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FULL LENGTH ARTICLE

The potentiality of hydrocarbon generation of the Jurassic source rocks in Salam-3x well, North Western Desert, Egypt

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Abstract The present work deals with the identification of the potential and generating capability of oil generation in the Jurassic source rocks in the Salam-3x well. This depending on the organo-geochemical analyses of cutting samples representative of Masajid, Khatatba and Ras Qattara formations, as well as, representative extract samples of the Khatatba and Ras Qattara formations. The geochemical analysis suggested the potential source intervals within the encountered rock units as follows: Masajid Formation bears mature source rocks and have poor to fair generating capability for generating gas (type III kerogen). Khatatba Formation bears mature source rock, and has poor to good generating capability for both oil and gas. Ras Qattara Formation constituting mature source rock has good to very good generating capability for both oil and gas. The burial history modeling shows that the Masajid Formation lies within oil and gas windows; Khatatba and Ras Qattara formations lie within the gas window. From the biomarker characteristics of source rocks it appears that the extract is genetically related as the majority of them were derived from marine organic matters sources (mainly algae) deposited under reducing environment and take the direction of increasing maturity and far away from the direction of biodegradation. Therefore, Masajid Formation is considered as effective source rocks for generating hydrocarbons, while Khatatba and Ras Qattara formations are the main source rocks for hydrocarbon accumulations in the Salam-3x well.

1. Introduction

The North Western Desert of Egypt represents an important part of the unstable shelf of the Northern Africa and comprises a total area of 700,000 square kilometers, west of the Nile River and Delta. It extends from the Libyan borders in the west of the Nile Delta and Nile River in the east, and from

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the Mediterranean Sea Coast to the Sudan borders in the south. Salam-3x well is located in the northern part of the Western Desert between latitudes 30°35′ and 30°50′ N and longitudes 26°36′ and 27°10′ E (Fig. 1). The stratigraphic column of the northern Western Desert is thick and includes most of the sedimentary succession from Pre-Cambrian basement complex to recent (Fig. 2) formations. The total thickness, despite some anomalies, increases progressively to the north and northeast from about 6000 ft in the southern region and reaches to about 25,000 ft along the coastal area [1]. Salam-3x was the first discovery by the Khalda Petroleum Company. From this well, a significant quantity of oil and gas are produced from Jurassic (Khatatba Formation) and Cretaceous (Alam El Bueib and Bahariya formations) rocks. Matbouly [2] pointed out that, the Jurassic source rocks have been able to generate oil and most of the potential source rocks in the North Western Desert. Abdel Aziz [3] considered the Lower Cretaceous source rocks (Alam El Bueib) and the Jurassic (Khatatba) formations to lie within the oil window. Douban [4] concluded that the Khatatba Formation is the main hydrocarbon source rock as it reached a maturation level enough to generate oil all over the entire Matruh basin. El Nady [5] showed that the Ras Qattara Formation entered the oil window during Paleocene times, Khatatba Formation during Late Cretaceous to Eocene times, Masajid Formation during Late Cretaceous to Late Miocene times in the North Western Desert. Sharaf and El Nady [6] recognized that the Alam El-Bueib Formation has poor to fair potential to generate oil at optimum maturity in the south Umbraka area. El Nady and Harb [7] recognized that Khatatba and Alam El Bueib source rocks act as a source and reservoir for oil generation in North Western Desert. Younes [8] proved that, the shale rock of the Khatatba formation in the Qarun Field reached the late mature stage of oil generation. Ramadan et al. [9] recognized that the Alam El Bueib source rock in the Tut oil field varies from poor to very good in organic richness with kerogen of type III and is characterized by immature to mature rocks. El Nady [10] showed that the Masajid Formation started to generate hydrocarbons during Late Cretaceous-Late Khatatba Formation during Late Cretaceous-Eocene and Ras Qattara Formation started to generate hydrocarbons during the Paleocene epoch.

The main objectives of this study are as follows: (i) to identify and characterize potential source rocks and their generating capability, (ii) to investigate the maturation level of the proven potential source formations for oil preservation dead lines, and (iii) to predict the levels of thermal maturity of the studied sequences in terms of hydrocarbon generation and expulsion. For these purposes "17" cutting samples of argillaceous dark-gray shales and limestones represented the Jurassic rock unit (Masajid, Khatatba and Ras Qattara formations.), and ten extracts sampled from Khatatba and Ras Qattara formations. These samples were taken at different depths from Salam-3x well.

2. Materials and methods

"17" cutting samples of argillaceous dark-gray shales and limestones represented the Jurassic rock unit (Masajid, Khatatba and Ras Qattara formations.), and ten extracts sampled from Khatatba and Ras Qattara formations.

1. Rock–Eval/total organic carbon (TOC) analysis was carried out by a Rock–Eval II analyzer. This procedure was used by Espitalie et al. [11], to obtain total organic carbon (TOC wt.%), free hydrocarbons (S_1% = mg HC/g rock), and residual petroleum potential (S_2% = mg HC/g rock). All these parameters are used in the present work to determine hydrogen index (HI = mg HC/g TOC) and oxygen index (OI = mg CO_2/g TOC), generating potential (GP = $S_1 + S_2$), type of hydrocarbon products (QI = S_2/S_3).
2. Vitrinite reflectance (R_o%) measurements were made on thin section under reflected light.
3. The thermal burial history modeling was constructed using the method introduced by Lopatin, [12] that was modified and calibrated by Waples [13,14] to predict the level of thermal maturity of the studied sequences in terms of hydrocarbon generation and expulsion.

Figure 1 Index map showing the studied well in the North Western Desert, Egypt.

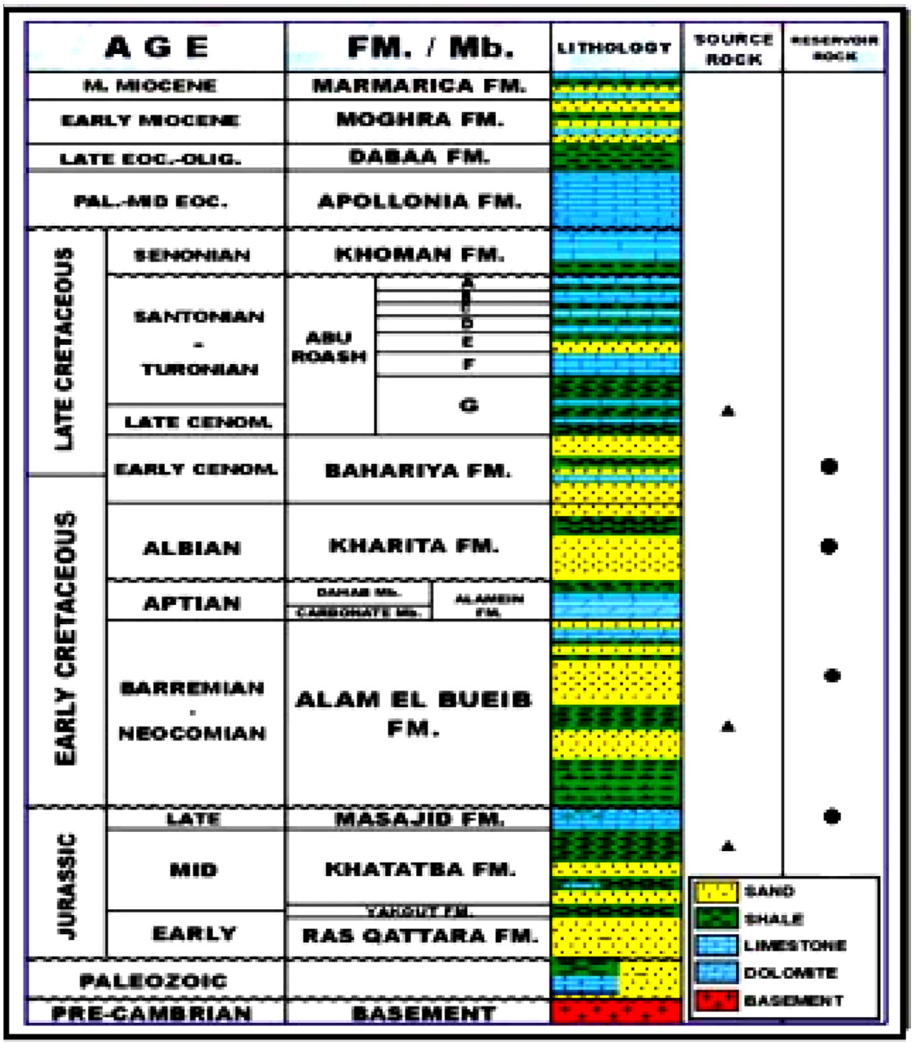

Figure 2 Generalized litho-stratigraphic column of the North Western Desert [1].

4. The saturated hydrocarbons fractions of rock extracts were subjected to gas chromatography. The instrument used was Agilent 6890 Series, provided with a flame ionization detector (FID) and splitt-aplittless injector. Oven temperature was programed for 100–3000 °C at fixed rate of 30 °C/min. and final time 20 min. HP-1 fused silica capillary column (60 m in length, 0.53 mm internal diameter and 0.5 μm film thicknesses) was used for the analysis. Nitrogen was used as carrier gas, the optimum flow rate was 6 ml min. Theses analyses were done in the laboratories of StratoChem and supplied to the authors after Egyptian General Petroleum Corporation.

3. Results and discussion

The potentiality and generating capability of source rocks for oil generation is evaluated by measuring of total organic carbon "TOC" pyrolysis derived "S_1, S_2", "T_{max}" and vitrinite reflectance (R_o%) and biomarker characteristics of the rock samples.

3.1. Organic richness

The organic carbon richness of the rock samples, as expressed by the weight percent of total organic carbon content (TOC %). Peters [15] and Gogoi et al. [16] reported that rocks containing less than 0.5% TOC are considered as poor source rocks. Between 0.5% and 1% TOC indicates fair source rock. TOC% value between 1% and 2% indicates good source rocks. TOC% values above 2% often indicate highly reducing environment with excellent source potential.

The total organic carbon (TOC wt.%) of Masajid Formation ranging from 0.60 to 0.80 (Table 1) revealing the organic richness of this formation varies from poor to fair (Fig. 3a). The pyrolysis-derived S_1 and S_2 value of Masajid Formation range from 0.46 to 0.71 mg/g and 0.68 to 0.95 mg/g, respectively (Table 1) indicating poor to fair generating source potential. The representation of S_2 values (Fig. 3b) confirms that the generating potential of the source rocks of the Masajid Formation is rated from poor to fair.

The generation potential (S_1 + S_2) of the Masajid Formation ranging from 1.21 to 1.58 mg HC/g rock (Table 1) revealing

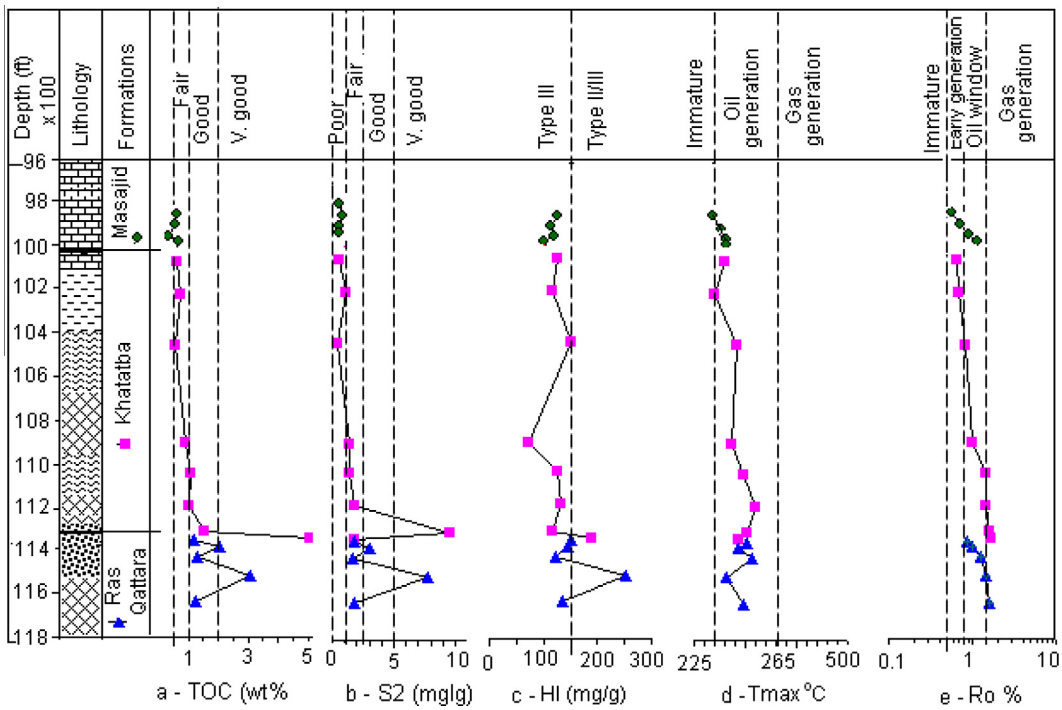

Figure 3 Stratigraphic log and geochemical diagrams of Jurassic source rocks at Salam-3x well, North Western Desert, Egypt.

the organic richness of this formation varies from poor to fair [17]. The type of hydrocarbon products (S_2/S_3) ranging from 0.32 to 0.85 (Table 1) indicate mainly fair oil generation.

The analyzed samples of the Khatatba Formation at Salam-3x well consist of 95% olive black to dark gray shale, 5% coal and trace sandstone. It has a total organic carbon content (TOC wt.%) ranging from 0.55 wt.% to 5.10 wt.% (Table 1) reflecting that the Khatatba source rocks are variegated mainly from fair to very good source rocks (Fig. 3a). The studied samples of the Khatatba Formation are characterized by S_1 and S_2 values that range from 0.24 mg/g to 1.59 and 0.59 to 9.59, respectively (Table 1) reflecting poor to good source potential (Fig. 3b). The generation potential ($S_1 + S_2$) of the Khatatba Formation ranges from 0.64 to 11.18 mg HC/g rock (Table 1) revealing that the organic richness of this formation varies from poor to good. The type of hydrocarbon products (S_2/S_3) ranging from 0.69 to 19.18 (Table 1) indicate mainly fair to good oil generation.

Ras Qattara Formation consists mainly of sandstones and shales with some dolomite intercalations. It has a total organic carbon content (TOC wt.%) ranging from 1.22 wt.% to 3.06 wt.% (Table 1) indicating good to very good source rocks. TOC values follow the same contouring pattern as the organic richness as indicated by TOC versus depth (Fig. 3a). The pyrolysis-derived "S_1" and "S_2" values of the Ras Qattara Formation samples range from 1.36 to 2.11 mg/g and 1.63 to 2.99 mg/g, respectively (Table 1), indicating poor to good generation potential. The S_2 values follow the same contouring pattern as the organic richness as indicated by the generating potential graph (Fig. 3b).

The generation potential (GP), is identified by using the sum of $S_1 + S_2$ obtained from pyrolysis analysis ranging from 3.04 to 9.82 mg HC/g rock (Table 1). These data indicate that the Ras Qattara Formation has organic matter that is rated from poor to good as regards generation potential. The type of hydrocarbon products (QI) S_2/S_3 ratio of the Ras Qattara Formation ranges from 1.74 to 8.47 (Table 1) indicating that the Ras Qattara Formation is mainly a good source for oil generation.

3.2. Kerogen types

Waples [13] used the hydrogen indices values (HI) to differentiate between the types of organic matter. Hydrogen indices below about 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 above 300 mg/g contain 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 above 600 mg/g usually consists of nearly type I or type II kerogen, they have excellent potential to generate oil.

The hydrogen index "HI" values of the Masajid Formation range from 110 to 134 mg/g and oxygen index "OI" ranges from 148 to 382 mg/g (Table 1) which suggest a potential to generate type III kerogen. This is confirmed by the relation between hydrogen index and depth (Fig. 3c). From the relation between TOC% and HI (Fig. 4) indicate that the oil potential of this Formation is increased upward to good source.

The hydrogen index (HI) values of the Khatatba Formation range from 70 to 212 mg/g, and OI (oxygen index) range from 17–270 mg/g (Table 1) which indicate that the organic matter is classified as type III/II kerogen (mixed type) (Fig. 3c). The relation between TOC% and hydrogen index (HI) indicates that the oil potential of this formation is a good source except one sample which is rated as poor source (Fig. 4).

Table 1 Rock Eval pyrolysis and vitrinite reflectance analysis of the Jurassic source rocks in the Salam-3x well, North Western Desert, Egypt.

Depth (ft)	TOC (wt.%)	S_1 (mg/g)	S_2 (mg/g)	S_3 (mg/g)	T_{max} (°C)	R_o (%)	PI	$S_1 + S_2$	S_2/S_3	HI (mg/g)	OI (mg/g)
Masajid Formation (Upper Jurassic)											
9830	0.62	0.66	0.78	0.92	434	0.59	0.46	1.44	0.85	126	148
9890	0.80	0.63	0.95	1.79	437	0.75	0.40	1.58	0.36	119	328
9950	0.60	0.48	0.73	1.88	441	0.91	0.40	1.21	0.32	122	382
9980	0.62	0.71	0.68	2.83	441	1.10	0.51	1.39	0.36	110	303
Khatatba Formation (Middle Jurassic)											
10,040	0.61	0.67	0.76	1.02	440	0.65	0.47	1.43	0.75	125	167
10,190	0.72	0.39	0.59	0.86	435	0.69	0.40	0.98	0.69	118	172
10,430	0.55	0.43	1.10	1.30	446	0.83	0.28	1.53	0.85	153	181
10,890	0.93	0.24	0.40	0.59	443	0.99	0.38	0.64	0.68	73	107
11,030	1.11	0.42	1.39	0.68	449	1.45	0.23	1.81	2.04	125	61
11,180	1.02	0.32	1.36	0.43	455	1.45	0.19	1.68	3.16	133	42
11,300	1.55	0.53	1.81	0.80	451	1.61	0.23	2.34	2.26	117	52
11,335	5.10	1.59	9.59	0.50	447	1.67	0.14	11.18	19.18	188	10
Ras Qattara Formation (Lower Jurassic)											
11,345	1.22	1.36	1.84	1.84	1.84	0.87	0.43	3.20	2.00	151	75
11,375	2.05	1.65	2.99	2.99	2.99	0.98	0.36	4.64	3.29	146	44
11,420	1.32	1.41	1.63	1.63	1.63	1.24	0.46	3.04	1.99	123	62
11,510	3.06	2.11	7.71	7.71	7.71	1.43	0.21	9.82	8.47	252	30
11,630	1.28	1.54	1.74	1.74	1.74	1.57	0.47	3.28	1.74	136	78

Note: TOC: total organic carbon in weight percent; S_1: free hydrocarbons percent in the rock (mg HC/g rock); S_2: residual petroleum potential (mg HC/g rock); HI: hydrogen index (mg HC/g TOC); OI: oxygen Index (mg CO_2/g TOC). T_{max}: the temperature at which the maximum pyrolytic hydrocarbon (S_2) liberated. R_o (%): vitrinite reflectance measurements. PI: production index = $S_1/S_1 + S_2$.

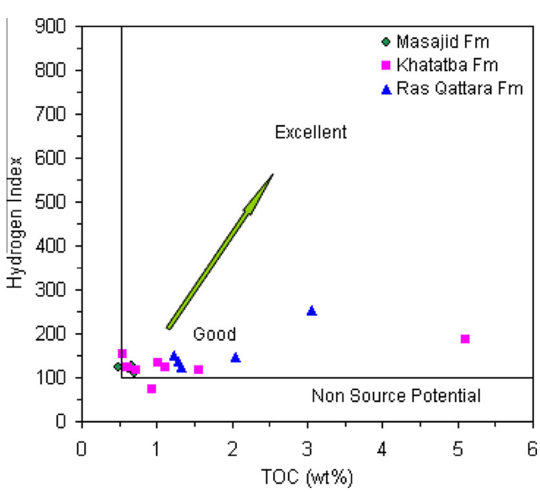

Figure 4 Hydrogen index versus total organic carbon showing the type of source rocks of the studied formations in Salam-3x well, North Western Desert, Egypt.

For Ras Qattara Formation the hydrogen index and the oxygen index range from 120 to 252 mg/g and 15 to 88 mg/g (Table 1). This reflects that this formation has formation has a potential source rock for generating mixed oil and gas (type III/II of kerogen) as shown in the relation between depth and hydrogen index (Fig. 3c). According to TOC% and HI relation (Fig. 4) of this section this formation is considered as good and increases toward excellent source potential.

3.3. Maturation

In the present study, the thermal maturity level of the source rocks has been determined by the study of the geochemical parameters as Rock–Eval temperature pyrolysis "T_{max}", production index "PI" [15,18]. Espitalie et al. [11] and Peters [15] reported that oil generation from source rocks began at "T_{max}" 435–465 °C, vitrinite reflectance "R_o%" between 0.5% and 1.35% and production index "PI" between 0.2 and 0.4, the organic matters are in immature stage when "T_{max}" has a value less than 435 °C, "R_o%" less than 0.5 and "PI" less than 0.2 and the gas generation from source rocks began at "T_{max}" 470 °C , "R_o%" more than 1.35% and the production index "PI" more than 0.4.

The Masajid Formation (Upper Jurassic) has "T_{max}" values that range from 430 °C to 441 °C (Table 1) reflecting that the samples lie in between marginally mature to mature stage (Fig. 3d) The vitrinite reflectance measurements of the Masajid Formation range from 0.95–0.1.10% (Table 1) which places this formation within the early stage of hydrocarbon generation to oil window (Fig. 3e), where the source rocks of this formation are considered as mature source rock. Production index "PI" of this formation ranges from 0.376 to 0.51 (Table 1) indicating that the samples lie in between oil generation and gas generation stages. Moreover, the cross plot of the pyrolysis "T_{max}" and hydrogen index "HI" (Fig. 5) reveal that type III kerogen of organic matters lie in the mature stage of oil zone. The relation between production index (PI = $S_1/S_1 + S_2$) and "T_{max}" (Fig. 6) indicates that the source rock of Masajid Formation is marginally mature approaching the main stage of hydrocarbon generation.

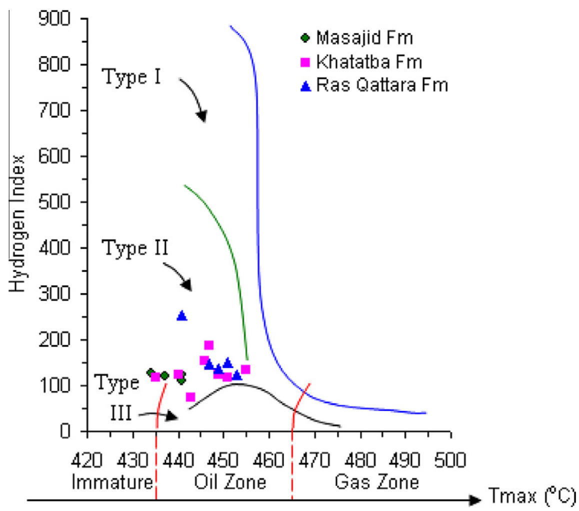

Figure 5 Cross plot of T_{max} and hydrogen index of the studied formations in Salam-3x well, North Western Desert, Egypt.

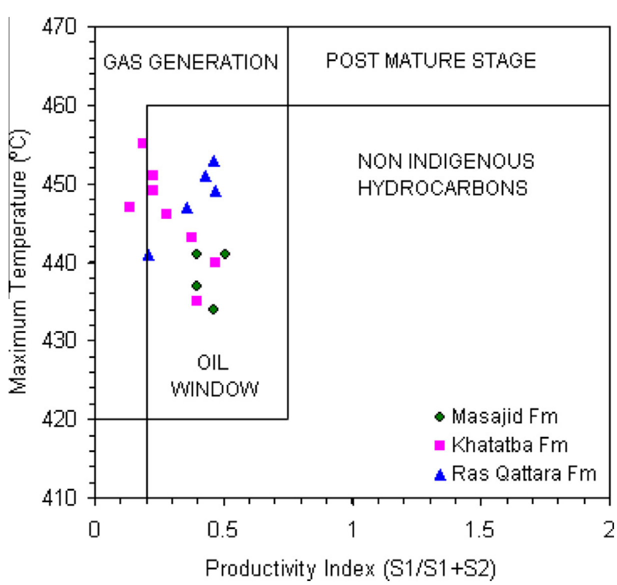

Figure 6 Relation between Productivity Index ($S_1/S_1 + S_2$) and T_{max} showing the locations of studied formations in Salam-3x, North Western Desert, Egypt.

The maturity parameters of the Khatatba Formation as indicated by "T_{max}" values ranging from 435 to 455 °C, vitrinite reflectance measurements ranging from 0.65% to 1.67% (Table 1) revealing that they lie within themature stage of hydrocarbon generation (Fig. 3d and e). Furthermore, the production index "PI" of this formation ranges from 0.14 to 0.60 (Table 1) indicating that the sample is a mature source rocks.

Moreover, the cross plot of the pyrolysis "T_{max}" and hydrogen index "HI" (Fig. 4) reveal that type III kerogen of organic matters of the Khatatba Formation lie in the mature stage of the oil zone. The relation between PI and "T_{max}" (Fig. 6) indicates that the source rock of the Khatatba Formation is mature approaching the main stage of hydrocarbon generation.

Ras Qattara Formation has "T_{max}" values that range from 440 °C to 454 °C (Table 1) indicating that the samples lie within the oil generation stage (Fig. 3d). and "R_o%" values range from 0.87% to 1.57% (Table 1) indicating that the source rocks are mature where the majority of the samples lie within the oil generation stage and two samples lie within the gas generation stage (Fig. 3e). On the other hand, the production index "PI" of this formation ranges from 0.11 to 0.47 (Table 1) revealing that the samples lies within the gas generation stage and the oil generation stage. In addition, the relation between hydrogen index "HI" and "T_{max}" values confirms that the Ras Qattara Formation is a mature (oil generative) source rock and also shows that the organic matter of this formation ranges between type III and type III/II (Fig. 5). Furthermore, the relation between PI and "T_{max}" (Fig. 6), indicates that the Ras Qattara Formation is mature approaching the main stage of hydrocarbon generation.

3.4. Timing of petroleum generation

In the present study, the burial history model of the different hydrocarbon bearing rock units in the Salam-3x well (Fig. 7) was constructed to predict the maturity of the source rock, timing of hydrocarbon generation, expulsion and migration. The oil window in this work is defined as the depth interval between the peak of hydrocarbon generation (R_o = 0.85%) and the oil floor (R_o = 1.35%) according to Waples [13,14].

Burial modeling (Fig. 7) shows that the Masajid Formation entered the early stage of hydrocarbon generation at 90 Mybp (million years before present) during Early Cretaceous times. It reached to the oil window during the Late Cretaceous time at 75 Mybp till Oligocene time at 35 Mybp and entered the gas generation time at 40 Mybp during Eocene till the present time (Fig. 7). Khatatba Formation started to generate hydrocarbons during the Cretaceous time at 93–76 Mybp as indicated by the thermal burial history model (Fig. 7). It reached the oil window (peak of hydrocarbon generation) during Late Cretaceous at 90 Mybp till Eocene time at 42 Mybp and reached the gas generation time at 72 Mybp during Late Cretaceous till the present time. Khatatba Formation bears a mature source rock with good generating capability for both oil and gas. Ras Qattara Formation entered the early stage of hydrocarbon generation during Early Cretaceous time at 100 Mybp. It reached the oil window during the Late Cretaceous time at 92–72 Mybp (million years before present) and entered the gas generation time at 76 Mybp during Late Cretaceous till the present time.

3.5. Biomarker characteristics

In the Middle Jurassic source rocks (Khatatba Formation), there is a marked increase in normal alkanes of n-C_{15} to n-C_{25} and moderately to low concentration of heavy normal alkanes with CPI values that range from 1.05 to 1.12 (Fig. 8a, Table 2). This indicates the marine organic source with input from terrestrial organic matters. The pristane/phytane ratio for the Khatatba Formation ranges from 0.53 to 1.61 (Table 2) indicating that these sediments were deposited under reducing conditions.

The fingerprints of gas chromatography for the saturated hydrocarbon fractions of the studied samples of the Lower

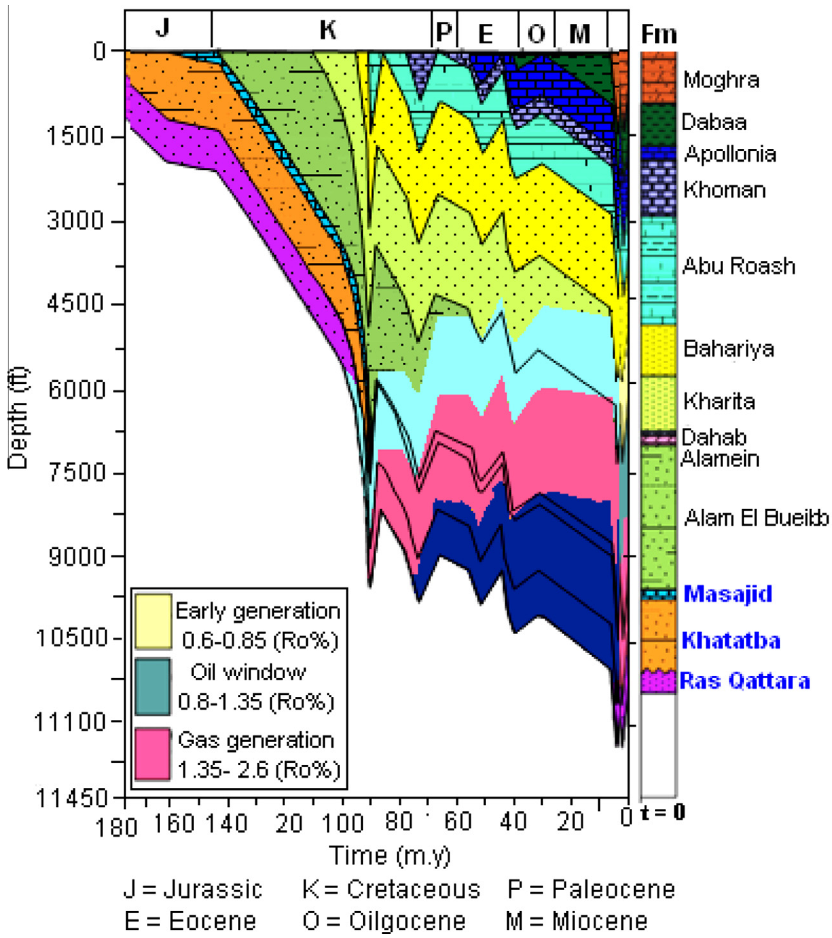

Figure 7 Burial history model for Salam-3x well in the North Western Desert, Egypt.

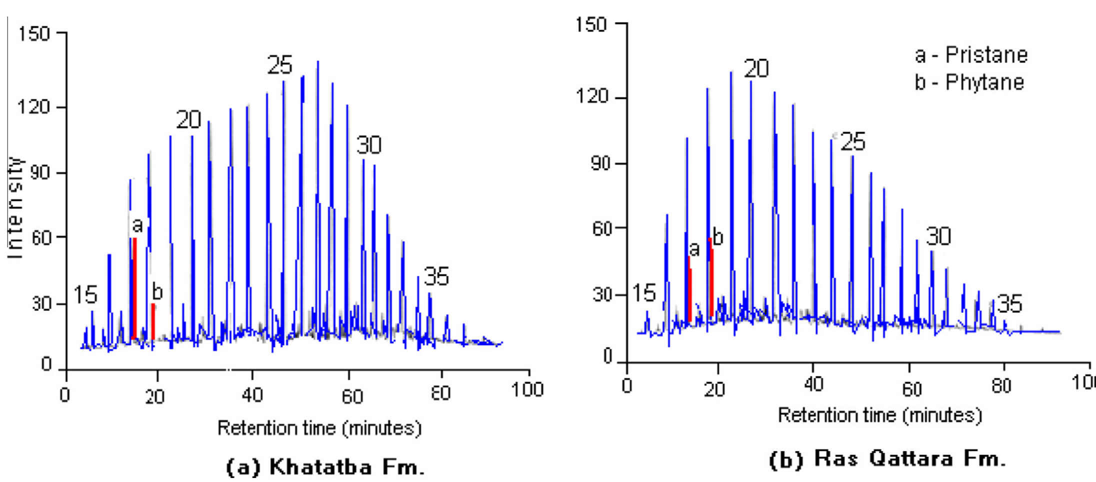

Figure 8 Representative fingerprints of gas chromatograms of saturated hydrocarbon fractions from the Khatatba and Ras Qattara extract samples in Salam-3x well, North Western Desert, Egypt.

Jurassic (Ras Qattara) Formation show that the Ras Qattara Formation is characterized by high concentrations of normal alkanes in the range of n-C_{17} to n-C_{27} and moderate to low concentrations of heavy normal alkanes with no odd or even carbon preference index ; CPI values range from 1.06 to 1.14 (Fig. 8b, Table 2) indicating a significant input of marine organisms to the sediments with contribution of terrestrial organic remains [14,19]. The pristane/phytane ratio for Ras Qattara Formation ranges from 0.66 to 1.2 (Table 2) indicating that these sediments were deposited under reducing conditions.

In source rock studies, the ratios of isoprenoids to n-alkanes are widely used since they provide information on maturation

Table 2 Geochemical parameters derived from Gas chromatography analysis of the Khatatba and Ras Qattara extract samples in the Salam-3x well, North Western Desert, Egypt.

Formations	Depth (ft)	CPI	Pristane/phytane	Pristane/n-C_{17}	Phytane/n-C_{18}
Khatatba	10,410	1.10	0.69	0.53	0.54
	10,980	1.08	0.53	0.25	0.23
	11,090	1.05	0.77	0.28	0.27
	11,290–11,300	1.10	1.29	0.27	0.21
	11,330–11,340	1.12	1.61	0.29	0.18
Ras Qattara	11,340–11,350	1.14	1.20	0.22	0.18
	11,380–11,390	1.10	1.07	0.23	0.20
	11,450	1.07	0.66	0.32	0.34
	11,510	1.06	0.76	0.28	0.31
	11,570	1.06	0.78	0.29	0.31

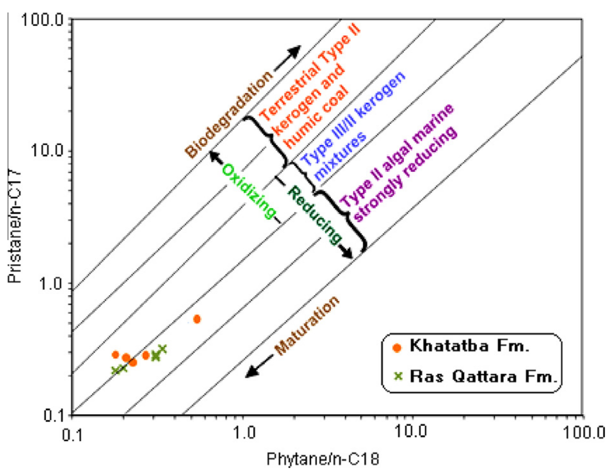

Figure 9 Plot of pristane /n-C_{17} versus phytane/n-C_{18} [22] of the Khatatba and Ras Qattara extract samples in Salam-x well, North Western Desert, Egypt.

and biodegradation [20]. The studied extract samples have isoprenoids/n-alkanes ratio ranging from 0.22 to 0.53 for pristane/n-C_{17} and from 0.18 to 0.54 for phytane/n-C_{18} ratio (Table 2). Consequently, a plot of Pr/n-C_{17} versus Ph/n-C_{18} (Fig. 9) shows that the majority of extract samples were derived from marine organic matter source (mainly algae) deposited under reducing environment except for three samples of the Ras Qattara and Khatatba formations plotted in the region of mixed organic matter with the source rocks being deposited under reducing conditions and receiving significant clastic input [21]. This indicates a genetic close relation between the studied oils. In addition, it is clear that the studied extract samples take the direction of increasing maturity and far away from the direction of biodegradation.

4. Conclusions

The geochemical analysis of Jurassic source rocks in the Salam-3x well suggested the potential source intervals within the encountered source rocks as follows:

1. Masajid Formation bears mature source rocks and have poor to fair generating capability for generating gas (type III kerogen).
2. Khatatba Formation bears mature source rock, and has poor to good generating capability for both oil and gas.
3. Ras Qattara Formation constitutes mature source rock has good very good generating capability for both oil and gas.
4. The burial history modeling of the sedimentary section shows that the Masajid Formation lies within oil and gas windows; Khatatba and Ras Qattara formations lie within the gas window.
5. From the biomarker characteristics of source rocks, it appears that extract rocks are genetically related as the majority of them were derived from marine organic matters source (mainly algae) deposited under reducing environment. In addition, it is clear that the studied extract samples take the direction of increasing maturity and far away from the direction of biodegradation.

Therefore, from the results of source rock characterization of the studied succession, it can be stated that Ras Qattara and Khatatba formations are the main source rock for hydrocarbons accumulations, and Masajid and Alam El-Bueib formations are rich enough with organic sediments and could be considered as effective source rocks for generating hydrocarbons.

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