of organic matter. Additionally, the basin modeling technique was used for constructing different 1D models such as vitrinite reflectance, burial histories, and hydrocarbon zones. The Upper Safa member is sub-divided into two zones (Upper Safa Top and Upper Safa Bottom), with TOC values ranging from 1.31 to 80.4 wt.%, indicating varying source rock quality from poor to very good. The modified Van Krevelen diagrams indicate that the sediments are primarily consisting of type (III) kerogen with some extent of type (II) kerogen. The sediments have reached late maturity based on Tmax values, which range from 462 to 475 degrees Celsius. The Ro% values range from 0.7 to 1.09, indicating that the sediments are in the mature stage, have passed the peak of oil generation, and are in the peak of the gas generation stage. The estimated hydrocarbon generation windows indicate that the Middle Jurassic Upper Safa Shale has been generating gas from the Middle Paleogene to the Neogene and continues to generate gas to date. This study provides valuable information for the exploration and development of shale gas resources in the Middle Jurassic Upper Safa Shale in the Amoun field, Shushan Basin, Western Desert, Egypt, and indicates a strong resemblance between the evaluated sediments and highly productive shale gas reservoirs around the world.

Keywords: Unconventional reservoirs; Shale gas; Shale play; Shale resources; Source rock; Geochemical evaluation; Geochemistry; Rock-Eval pyrolysis

INTRODUCTION

A shale resource system is a continuous rock formation rich in organic material that can act as both a source and reservoir for petroleum (oil and gas) or as a barrier to prevent the movement of petroleum between adjacent rock formations that have low organic content. Producible natural gas shale resource systems in the United States provide a means of energy independence in natural gas for the foreseeable future. This may be for the next decade or for decades to come, depending on the economic, environmental, and political conditions for shale-gas production [1]. Basin modeling can play a key role in the shale gas evaluation process [2], Shushan Basin is a part of the northern Western Desert of Egypt, which has numerous of oil and gas potential and may jump soon as a great petroleum province. The Western Desert still has a significant hydrocarbon potential as recent oil and gas discoveries have suggested [3]. Perhaps 90% of undiscovered oil reserves and 80% of undiscovered gas reserves in Egypt are located in the Western Desert [4]. The area of study deals with this basin and lies between latitudes 30° 49’ 52”-30° 51’ 00” N and longitudes 26° 58’ 12”-27° 00’ 00” E (Figure 1).

Geological settings

Since 1961, several studies have investigated the structural and stratigraphic features of the Egyptian Western Desert, including works by Amin [5], Said [6,7], Norton [8], Parker [9], Meshref [10], Zein El Din, et al. [4,11], and Abdel-Gawad, et al. [12]. However, the study area is characterized by a three-way dip-closure that has been influenced by a major fault trend, significantly impacting the disposition of the stratigraphic formations in the

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region. This fault likely formed during the Early Tertiary Age due to the rifting process that occurred in the northern Western Desert, specifically the Red Sea system, and trends in a North West-South East direction. The northern Western Desert's generalized stratigraphic column (Figure 2) [13], comprises most of the sedimentary succession from the Pre-Cambrian basement complex to recent times and thickens progressively towards the north and northeast directions, ranging from about 6000 ft. in the south to about 25,000 ft. in the coastal area. The Upper Safa member (Middle Bathonian) which is the most important gas, condensate, and oil productive zone in the Shushan basin, is situated at a True Vertical Depth (TVD) of approximately 12050 ft. and has an average total thickness of approximately 696 ft. (TVT).

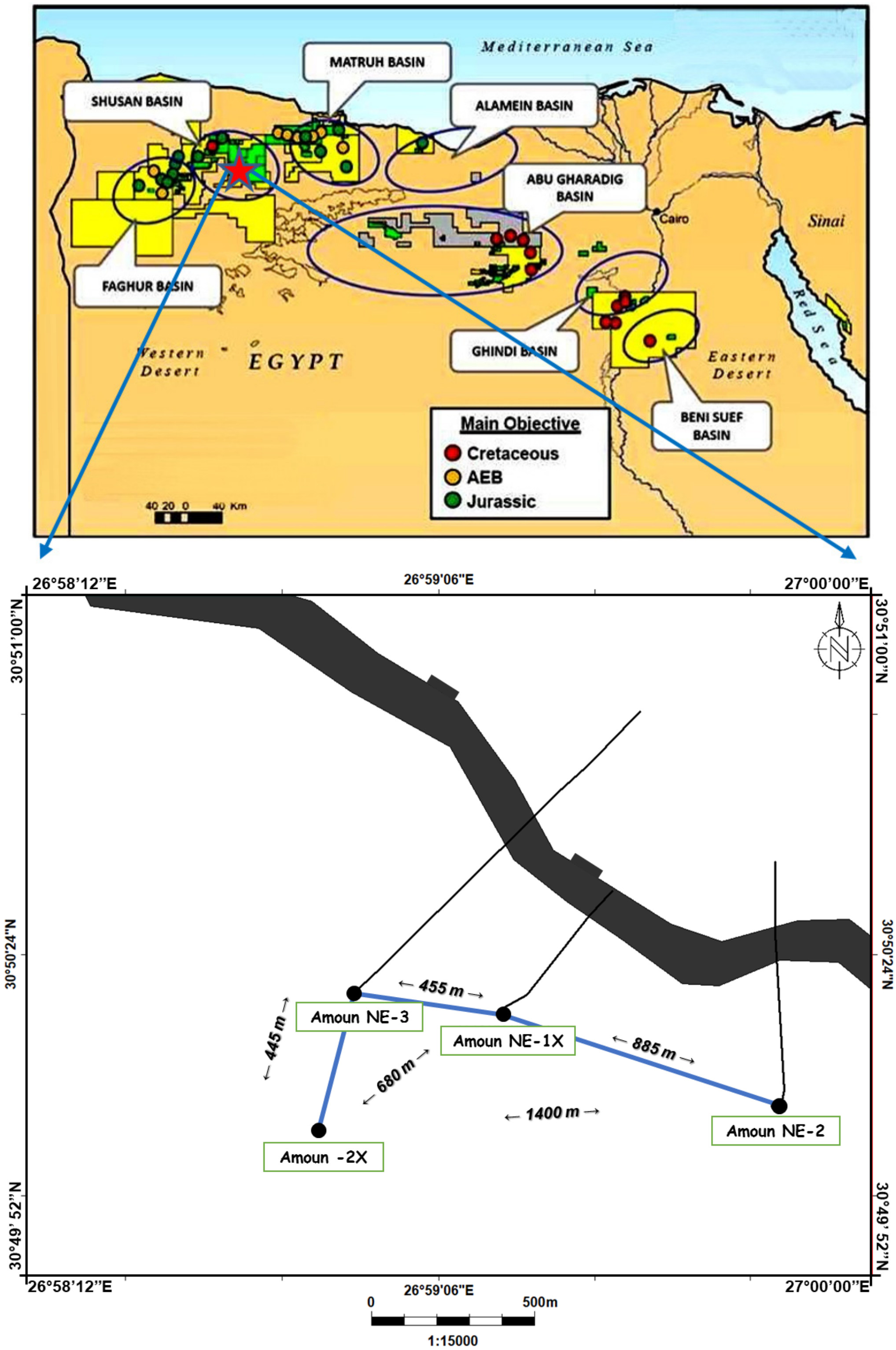

Figure 1: Location map and structural features of the study area, with emphasis on four wells locations and their relationship to the primary basins of Egypt's north Western Desert.

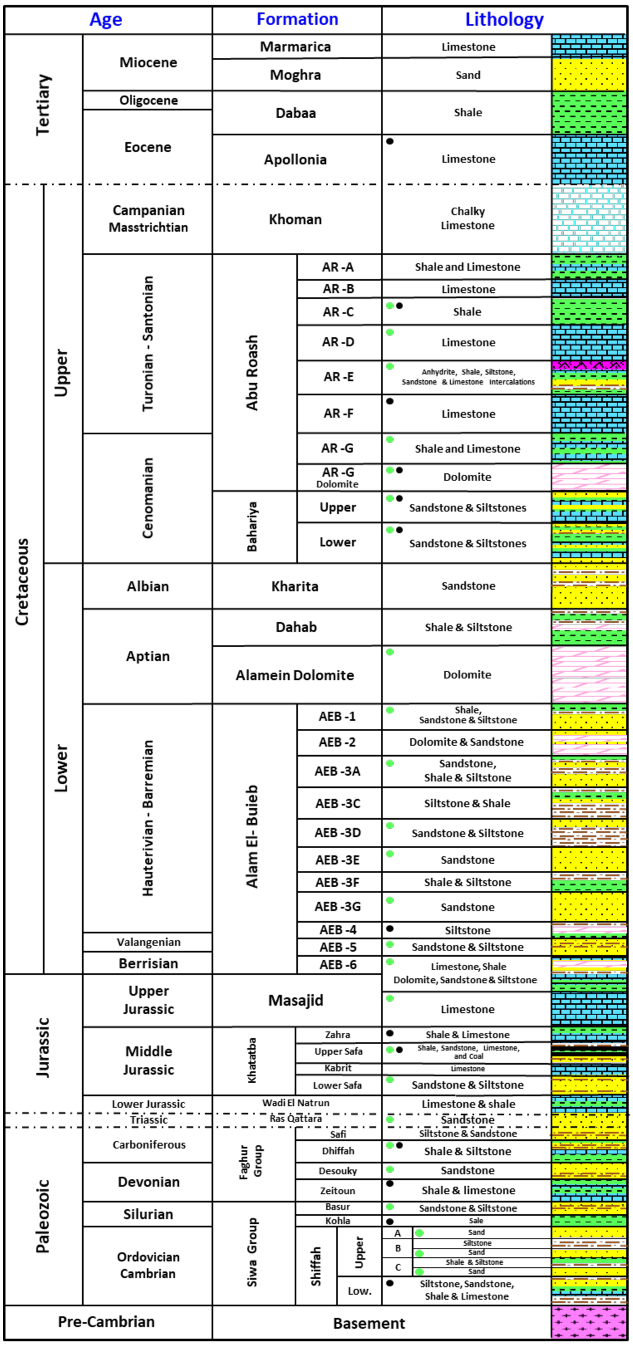

Figure 2: Generalized stratigraphic column of north-Western Desert, Egypt [13]. **Note:** ( ) Basement, ( ) Chalky limestone, ( ) Dolomite, ( ) Limestone, ( ) Sandstone, ( ) Shale, ( ) Siltstone, ( ) Coal.

MATERIALS AND METHODS

The geochemical evaluation of Middle Jurassic Upper Safa Sediments in the study area was conducted to assess their potential as a shale play. This involved analyzing geochemical measurements from three wells (Amoun NE-1X (using 3 ditch samples), Amoun NE-2 (using 46 ditch samples), and Amoun NE-3 (using 312 core samples plus 36 ditch samples), including Total Organic Carbon (TOC), pyrolysis data, and vitrinite reflectance (Ro%), which was analyzed for Amoun NE-2 (using 3 ditch samples) and Amoun NE-3 (using 7 core samples and 4 ditch samples). The evaluation consisted of two steps: (1) Assessing various geochemical parameters such as TOC, S1, S2, S3, Tmax, HI, OI, etc., and (2) using the results to predict and model maturation, hydrocarbon generation, and sedimentation rates over time with Schlumberger PetroMod v. 2012.2 software, additionally, the Schlumberger PETREL v. 2020 was used for generating the TOC maps. Considering that the primary conventional Upper Safa sandstone reservoir is located in the upper interval of the Upper Safa Member, the Upper Safa was sub-divided into two parts, namely Upper Safa Top (upper interval) and Upper Safa Bottom (lower interval). The aim of the study was to determine the potential of the Upper Safa shales for the hydrocarbon generation and identify the different types of hydrocarbons that might be generated, as well as to determine the generation windows.

RESULTS AND DISCUSSION

TOC evaluation

For the Upper Safa Top, the Amoun NE-1X well had a high TOC content of 3.91 wt.%. In Amoun NE-2 well, the range of TOC values was between 0.4 to 3.85 wt.%, with an average of 1.8 wt.%. For the Amoun NE-3 well, the TOC values ranged from 0.1 to 80 wt.%, with an average value of 2.2 wt.%. Similarly, the Upper Safa Bottom in the Amoun NE-1X well had a good TOC content of 1.31 and 1.55 wt.%, with an average of 1.43 wt.%. In the Amoun NE-2 well, the range of TOC values was between 0.04 to 4.53 wt.%, with an average of 1.1 wt.%. For the Amoun NE-3 well, the TOC values ranged from 0.14 to 18.8 wt.%, with an average value of 1.8 wt.%.

In general, the TOC values were classified based on Peters. [14] scheme, revealing that the Middle Jurassic Upper Safa shale in the study area is a high-quality hydrocarbon source rock (Figures 3-5). Additionally, the TOC content was estimated using the ΔlogR method of Passey, et al. [15], to generate a continuous TOC log for the Upper Safa member in all wells of study. The estimated TOC values were compared with the measured TOC for the Amoun NE-1X, Amoun NE-2, and Amoun NE-3 wells. The comparison exhibited an excellent level of agreement between ΔlogR TOC and the measured TOC (Figures 6-11). Furthermore, as direct Total Organic Carbon (TOC) measurements were not available for the Amoun-2X well, the nearby wells' measurements were used for calibration. Despite this challenge, randomly selected TOC values ranged from 1.04 to 4.59 wt.% with an average of 2.25 wt.%, suggesting a good to very good TOC content within the Upper Safa member in the Amoun-2X well (Figures 12-14). However, the TOC concentration in all wells of study is sufficient to produce a significant amount of hydrocarbons during thermal maturation that can overcome adsorption and surface tension effects, leading to commercially significant expulsion of hydrocarbons from the rock matrix [16].

The average TOC distribution map of Upper Safa Top (Figure 15) reveals an increase in the average TOC towards the fault direction and decreases in the opposite directions. Furthermore, the average TOC distribution map of the Upper Safa Bottom (Figure 16) shows a significant increase in TOC values towards the northwestern direction, and showing a general decrease in TOC values towards the central region of the study area.

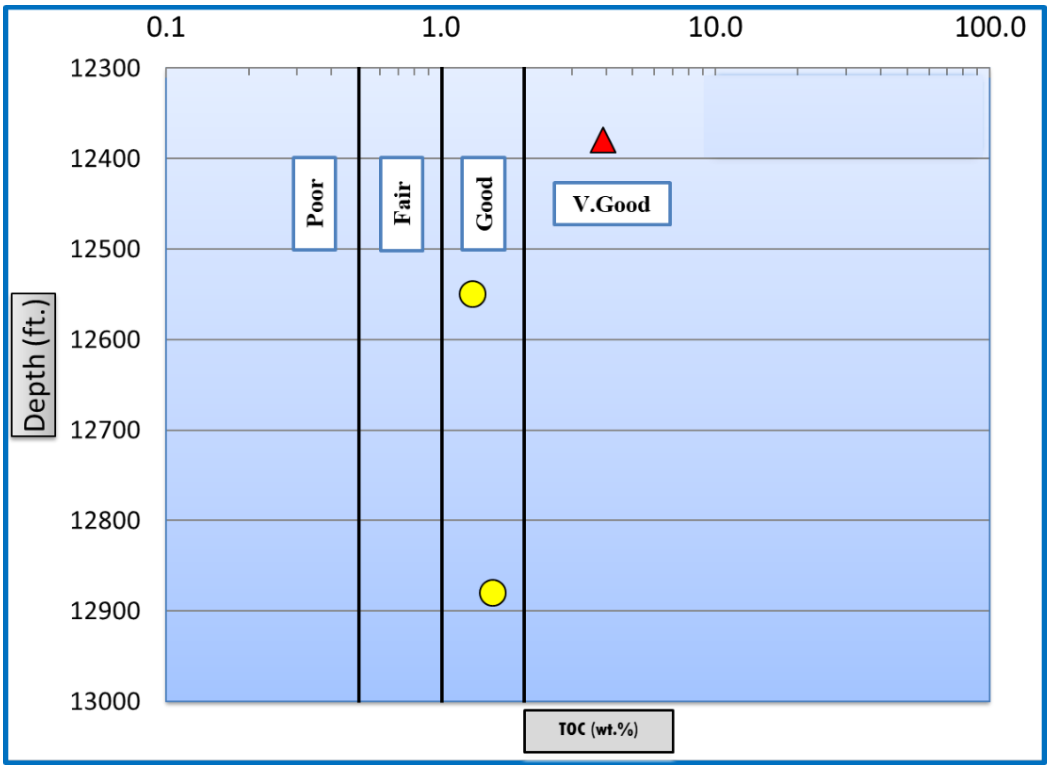

Figure 3: TOC of the Upper Safa member, Amoun NE-1X well, according to the classification of Peters. [14]. **Note:** (▲) Upper Safa Top, (●) Upper Safa Bottom.

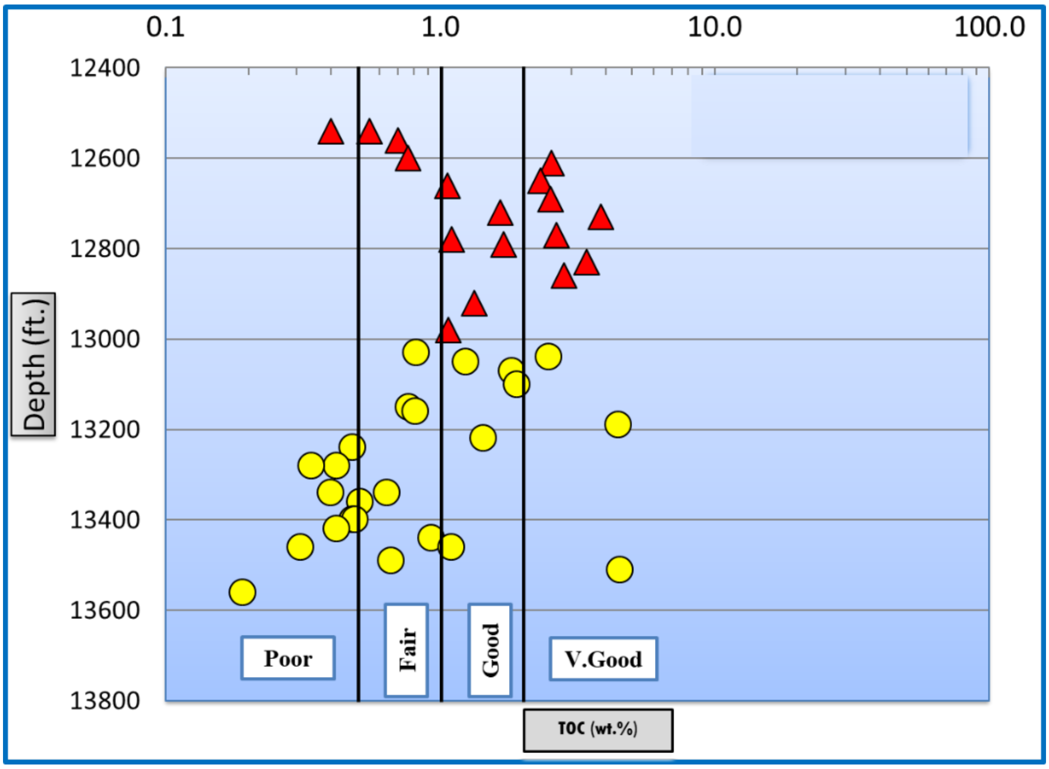

Figure 4: TOC of the Upper Safa member, Amoun NE-2 well, according to the classification of Peters. [14]. **Note:** (▲) Upper Safa Top, (●) Upper Safa Bottom.

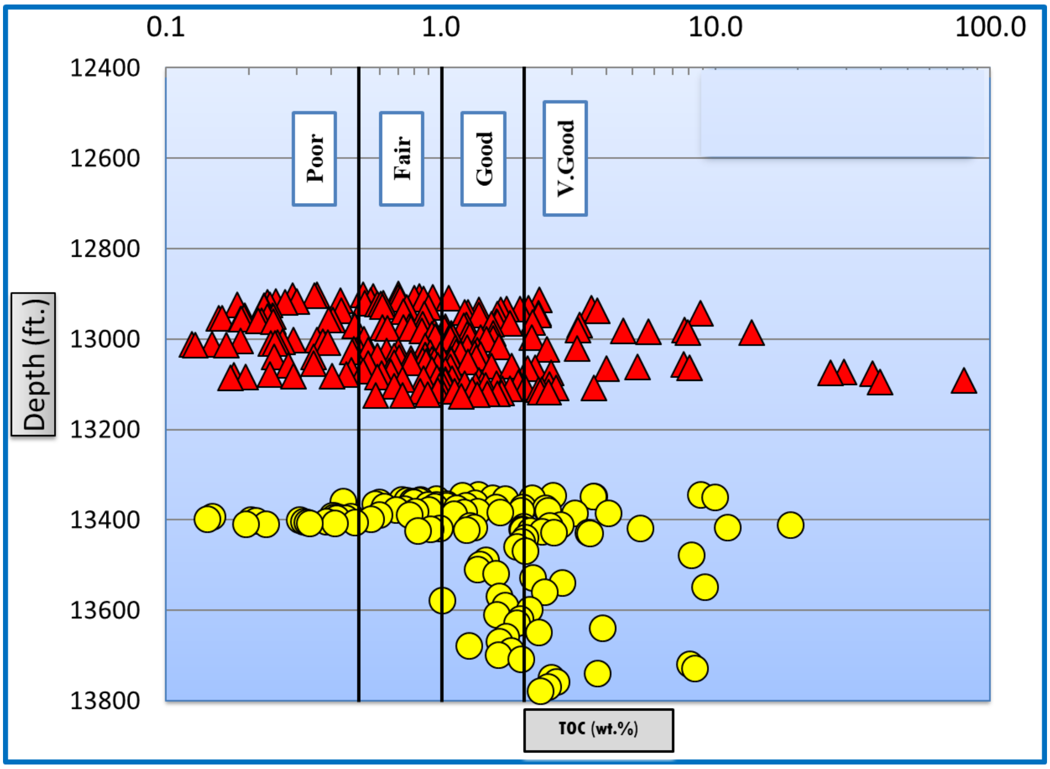

Figure 5: TOC of the Upper Safa member, Amoun NE-3 well, according to the classification of Peters. [14]. **Note:** (▲) Upper Safa Top, (●) Upper Safa Bottom.

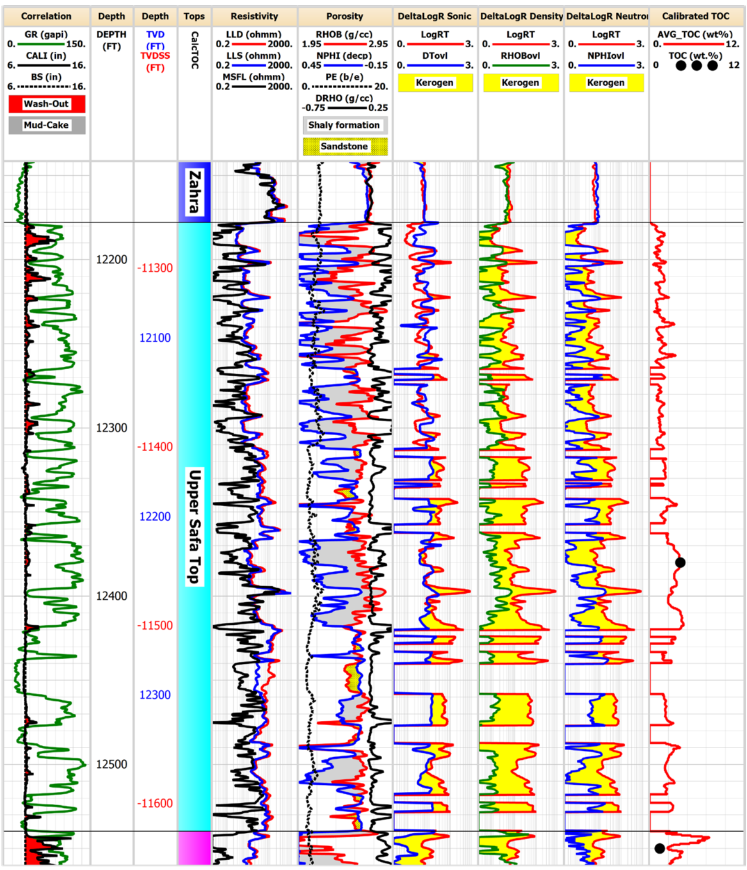

Figure 6: ΔlogR calibrated TOC log for the Upper Safa Top, Amoun NE-1X well.

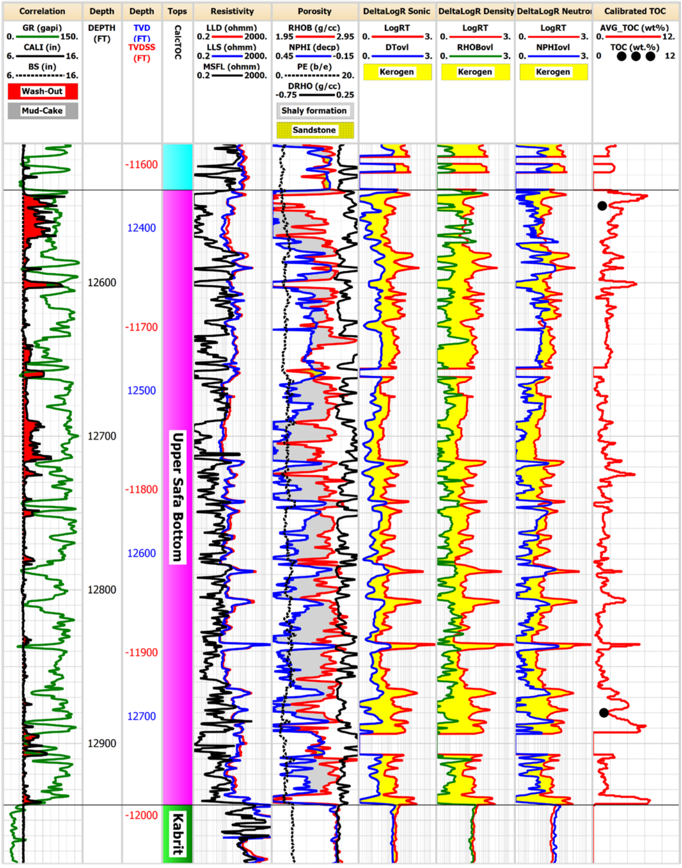

Figure 7: ΔlogR calibrated TOC log for the Upper Safa Bottom, Amoun NE-1X well.

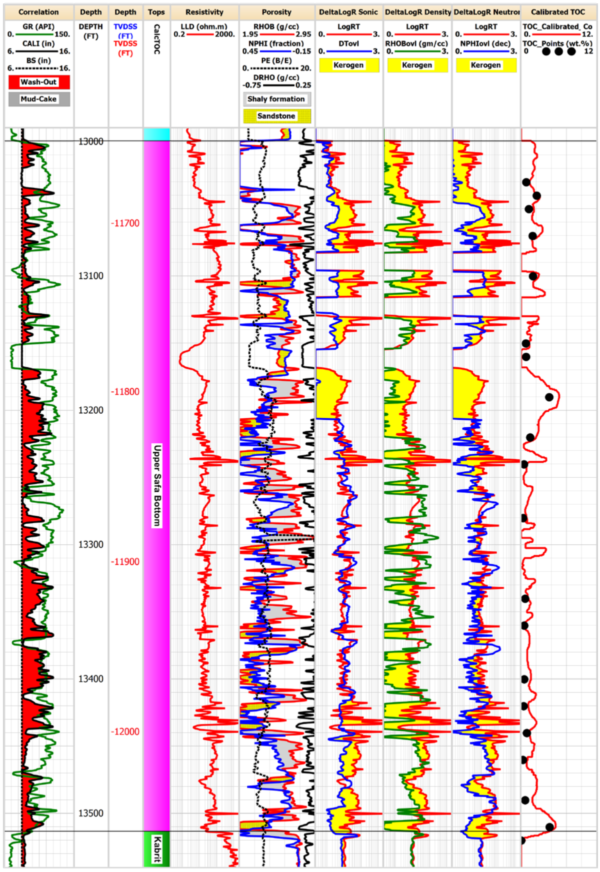

Figure 8: ΔlogR calibrated TOC log for the Upper Safa Top, Amoun NE-2 well.

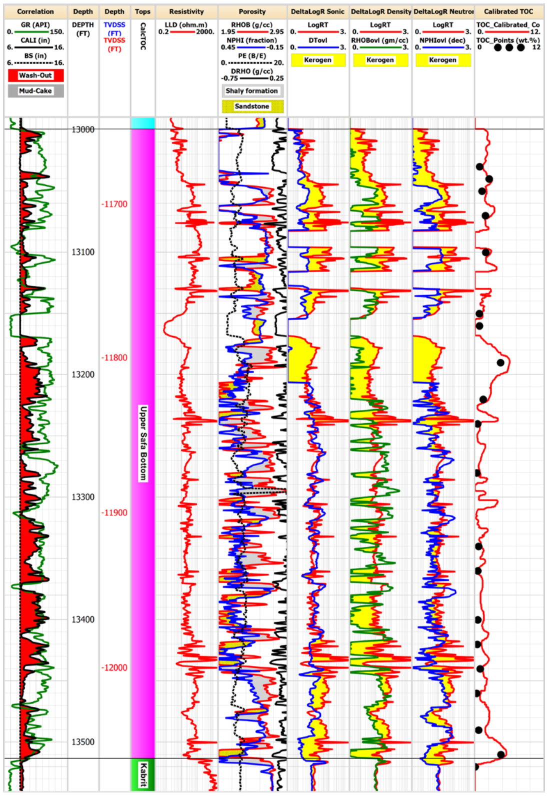

Figure 9: ΔlogR calibrated TOC log for the Upper Safa Bottom, Amoun NE-2 well.

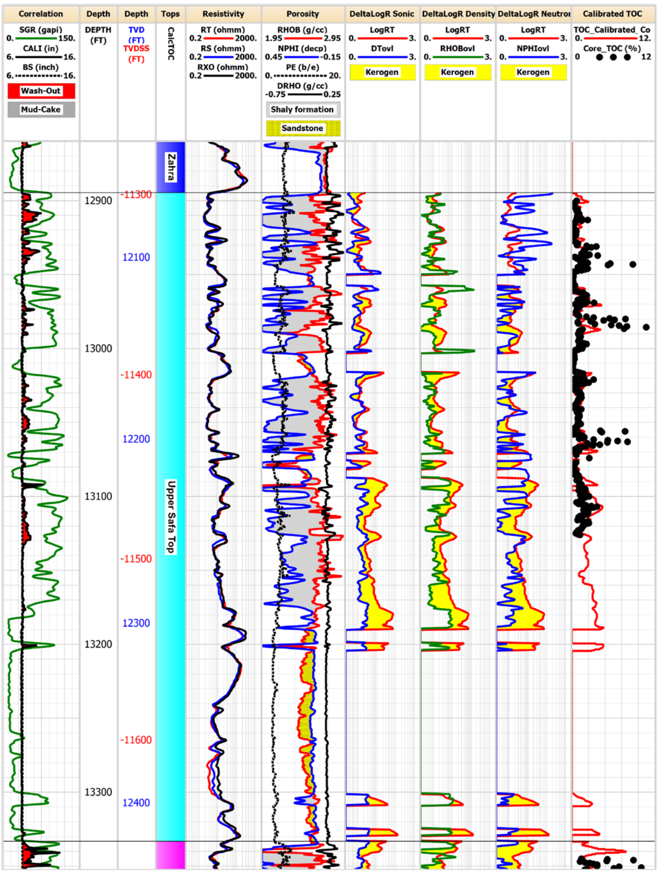

Figure 10: ΔlogR calibrated TOC log for the Upper Safa Top, Amoun NE-3 well.

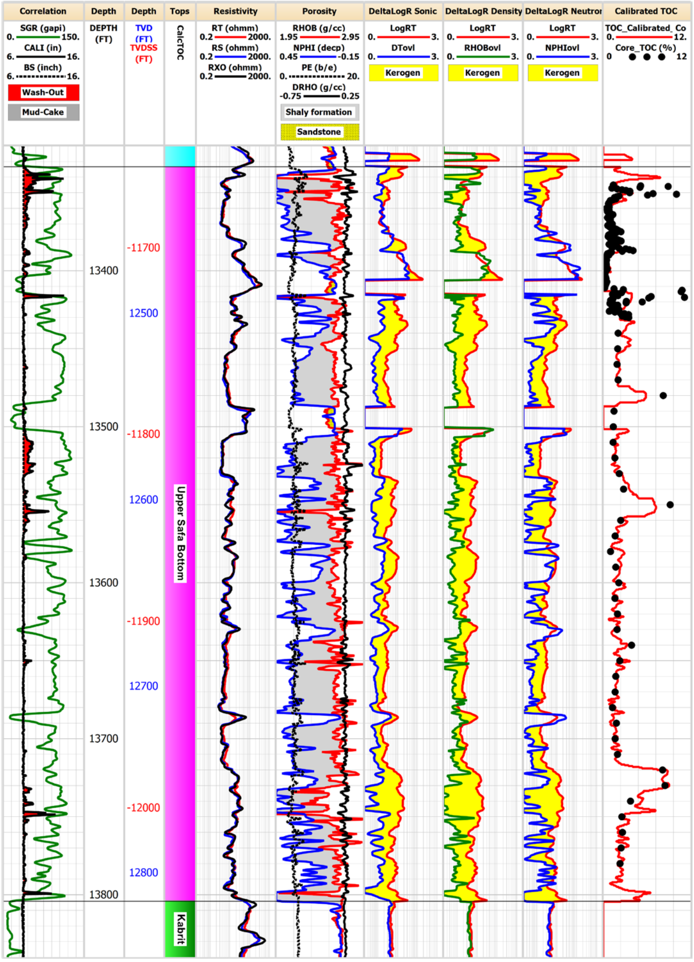

Figure 11: ΔlogR calibrated TOC log for the Upper Safa Bottom, Amoun NE-3 well.

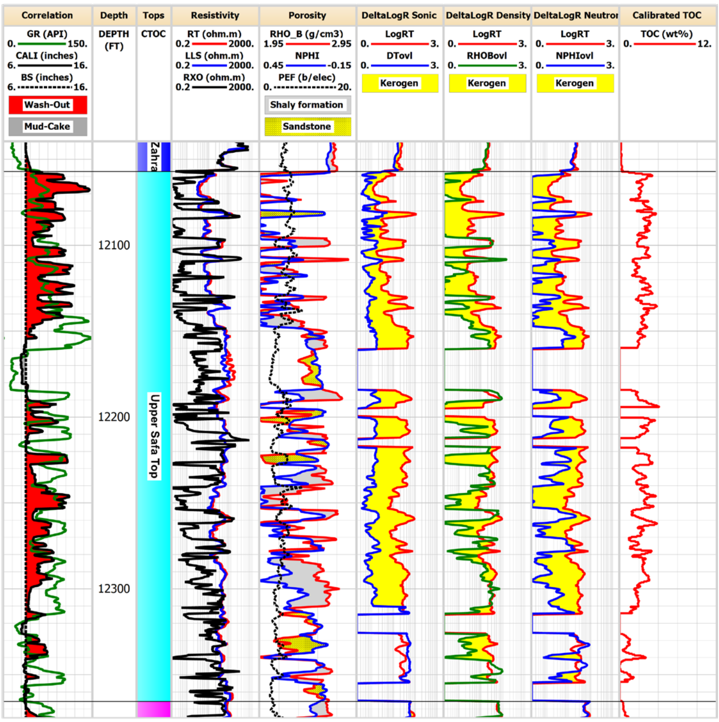

Figure 12: ΔlogR calibrated TOC log for the Upper Safa Top, Amoun-2X well.

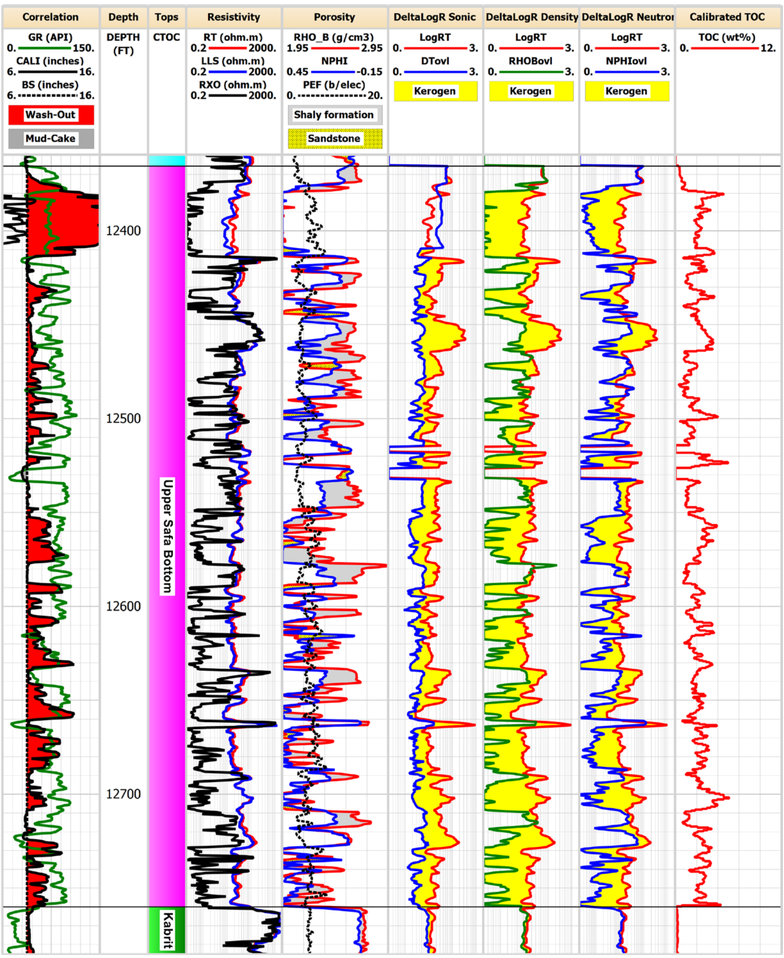

Figure 13: ΔlogR calibrated TOC log for the Upper Safa Bottom, Amoun-2X well.

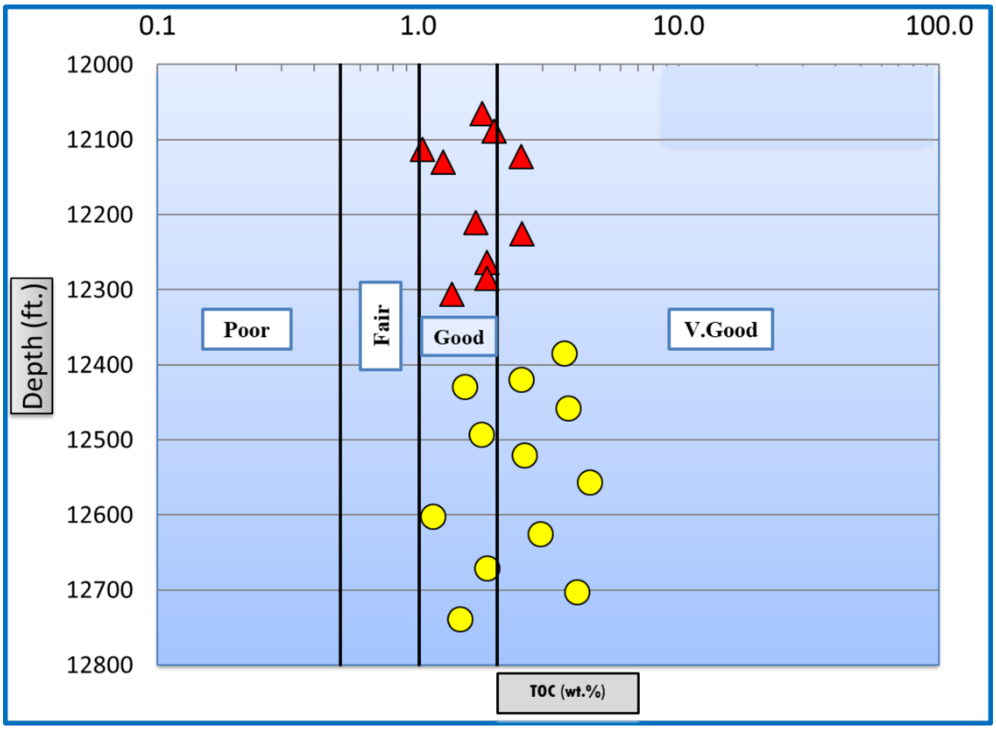

Figure 14: Evaluation of randomly selected calculated TOC of the Middle Jurassic Upper Safa shales, Amoun-2X well, according to the classification of Peters. [14]. **Note:** (▲) Upper Safa Top, (○) Upper Safa Bottom.

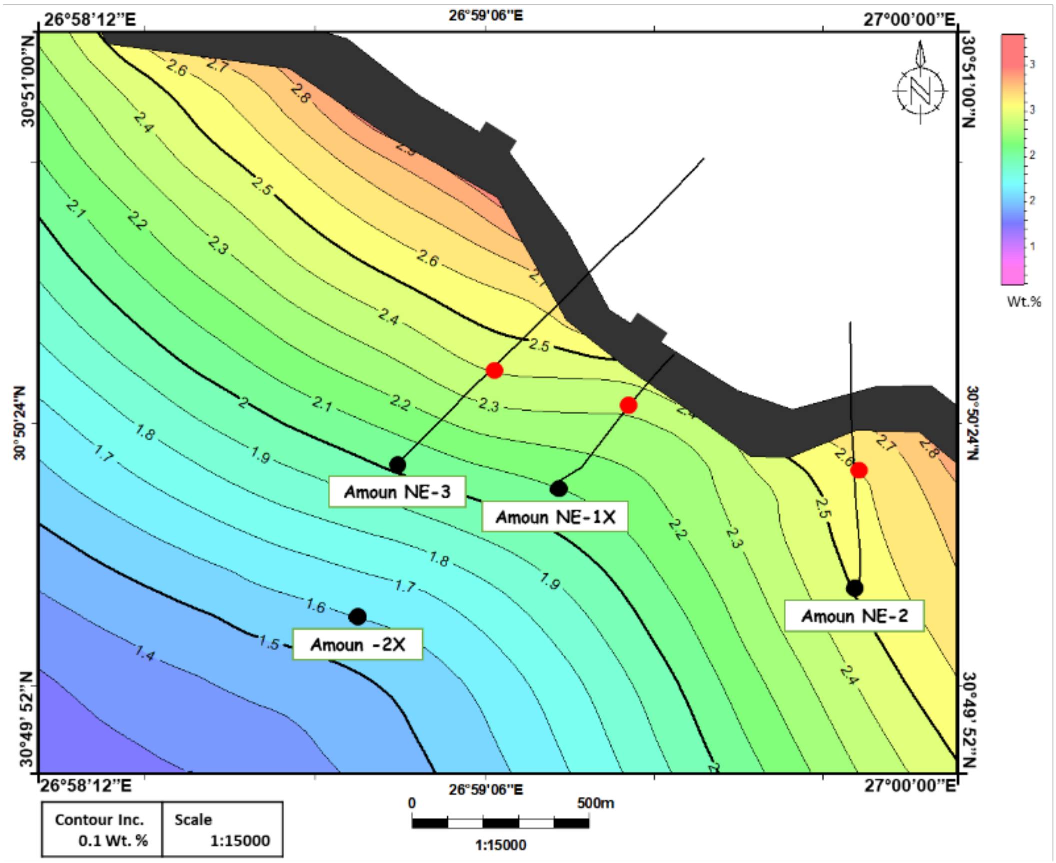

Figure 15: TOC distribution map of the Upper Safa Top in the study area.

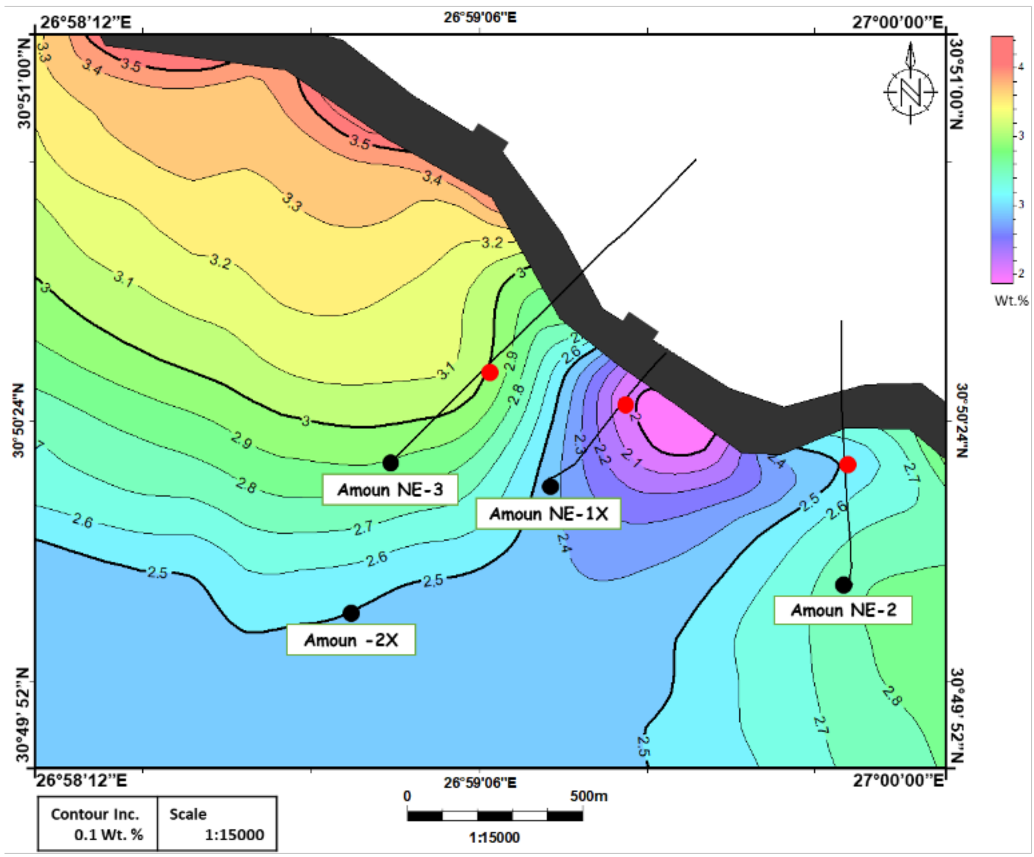

Figure 16: TOC distribution map of the Upper Safa Bottom in the study area.

Kerogen type

The Middle Jurassic Upper Safa shale in the study area exhibits Hydrogen Index (HI) values ranging from 88 to 136.8 on average, indicating kerogen type III with some extent to kerogen type II and III, according to Waples. [17] classification. Additionally, the modified van Krevelen diagram (Figures 17-19) indicates that the Upper Safa member shale in the study area is predominantly composed of type III kerogen, with some extent to type II. These findings suggest that the Middle Jurassic Upper Safa shale has a high potential for gas generation, with marginal potential for liquid generation.

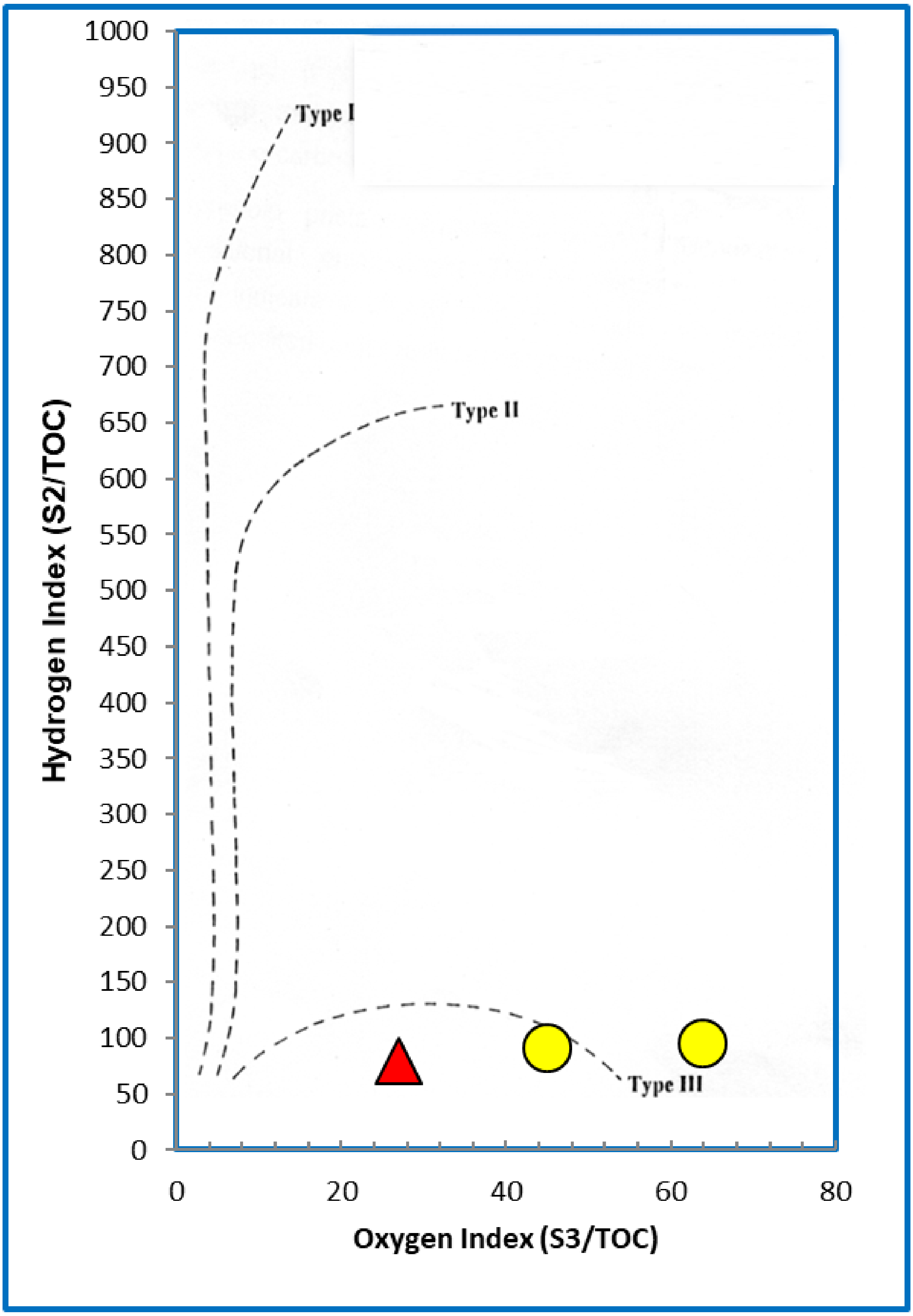

Figure 17: Modified Van Krevelen diagram revealing the kerogen type of the Upper Safa, Amoun NE-1X well. **Note:** (▲) Upper Safa Top, (○) Upper Safa Bottom.

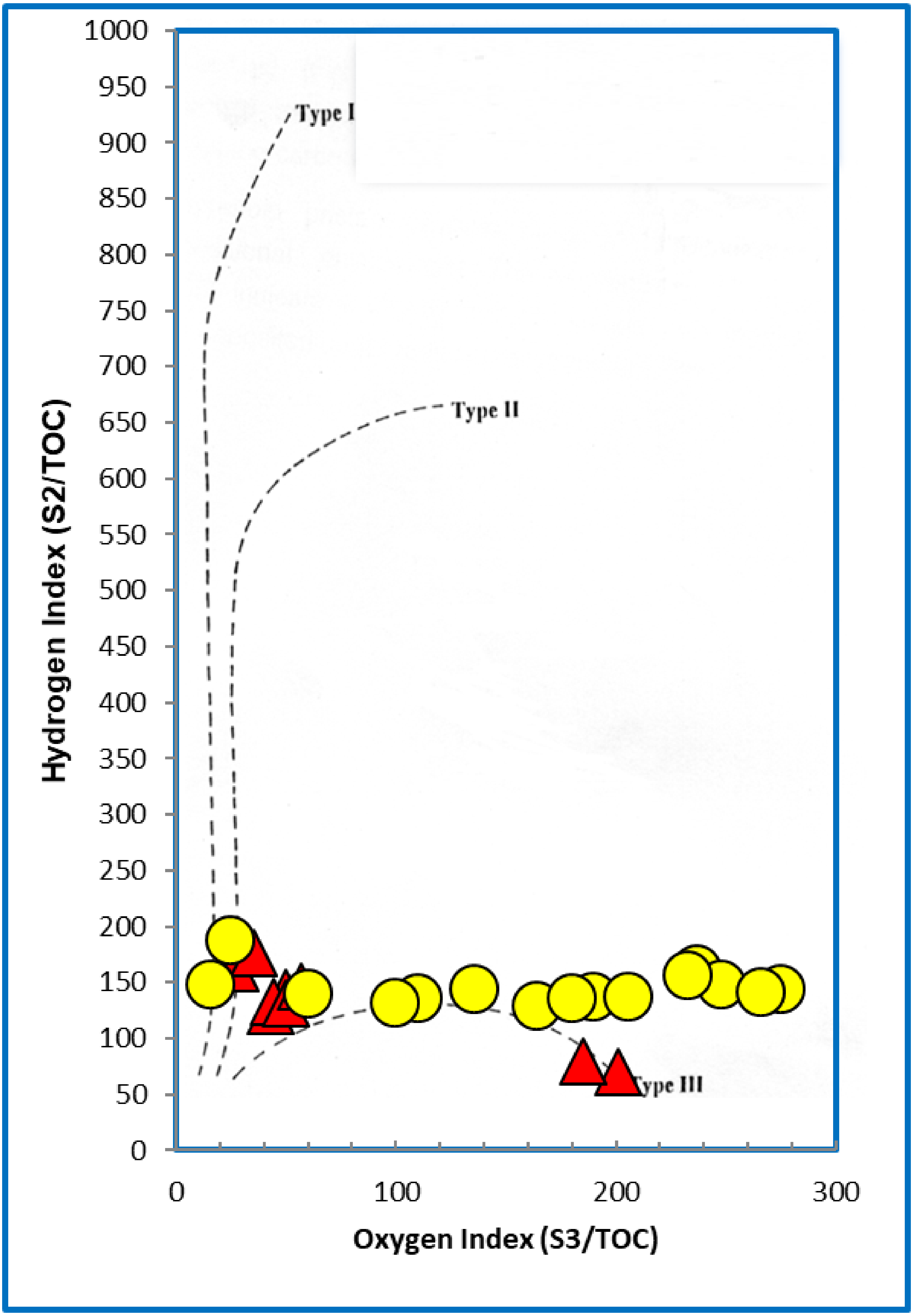

Figure 18: Modified Van Krevelen diagram revealing the kerogen type of the Upper Safa, Amoun NE-2 well. **Note:** (▲) Upper Safa Top, (●) Upper Safa Bottom.

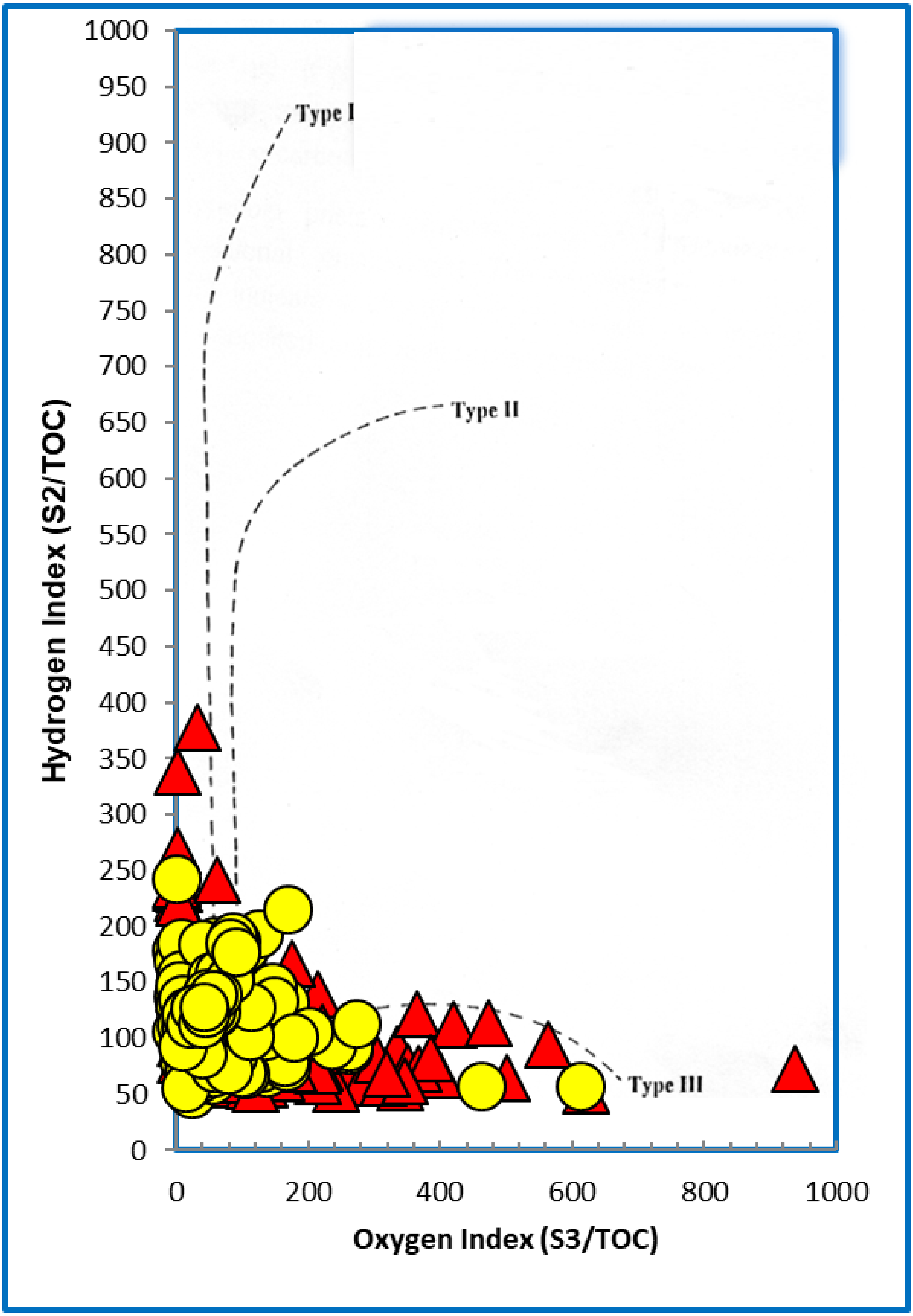

Figure 19: Modified Van Krevelen diagram revealing the kerogen type of the Upper Safa, Amoun NE-3 well. **Note:** (▲) Upper Safa Top, (●) Upper Safa Bottom.

Maturity of organic matter

The Tmax values of the Upper Safa shales in the study area were classified using the classification scheme of Peters and Cassa [18], (Figures 20-22). For the Amoun NE-1X well, the Tmax values of the entire Upper Safa Sediments range from 453°C to 462°C with an average value of 456.3°C. This indicates that these sediments are located in the late maturation stage. For the Amoun NE-2 well, the Tmax values of the entire Middle Jurassic Upper Safa sediments show a wide range, from 280°C to 467°C, with an average value of 444.3°C, indicating that these sediments have passed through the early to late maturation stages. For the Amoun NE-3 well, the Tmax values have a wide range from 400°C to 475°C, with an average value of 446°C. These values indicate that the majority of these sediments have entered the late maturation stage, having passed through the early and peak of maturation stages, with some points still located in the immature stage. In general, the Tmax values in all wells of the study area confirm that the majority of these sediments have already entered the late maturation stage.

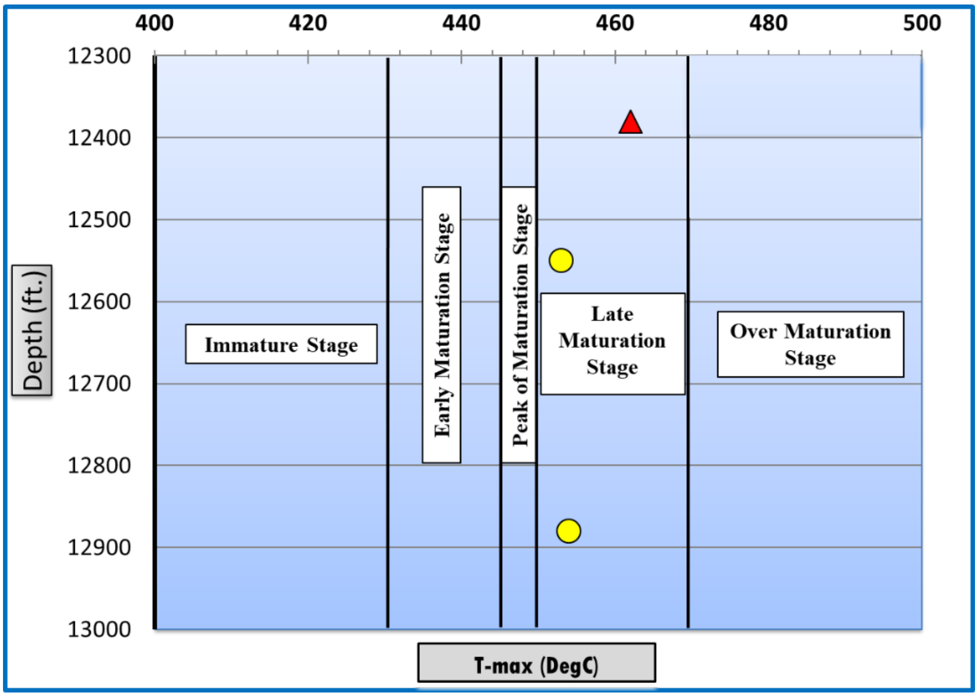

Figure 20: Thermal maturity of the Upper Safa, Amoun NE-1X well, according to the classification of Peters and Cassa [18]. **Note:** (▲) Upper Safa Top, (○) Upper Safa Bottom.

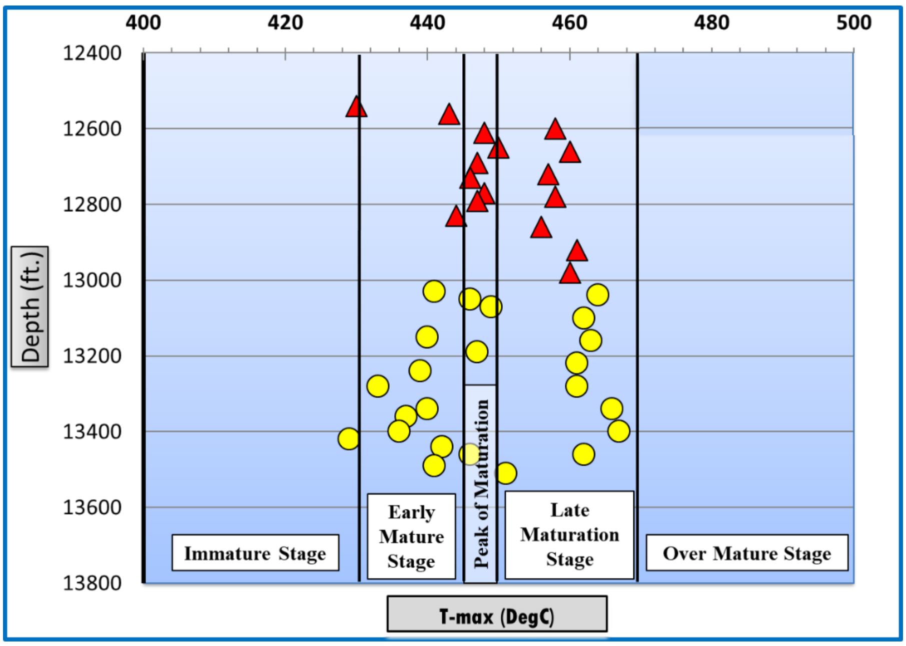

Figure 21: Thermal maturity of the Upper Safa, Amoun NE-2 well, according to the classification of Peters and Cassa [18]. **Note:** (▲) Upper Safa Top, (○) Upper Safa Bottom.

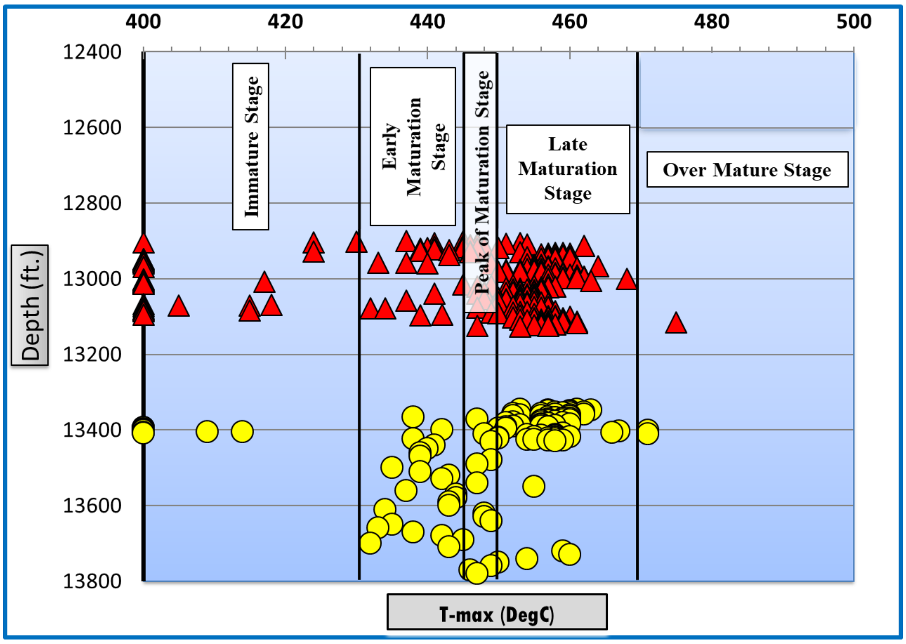

Figure 22: Thermal maturity of the Upper Safa, Amoun NE-3 well, according to the classification of Peters and Cassa [18]. **Note:** (▲) Upper Safa Top, (●) Upper Safa Bottom.

The Amoun NE-2 and Amoun NE-3 wells have been analyzed for their vitrinite reflectance (%Ro) values, which range from 0.7 to 1.09% with an average value of 0.963% and from 0.72 to 1% with an average value of 0.83%, respectively. These values have been classified according to Peters. [14], and indicate that the sediments have already reached the mature stage (Figures 23 and 24). Additionally, detailed Ro values have been classified according to Dow. [19], to identify the hydrocarbon generation type (Figures 25 and 26). The results show that the shales have passed the peak of the oil generation and are now in the wet gas and peak of gas generation stages. The results obtained from the Amoun NE-2 and Amoun NE-3 wells suggest that the shale in the study area have undergone significant thermal maturation.

Modeled vitrinite reflectance

The maximum Ro% values have been estimated from the available present-day Ro% values, and both have been integrated as a guide for the software calculations and modeling. The modeled Ro% values for the study area (Figures 27-30) show an increasing trend with depth. The average Ro% values at the base of the Upper Safa member have been found to be 1.26, 1.37, 1.40 and 1.20 for the Amoun NE-1X, Amoun NE-2, Amoun NE-3 and Amoun-2X wells respectively, as presented in Figures 27-30. These values, according to the classification of Dow. [19], indicate that these shales are mature and are currently located in the peak of gas generation stage.

Burial history and hydrocarbon zones

The constructed thermal burial history models and the location of the oil and gas windows for each well, illustrate the hydrocarbon generation potential of the study area. These models also indicate the depth and age of both oil and gas generation for each well. It is noteworthy that the depth of the oil and gas windows varies from one well to another. The oil generation window for the Amoun NE-1X, Amoun NE-2, Amoun NE-3, and Amoun 2X wells was reached at 6911, 6856, 6568, and 6447 ft., respectively. The gas generation window was reached at 12874, 12908, 13077, and 13789 ft., for the same wells. The timing of oil and gas generation also varies significantly from well to well. The time of oil generation is 130.17, 130.69, 130.03, and 120.15 Mabp, while the time of gas generation is 43.6, 43.93, 48.35, and 11.95 Mabp, for the Amoun NE-1X, Amoun NE-2, Amoun NE-3, and Amoun 2X wells, respectively (Figures 31-34). These results suggest that the Upper Safa shales of the study area may have commenced generating oil during the Early Cretaceous. On the other hand, gas generation may have begun during the Middle Paleogene to the Neogene, and is still ongoing up to the present time.

Global geochemical benchmarks for assessing Upper Safa Shale as a shale gas reservoir

The importance of an integrated approach to evaluate unconventional reservoirs was emphasized by Jarvie. [1]. He compiled a set of average geochemical parameters from the world's top ten productive shale gas reservoirs, including Marcellus, Haynesville, Bossier, Barnett, Fayetteville, Muskwa, Woodford, Eagle Ford, Utica, and Montney, which serve as benchmarks for assessing unconventional reservoirs. These parameters include Total Organic Carbon (TOC) content, Hydrogen Index (HI), and vitrinite reflectance (%Ro). According to the study, the TOC content averages ranged from 0.2 to 13 wt.%, HI averages ranged from 10 to 80, and %Ro averages ranged from 0.7 to 5. Jarvie cautioned that these averages could vary from one basin to another.

Jarvie's findings are highly relevant to the Middle Jurassic Upper Safa shale in the Shushan Basin, Egypt's Western Desert. Across all study wells in the area, the measured TOC content averaged between 1.4 to 2.256 wt.%, while the measured %Ro averages ranged from 0.83 to 1%, and the calculated %Ro averages were found to be between 1.2 to 1.4, and the HI average ranged from 88 to 136.8. All of these values fall within the ranges described by Jarvie. [1], for the top ten productive shale gas reservoirs worldwide, indicating that the Middle Jurassic Upper Safa shale of the study area has promising potential as a shale gas reservoir.

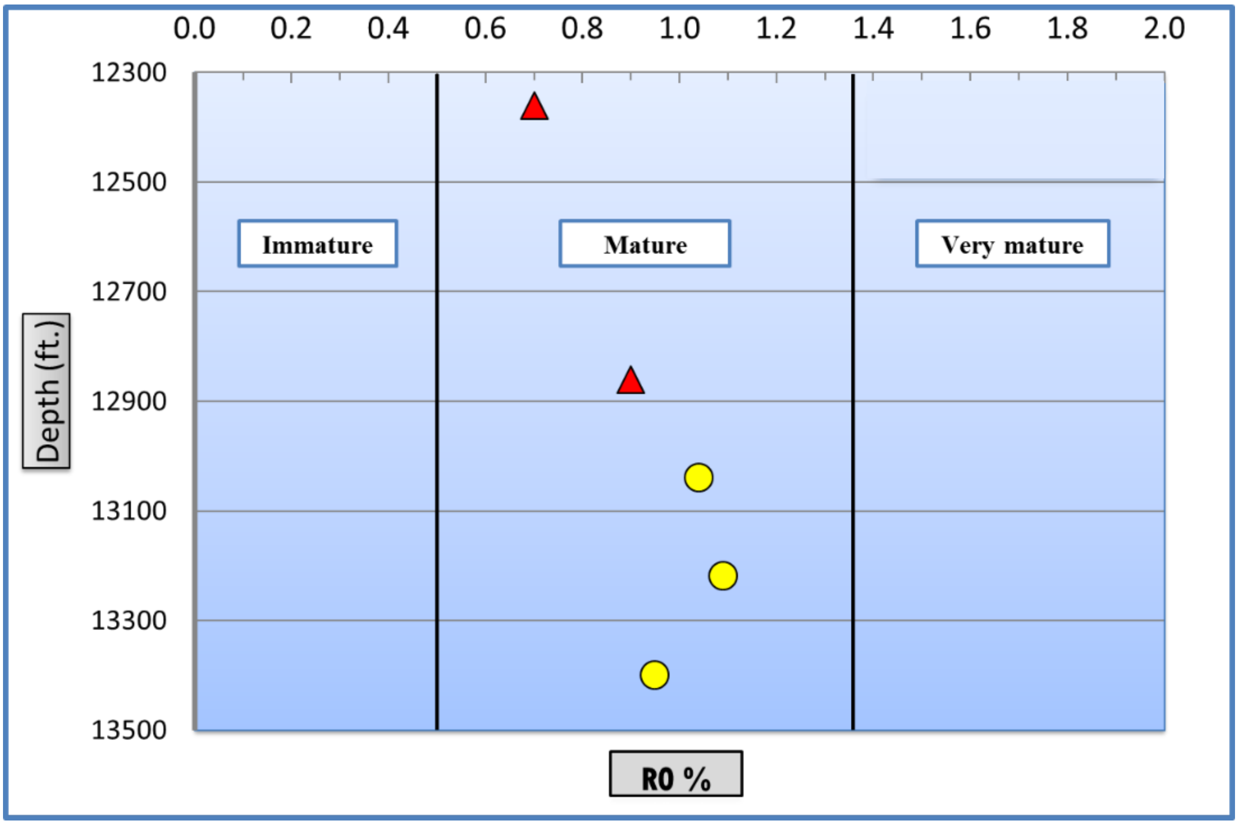

Figure 23: Ro maturity of the Upper Safa, Amoun NE-2 well, according to the classification of Peters. [14]. **Note:** (▲) Upper Safa Top, (●) Upper Safa Bottom.

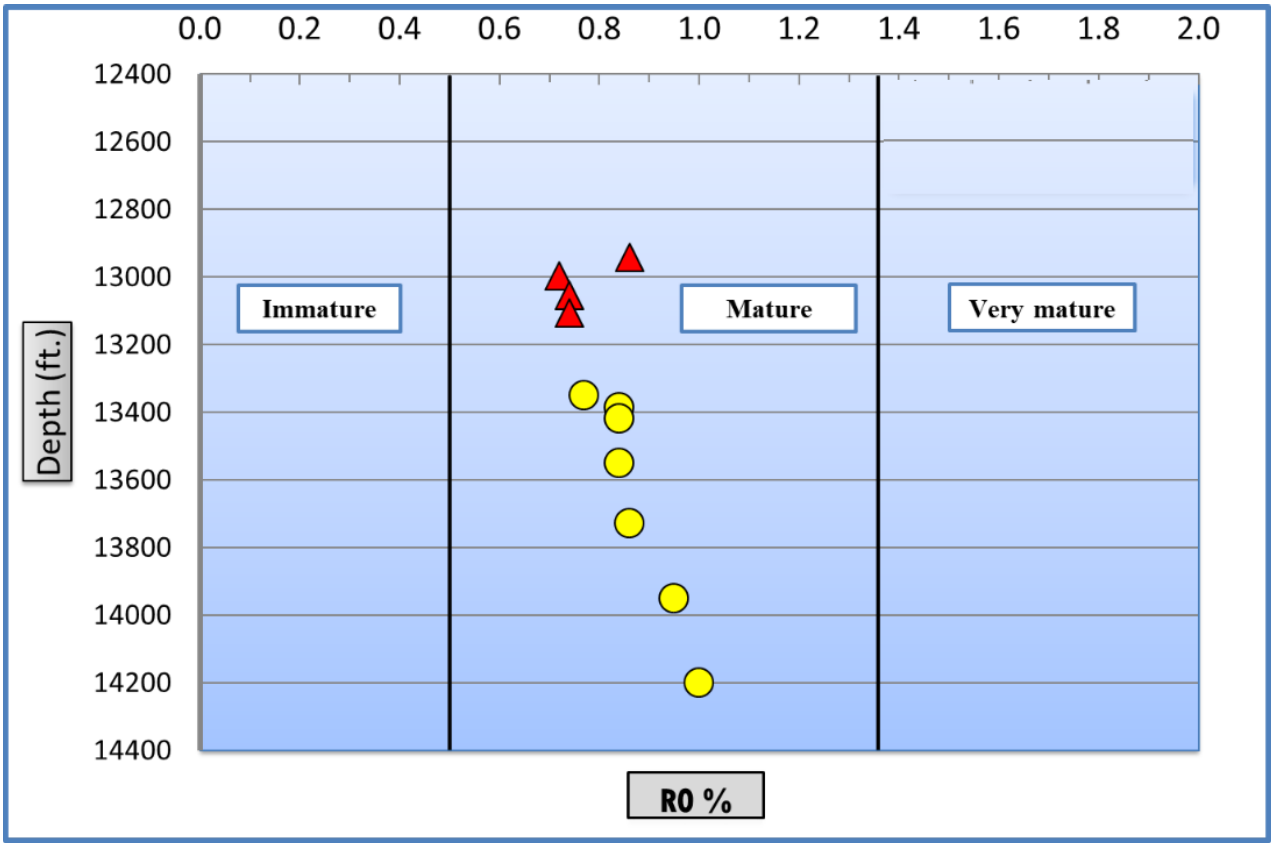

Figure 24: Ro maturity of the Upper Safa, Amoun NE-3 well, according to the classification of Peters. [14]. **Note:** (▲) Upper Safa Top, (●) Upper Safa Bottom.

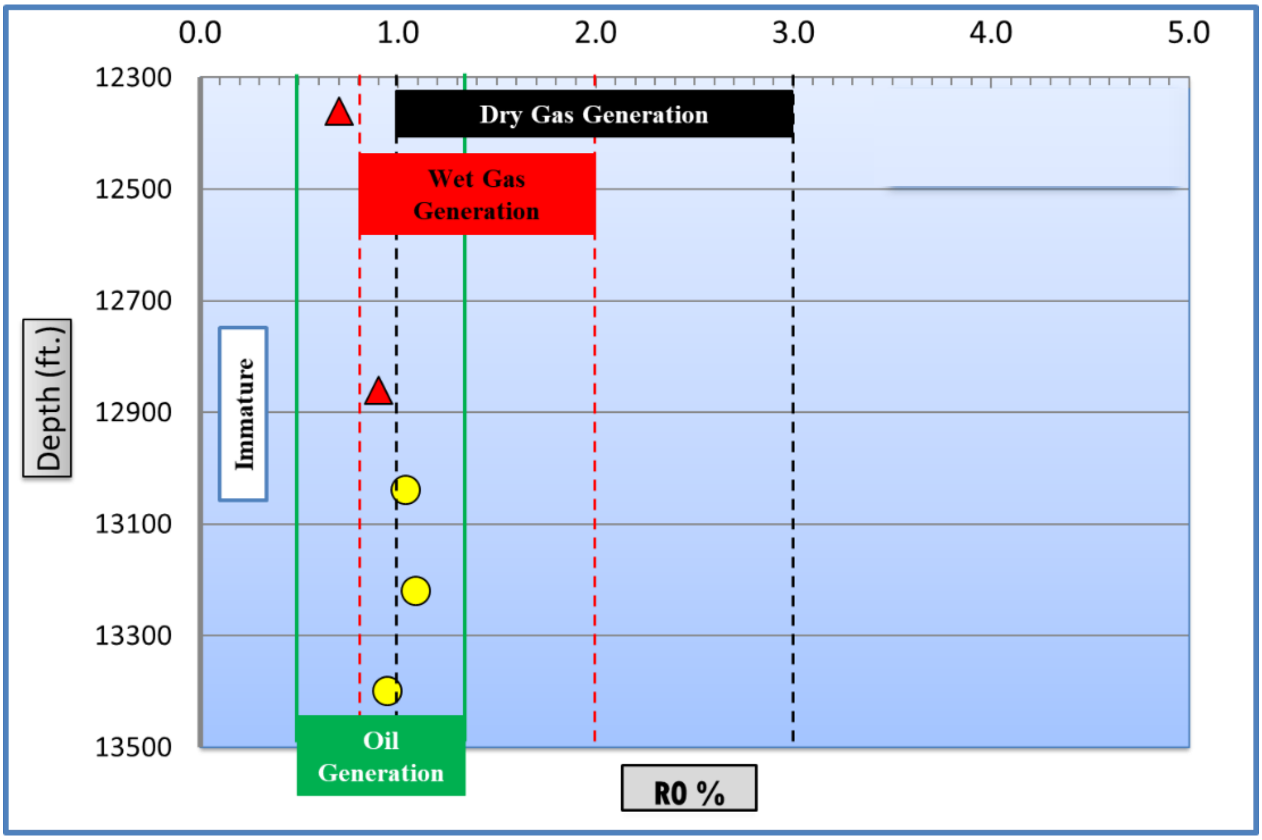

Figure 25: Ro maturity, and hydrocarbon generation of the Upper Safa, Amoun NE-2 well, according to the classification of Dow. [19]. **Note:** (▲) Upper Safa Top, (○) Upper Safa Bottom.

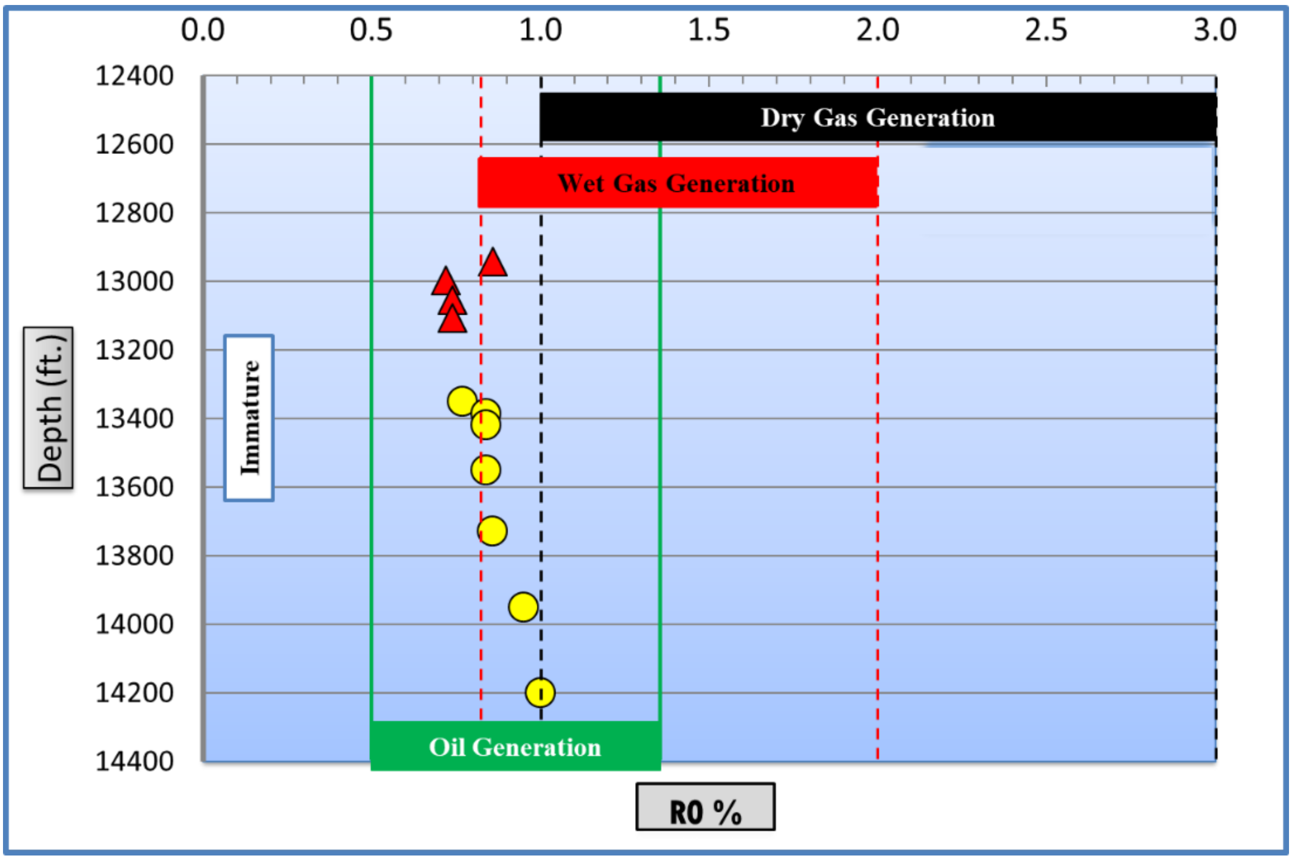

Figure 26: Ro maturity, and hydrocarbon generation of the Upper Safa, Amoun NE-3 well, according to the classification of Dow. [19]. **Note:** (▲) Upper Safa Top, (○) Upper Safa Bottom.

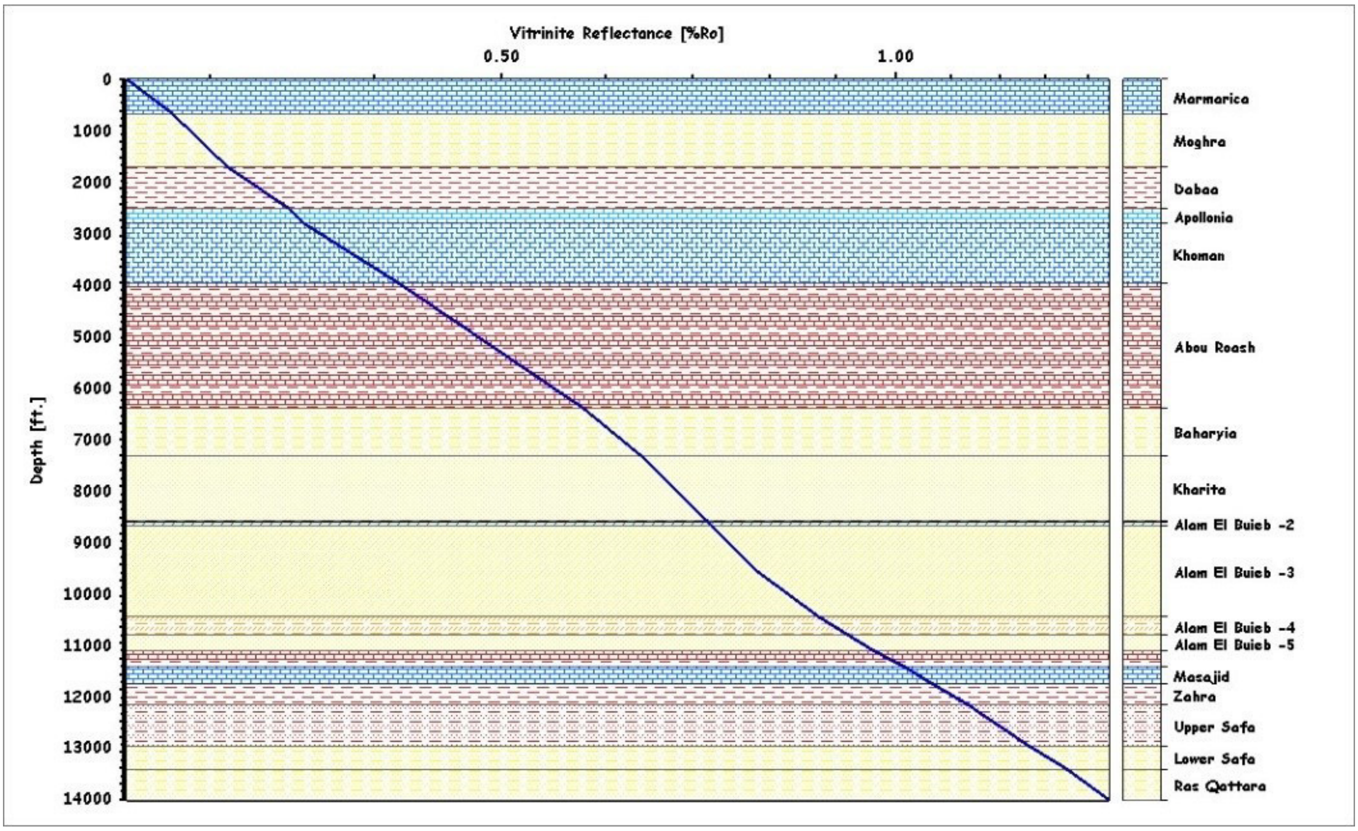

Figure 27: Modeled calculated vitrinite reflectance, Amoun NE-1X. **Note:** (▬) Vitrinite reflectance.

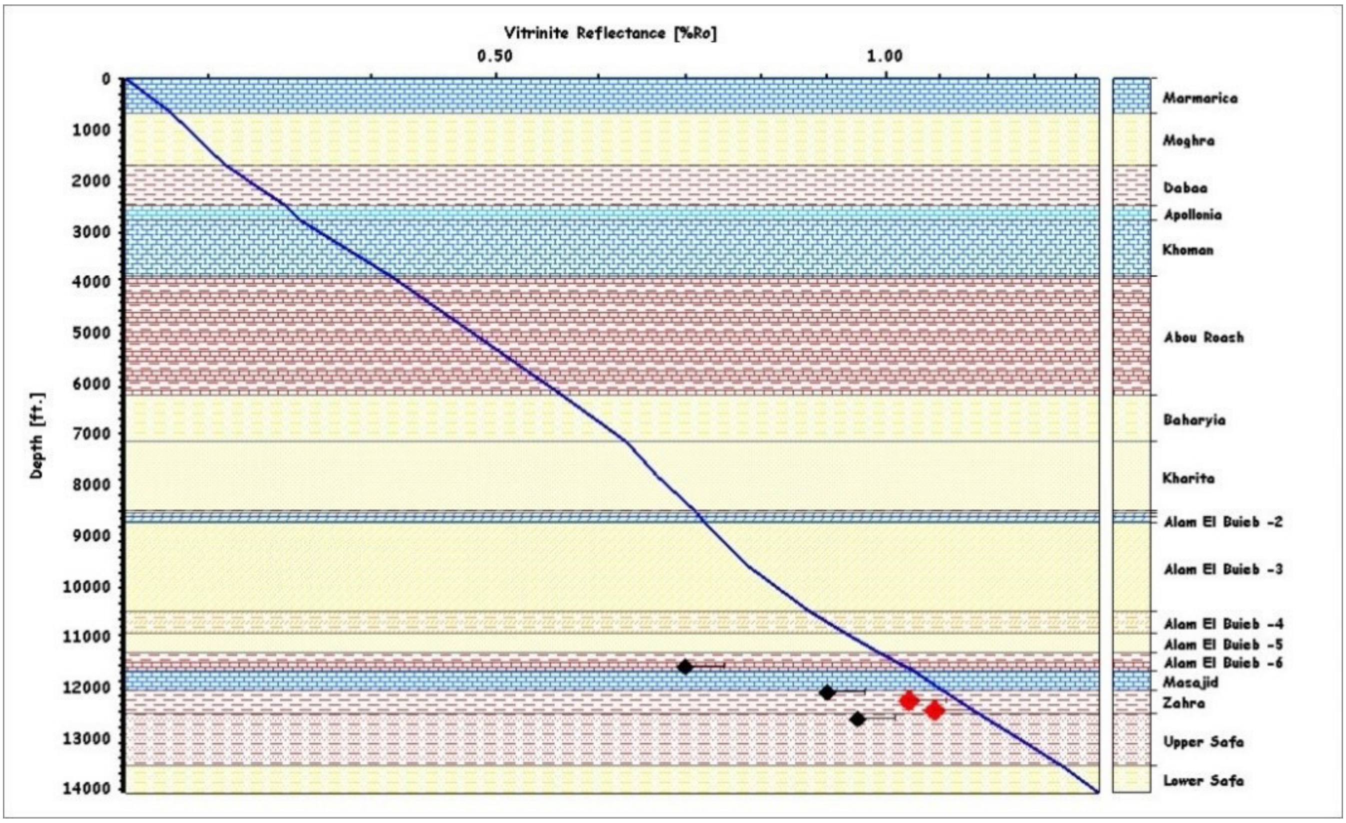

Figure 28: Modeled calculated (line) and measured (symbols) Vitrinite reflectance of the Amoun NE-2 well. **Note:** (▬) Vitrinite reflectance, (◆) Red symbols indicate good quality samples, (◆) black symbols indicate low quality samples.

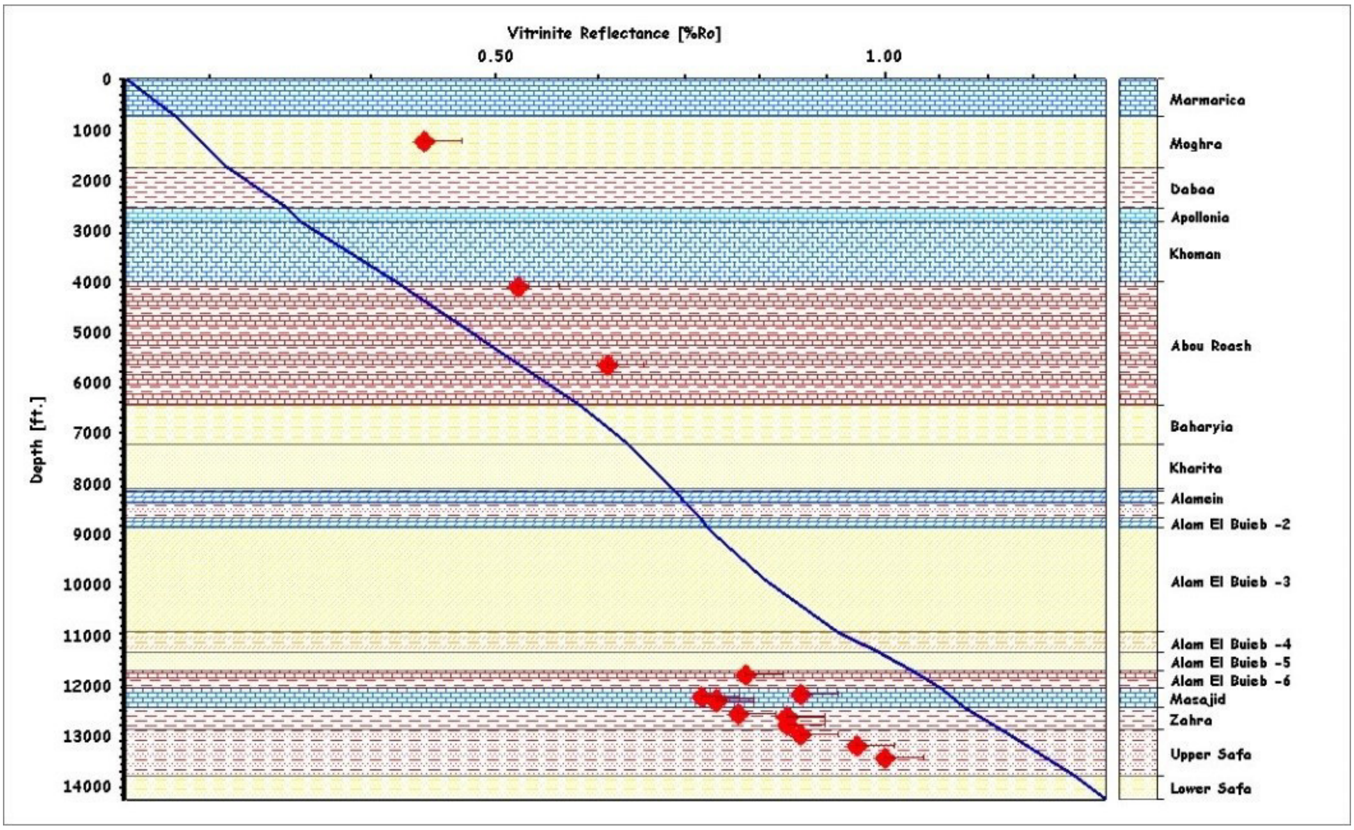

Figure 29: Modeled calculated vitrinite reflectance, Amoun NE-3 well. **Note:** (▬) Vitrinite reflectance, (◆) Red symbols indicate good quality samples.

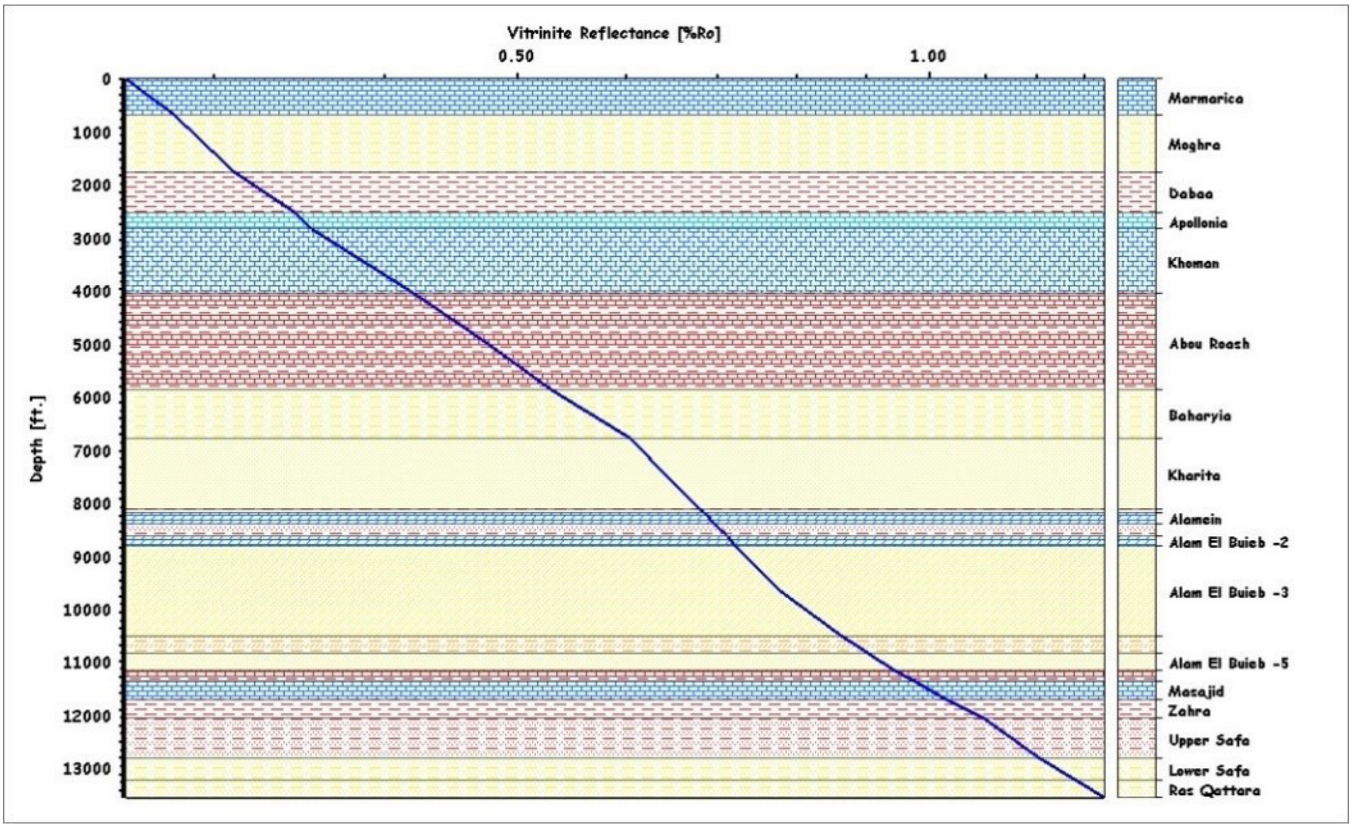

Figure 30: Modeled calculated vitrinite reflectance, Amoun-2X well. **Note:** (▬) Vitrinite reflectance.

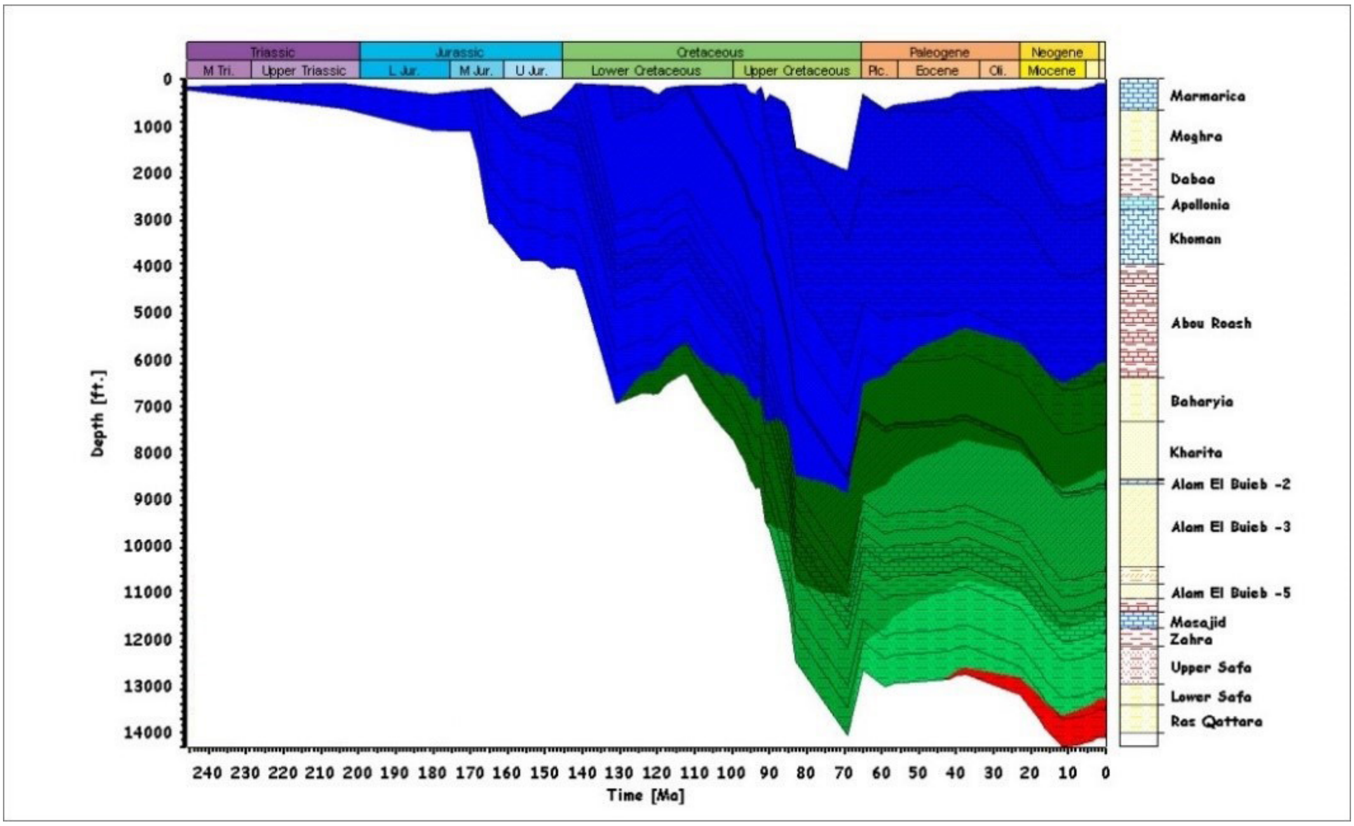

Figure 31: Burial history and hydrocarbon zones, Amoun NE-1X well. **Note:** Vitrinite reflectance (%Ro) ( ) Immature (0.00-0.55), ( ) Early oil (0.55-0.70), ( ) Main oil (0.70-1.00), ( ) Late oil (1.00-1.30), ( ) Wet gas (1.30-2.00), ( ) Dry gas (2.00-4.00), ( ) Over mature (4.00-5.00).

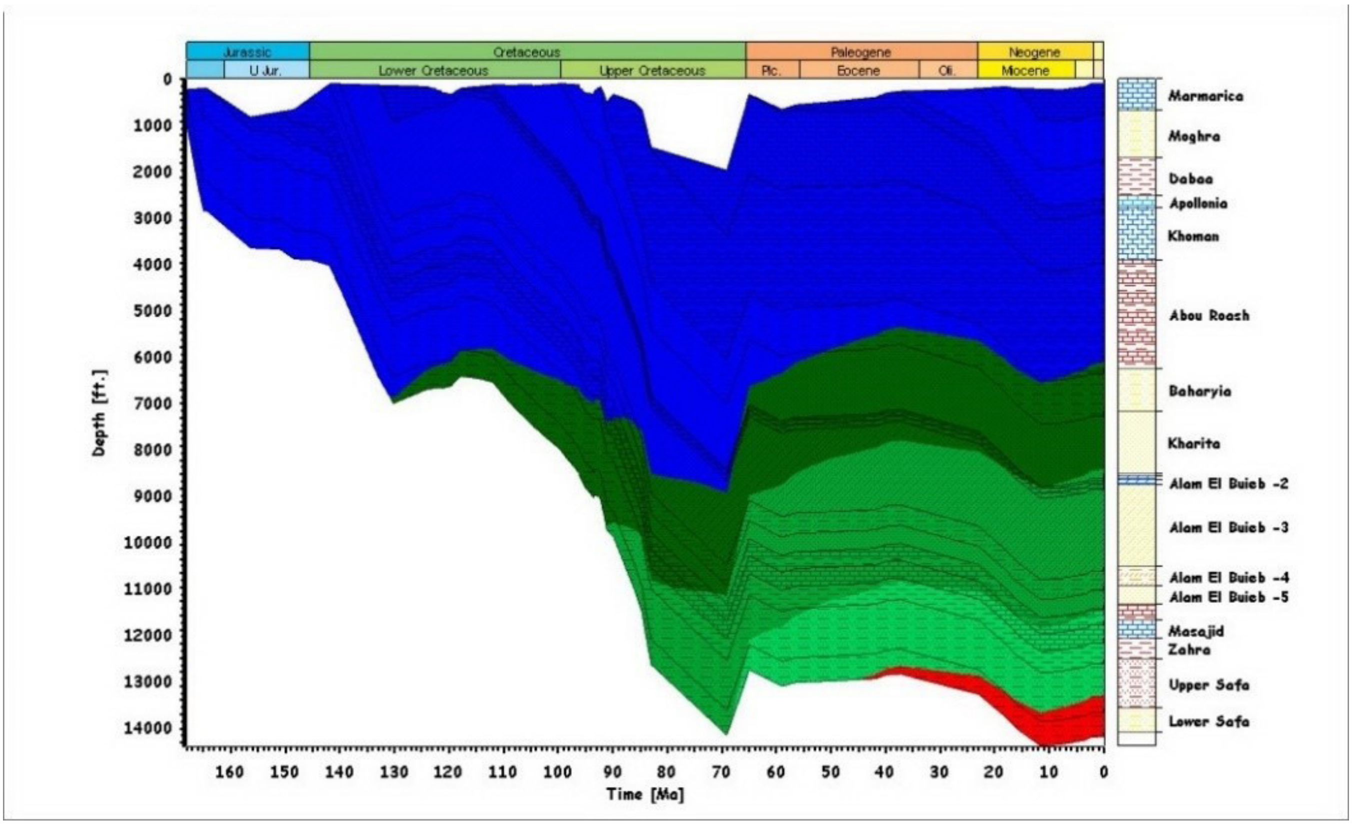

Figure 32: Burial history and hydrocarbon zones, Amoun NE-2 well. **Note:** Vitrinite reflectance (%Ro) ( ) Immature (0.00-0.55), ( ) Early oil (0.55-0.70), ( ) Main oil (0.70-1.00), ( ) Late oil (1.00-1.30), ( ) Wet gas (1.30-2.00), ( ) Dry gas (2.00-4.00), ( ) Over mature (4.00-5.00).

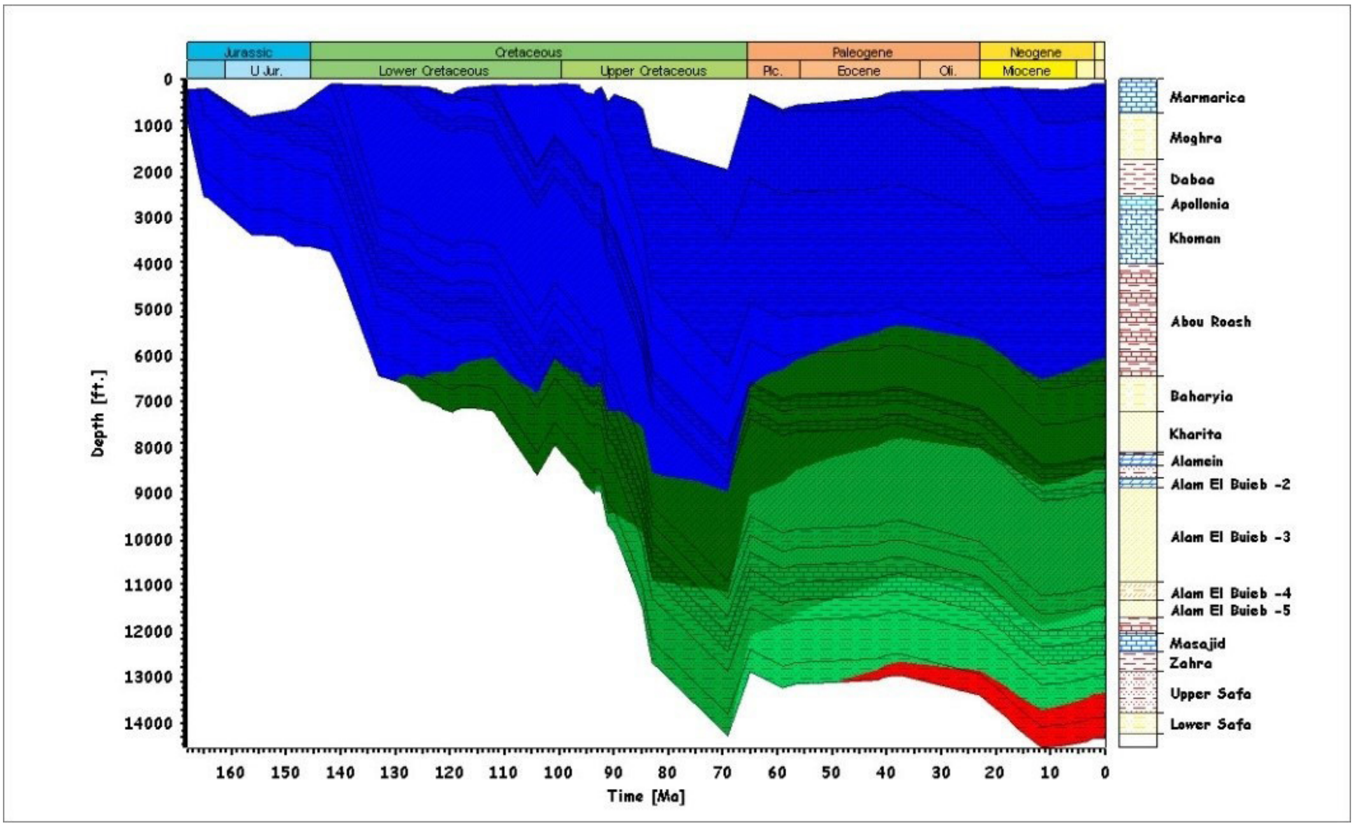

Figure 33: Burial history and hydrocarbon zones, Amoun NE-3 well. **Note:** Vitrinite reflectance (%Ro) (■) Immature (0.00-0.55), (■) Early oil (0.55-0.70), (■) Main oil (0.70-1.00), (■) Late oil (1.00-1.30), (■) Wet gas (1.30-2.00), (■) Dry gas (2.00-4.00), (■) Over mature (4.00-5.00).

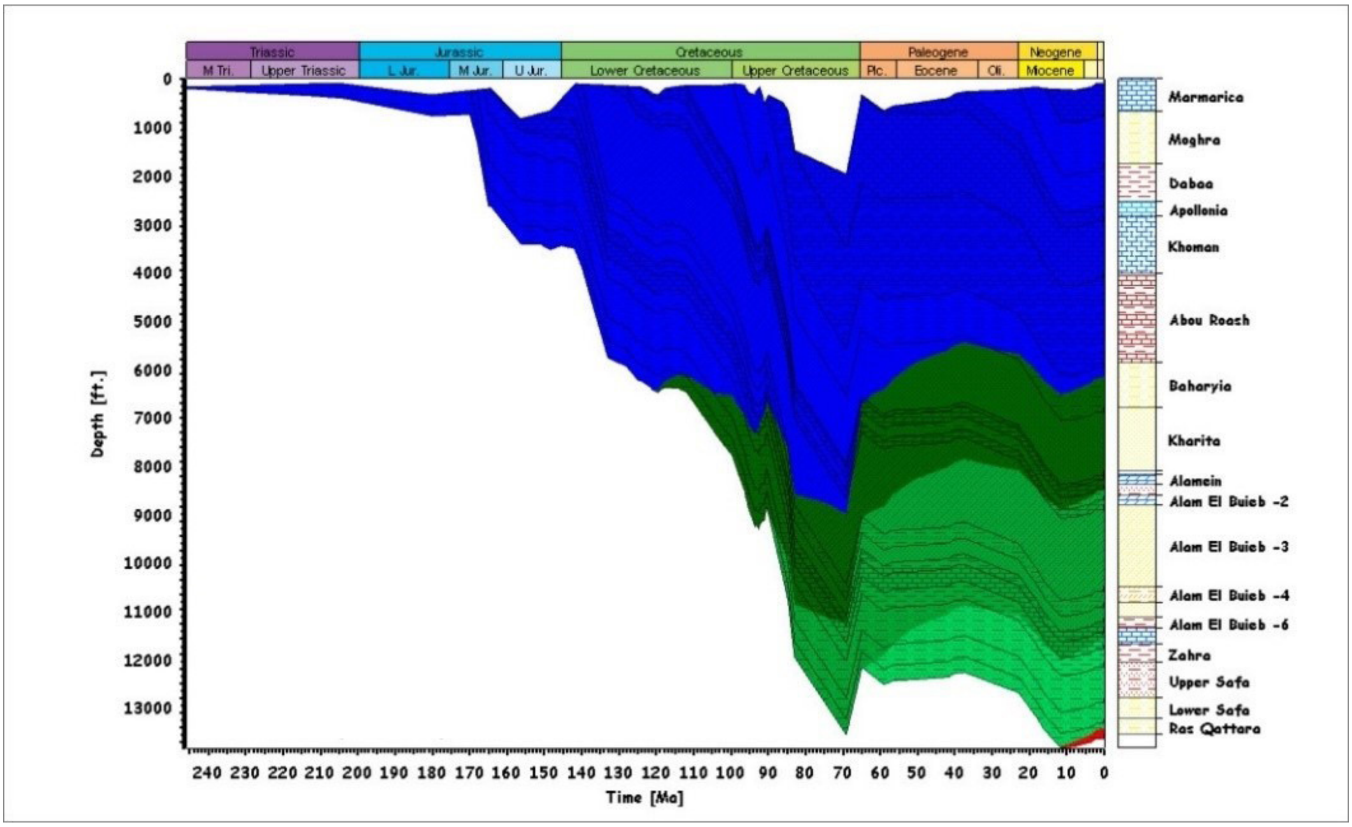

Figure 34: Burial history and hydrocarbon zones, Amoun-2X well. **Note:** Vitrinite reflectance (%Ro) (■) Immature (0.00-0.55), (■) Early oil (0.55-0.70), (■) Main oil (0.70-1.00), (■) Late oil (1.00-1.30), (■) Wet gas (1.30-2.00), (■) Dry gas (2.00-4.00), (■) Over mature (4.00-5.00).

CONCLUSION

- The Middle Jurassic Upper Safa shales in the Amoun field, Shushan Basin, Western Desert, Egypt, were geochemically evaluated to assess their potential as an unconventional shale gas reservoir.
- The results indicate that the TOC values of the studied shale range from 1.31 to 80.4 wt.% and indicate a variety of source rock from poor to very good.
- The kerogen found in the shale is of type (III) with some extent to type (II), and has reached the late maturity stage with Tmax values ranging from 462 to 475 degrees Celsius, measured %Ro values ranging from 0.7 to 1.09%, and calculated values of 1.2 to 1.4%, which suggest that the shale is in the peak of wet gas generation stage.
- The comprehensive geochemical analyses of the Middle Jurassic Upper Safa shale in the study area were compared to the top ten productive shale gas reservoirs worldwide. The findings suggest that the shale under study falls within the typical range of these top ten productive shale gas reservoirs worldwide. The results show significant potential for unconventional shale gas reservoir exploration and development in the Shushan Basin of Egypt's Western Desert.

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