Al-Azhar Bulletin of Science Vol. 30, No. 1, (June) 2019, pp. 25-34

CONTRIBUTION TO SOURCE ROCK EVALUATION OF THE BAHARIYA FORMATION IN SURFACE AND SUBSURFACE SECTIONS, NORTH WESTERN DESERT, EGYPT

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ABSTRACT

The present work deals with the identification of the generating capacity of oil generation and the hydrocarbon potentiality of the Bahariya Formation in Gebel El-Dist section and the Salam-1X well. This is depending on the organic geochemical analyses by using LECO SC632 and Rock Eval-6 pyrolysis techniques. The analysis shows that the studied samples of Gebel El-Dist are poor to fair organic richness, with poor hydrocarbon potentiality. The maturity evaluation using T_{max} showed that the studied samples have immature thermal maturation not reaching the stage of oil and gas generation. Also, the analyses revealed that the studied kerogen is type III kerogen originated mainly from terrestrial plant debris and aquatic organic matter. The expected generated HC is mainly gas. The studied Salam-1X samples are poor to good organic richness, with poor to good source potiental. The studied samples are marginally mature to mature thermal maturation reaching the stage oil generation. The kerogen type is a mixture of type III/II kerogen derived mainly from mixed organic sources.

Keywords: Source rock evaluation; Rock-Eval pyrolysis; Kerogen type; Hydrocarbon potentiality; Bahariya Formation.

1. INTRODUCTION

The Northern part of the Western Desert is a prolific area of hydrocarbon production in Egypt. In addition to its reservoir potentiality; it may represent a hydrocarbon source rock within the basin. The Cenomanian Bahariya Formation is characterized by wide vertical and lateral facies changes. So many deflects are found until now in the hydrocarbon production from the Bahariya Formation. **Mousa et al. [21]** concluded that the Upper Cretaceous Bahariya Formation is mainly poor to fair source rocks; the main expected kerogen type is type III indicating terrestrial organic input. **El Nady and Lotfy [9]** concluded that the Bahariya Formation is considered a poor source rock for oil generation and has a lesser degree of thermal maturation. **El Nady et al. [10]** stated that the extracts of Bahariya Formation are derived from mixed marine input with a limited terrestrial contribution. **Abd El-Gawad et al. [1]** suggested that the Bahariya oil has been sourced from Khatatba Formation with some contribution from Upper and Lower Bahariya source rocks. **AboulEla et al. [2]** suggested more common marine influence in the upper part of Bahariya Formation showing the exceptional high hydrocarbon potential, Such rising in the marine influence indicates marine transgression by the end of the Early Cenomanian time and most of Bahariya Formation points to more promising gas-prone kerogen type III. **Mahmoud et al. [20]** through the study of Salam-60 well indicated that the Bahariya Formation and the “G” Member of Abu Roash Formation have similar marginal to inner shelf depositional settings across most of the northern Western Desert except at west Matruh Basin, where they have a deeper open marine, middle shelf setting.

The main objectives of this study are: (i) to identify and characterize the Bahariya potential source rocks and their generating capability, (ii) to investigate the maturation level of the studied samples and compare a surface section with a subsurface section for the study formation is to evaluate the limits of changes which take place during the sedimentary process, including the several studied parameters controls the evaluation of organic matter and its level of maturation. In the study area, Gebel El-Dist section (surface section) is located in the northern escarpment of the Bahariya Oasis between latitude 28°28′51.19" N and longitude 28°55′31.72" E, and the Salam-1X Well (subsurface section) is located in the Salam Field in the shushan Basin between latitude 30°60′12" N and longitude 26°60′55" E at the North Western Desert of Egypt **(Fig. 1).**

2. GEOLOGIC SETTING

The type locality of the Bahariya Formation is located in Gebel El-Dist, Bahariya Oasis, where its base is not exposed **[25]** and it is the oldest exposed rock units and covered by the Lower–Middle Eocene El-Naqb Formation **[7,8]** with complete missing of upper Cretaceous-Paleocene rocks due to the effects of the Syrain Arc System. In the subsurface of the Western Desert, the Bahariya Formation is overlaying the Kharita Foramtion and is underlying the Abu Roash Formation **[15]**.The age of the Bahariya Formation is Early Cenomanian **[3, 26]**.The Bahariya Formation is also considered one of the most complex lithologies in Egypt, being consist of friable, cross - bedded, varigated sands and sandstones (sometimes micaceous and gypsiferous) with hard dark brown ferruginous bands, siltstones, clays and it have a limestone bed at base **[17]**. The Bahariya Formation reflects a complex deposional history that encompasses a wide range of sedimentary environments and exhibits significant lateral and vertical changes in facies. It shows evidences of fluvio-marine conditions **[11,24]**; partly restricted and reducing prodeltaic environment **[27]**; fluvial environment in the south Western Desert and shallow marine in the north Western Desert **[6]**.

3. MATERIALS AND METHODS

For these purposes seventy ‘‘70” subsurface core and surface samples representing the Upper Cretaceous Bahariya Formation were selected from the two studied sections: Gebel El-Dist (37 Samples) **(Table 1)** and Salam-1X well (33 Samples) **(Table 2)**. The selected samples were chosen for total carbon (TC), total sulfur (TS) and total organic carbon (TOC) analyses. According to the results of TOC analysis, twenty-eight (28) samples of Salam-1X well and 6 samples of Gebel El-Dist to be analyzed by Rock-Eval pyrolsis techniques. A brief explanation for the used techniques is given below:

1. The studied samples were investigated under the binocular microscope to remove contaminations and study of the lithology of the samples.
2. Selected rock samples were pulverized to a homogenous powder, dried and bagged for geochemical analysis.
3. About (200 mg) of the bulk sample were analysed by using a LECO SC632 direct combustion technique at 1350°C for the total carbon TC (wt%) and the total sulfer TS (wt%) analyses.
4. Another copy of samples were placed in a crucible with 10% HCl at 80 °C to remove

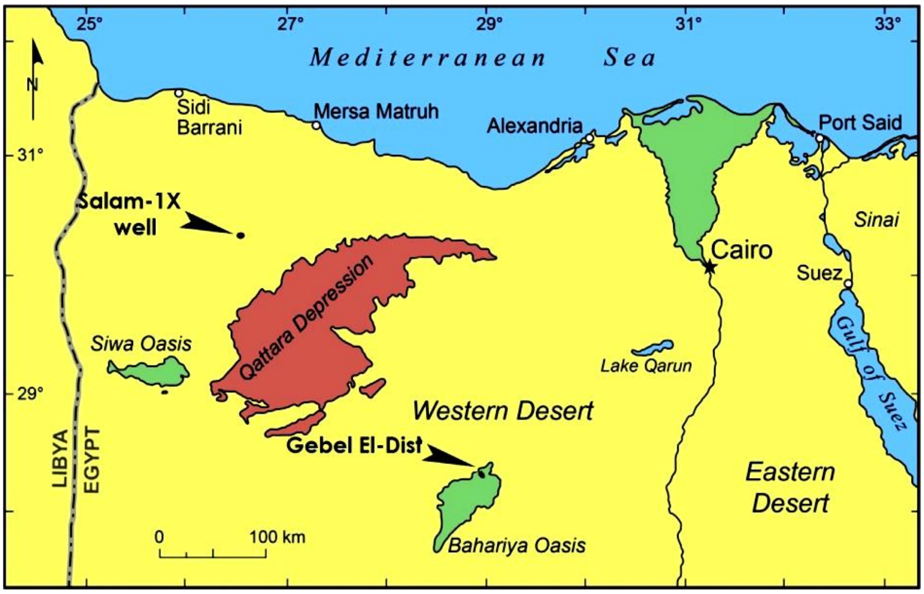

Fig. 1: Location map of the studied sections

carbonates. The total organic carbon content (TOC) was measured using a LECO SC632 instrument. Samples with TOC content exceeding 0.5 wt% were selected to screening analysis using Rock-Eval-6 instrument **[13]**.

5. About (60 mg) of the sample were analyzed using Rock-Eval 6 pyro-analyzer for the bulk rock mode. The measured parameters of the rock Eval pyrolysis represents S1 (free volatile hydrocarbons thermally flushed from a rock sample at 300 °C (mg HC/g rock)); S2 (pyrolysis HC detected from 300 °C to 600 °C (mg HC/g rock)); S3 (CO2 results from pyrolysis of organic matter (mg CO2/g)), and T_{max} (temperature at maximum of S2 peak). Calculated parameters such as: Hydrogen Index (HI = (S2 × 100)/TOC, mg HC/g TOC), Oxygen Index (OI = (S3 x 100)/ TOC, mg CO2/g TOC), Production Index (PI = S1 / (S1+S2)), Generative Potential (GP = S1 + S2, mg/g or kg/ton of rock), and type of hydrocarbon products (QI =S2/S3) are also

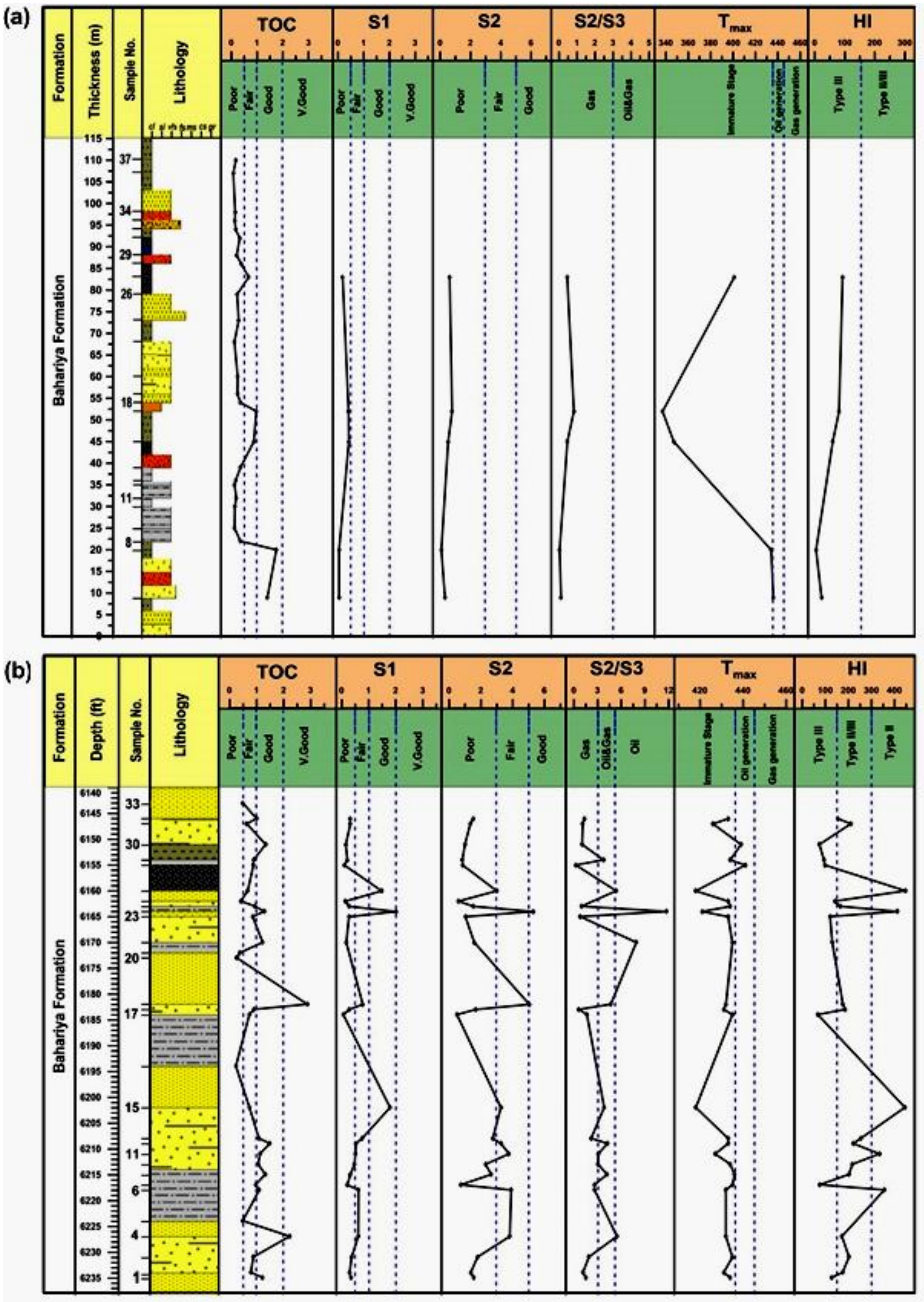

Fig. 2: Summarized plot of lithology and geochemical data for the two studied sections: a) Gebel El-Dist b) Salam-1X well

obtained.

The analyses were carried out at the labs of Egyptian Petroleum Research Institute (EPRI).

4. RESULTS AND DISCUSSIONS:

In order to evaluate the organic matter content and source rock maturity, different factors including quality and quantity of organic matter, generating potentialities, type of organic matter and thermal maturation were considered.

Results of analyses and calculated parameters are given in **(Tables 1&2)** while their vertical distribution is illustrated in **(Fig. 2 a&b)**.

4.1 Organic richness

The organic richness is determined by using the parameters; Total Organic Carbon "TOC", Free hydrocarbon "S1" and Hydrocarbon Potentiality "S2" of the rock samples and expressed by the weight percent of total organic carbon content (TOC%). **Peters and Cassa [23]** 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. The obtained data in **(Table 1)** show that the total organic carbon content and S2 values for the studied samples of Gebel El-Dist ranges from 0.07 to 1.75wt% and 0.07 to 0.78 (mg/g) respectively, indicating poor to fair source rock except samples number 3D and 7D that are of good organic richness **(Fig. 2a)**, while the TOC values for the studied samples of Salam-1X well ranges from 0.23 to 2.87 wt% and S2 values range from 0.49 to 5.27 mg/g) **(Table 2)**,which reflects poor to good organic richness except samples number 4S and 19S that are of very good organic richness **(Fig. 2b)**. This conclusion is confirmed by the plot of TOC (wt%) versus S2 **[5] (Fig.3)**. On the other hand; the plot of S1 versus TOC **(Fig. 4)** can be used to discriminate between non indigenous and indigenous hydrocarbons **[14]**. This relation shows that all of the studied rocks samples from Gebel El-Dist are characterized by indigenous hydrocarbons, while the majority of the studied rock samples from Salam-1 X well are characterized by indigenous hydrocarbons, except few samples are non indigenous indicating that the oil produced from the studied well was migrated from another source rock.

4.2 Hydrocarbon potentiality

The generation potential (GP), is identified by using the sum of S1 +S2 obtained from pyrolysis analysis. According to **Hunt [16]** source rocks with a GP <2 is considered to have poor generation potential, from 2 to 5 indicates fair generation potential, from 5 to 10 indicates good generation potential and >10 indicates very good generation potential. The hydrocarbon potentiality S1 from 0 to 0.5 mg/g represents poor hydrocarbon potentiality, from 0.5 to 1 mg/g consider fair, from 1 to 2 mg/g good, 2–4 mg/g very good and more than 4 mg/g is excellent **[22,23].**

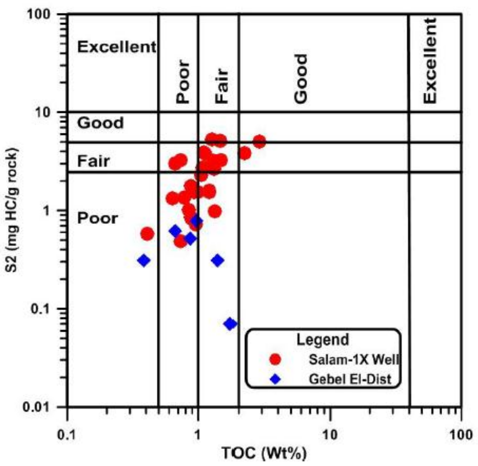

Fig. 3: Cross plot of TOC vs. S1 for the study samples [5]

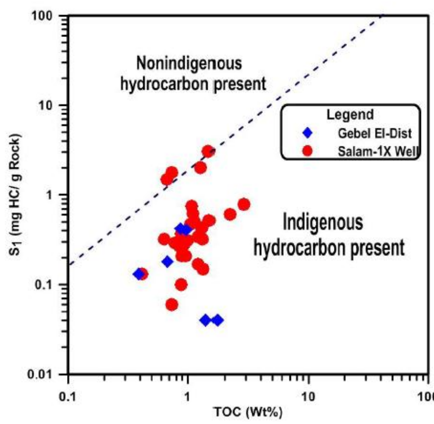

Fig. 4: Cross plot of TOC vs. S2for the study samples [14]

Table 1: Pyrolysis data of the Gebel El-Dist samples

Location	Sample No.	Thickness (m)	TS wt%	TC wt%	TOC wt%	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	Tmax °C	HI (mg/g)	OI (mg/g)	PI	S1+S2	S2/S3
Gebel El-Dist	37D	110	0.02	0.18	0.17	—	—	—	—	—	—	—	—	—
	36D	107	0.03	0.08	0.07	—	—	—	—	—	—	—	—	—
	34D	98	0.02	0.15	0.15	—	—	—	—	—	—	—	—	—
	33D	96	0.01	0.17	0.14	—	—	—	—	—	—	—	—	—
	32D	94	0.15	0.21	0.16	—	—	—	—	—	—	—	—	—
	31D	92	0.02	0.35	0.32	—	—	—	—	—	—	—	—	—
	29D	88	0.07	0.26	0.21	—	—	—	—	—	—	—	—	—
	28D	86	0.01	0.46	0.39	—	—	—	—	—	—	—	—	—
	27D	83	0.08	0.68	0.67	0.18	0.62	1.37	401	92	204	0.23	0.80	0.45
	26D	79	0.60	1.30	0.22	—	—	—	—	—	—	—	—	—
	24D	73	0.07	0.32	0.28	—	—	—	—	—	—	—	—	—
	23D	68	0.02	0.14	0.12	—	—	—	—	—	—	—	—	—
	20D	60	0.05	0.75	0.24	—	—	—	—	—	—	—	—	—
	19D	56	0.40	0.65	0.24	—	—	—	—	—	—	—	—	—
	18D	54	0.53	1.00	0.35	—	—	—	—	—	—	—	—	—
	17D	52	0.29	1.03	0.97	0.41	0.78	0.95	337	81	98	0.34	1.19	0.82
	16D	45	0.27	0.91	0.87	0.42	0.52	1.13	347	60	130	0.45	0.94	0.46
	14D	39	1.72	1.52	0.35	—	—	—	—	—	—	—	—	—
	13D	36	0.08	4.33	0.16	—	—	—	—	—	—	—	—	—
	12D	35	0.20	4.50	0.12	—	—	—	—	—	—	—	—	—
	11D	32	0.13	0.23	0.19	—	—	—	—	—	—	—	—	—
	10D	30	0.08	3.39	0.13	—	—	—	—	—	—	—	—	—
	9D	25	1.86	0.20	0.12	—	—	—	—	—	—	—	—	—
	8D	22	0.21	0.38	0.34	—	—	—	—	—	—	—	—	—
	7D	20	0.50	1.84	1.75	0.04	0.07	2.38	434	4	136	0.37	0.11	0.03
	3D	9	0.87	1.74	1.40	0.04	0.31	2.84	436	22	203	0.12	0.35	0.11

Note:

TOC: Total organic carbon in weight percent.
S1: Free hydrocarbons percent in the rock (mg HC/g rock).
S2: Residual petroleum potential (mg HC/g rock).
HI: Hydrogen index (mg HC/g TOC).
OI: Oxygen index (mg CO2/g TOC).
T_{max}: The temperature at which the maximum pyrolytic hydrocarbon (S2) liberated.
Generation potential (GP) = S1+S2.
Production index (PI)= S1/S1+S2.
Hydrocarbons products type (QI) =S2/S3.
D: El-Dist sample.
S: Salam-1X sample.

The pyrolysis-derived S1 and S2 values of the studied samples of Gebel El-Dist range from 0.04 to 0.42 (mg/g) and 0.07 to 0.78 (mg/g) respectively **(Table 1)** reflecting poor generating capability **(Fig. 2a)**. The generation potential (GP) of Gebel El-Dist samples ranges from 0.11 to 1.19 mg HC/g rock **(Table 1)** indicating poor generation potential **[14] (Fig. 5)**.

The type of hydrocarbon products (QI) is identified by using the division of S2/S3obtained from pyrolysis analysis ranging from 0.03 to 0.82 **(Table 1)**. These data indicate that Gebel El-Dist lie in the non-zone of hydrocarbons generation **(Fig. 6)**.

The studied samples of the Salam-1X samples are characterized by S1 and S2 values that range from 0.06 to 2.01 (mg/g) and S2 values range from 0.49 to 5.27 (mg/g) **(Table 2)** indicating poor to good hydrocarbon potentiality **(Fig. 2b)**. The generation potential(S1+S2) of Salam-1X well samples range from 0.55 to 7.28 mg HC/g rock revealed that the generation potential of this formation varies from poor to good **(Fig. 5)**.

The type of hydrocarbon products (S2/S3) of Salam-1X well samples ranging from 0.23 to 11.71 **(Table 2)** are mainly fair to good of gas to oil generation and few samples lie in fair gas generation area **(Fig. 6)**.

4.3 Genetic type of organic matter

Waples [31] used the hydrogen index values (HI) to differentiate between the types of organic matter. Hydrogen index below about 150 mg/g indicate a potential source for

Table 2: Pyrolysis data of the Salam-1X well samples

Location	Sample No.	Depth (ft)	TS wt%	TC wt%	TOC wt%	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	Tmax °C	HI (mg/g)	OI (mg/g)	PI	S1+S2	S2/S3
Salam-1X well	33S	6143	0.55	0.71	0.49	—	—	—	—	—	—	—	—	—
	32S	6146	0.24	1.65	0.99	0.31	1.53	1.16	433	154	117	0.17	1.84	1.32
	31S	6147	0.39	4.37	0.63	0.32	1.33	1.20	426	210	190	0.20	1.65	1.11
	30S	6151	0.03	5.99	1.33	0.15	0.99	0.97	439	74	73	0.13	1.14	1.02
	29S	6154	0.14	1.10	0.89	0.21	0.83	0.22	434	93	25	0.20	1.04	3.73
	28S	6155	2.16	1.07	0.88	0.10	0.85	3.73	441	97	424	0.10	0.95	0.23
	27S	6160	0.17	1.77	0.67	1.48	2.99	0.56	418	447	84	0.33	4.47	5.34
	26S	6162	0.30	1.02	0.41	0.13	0.58	0.00	433	141	0	0.19	0.71	
	25S	6163	0.37	1.37	0.94	0.28	1.53	1.61	434	164	172	0.15	1.81	0.95
	24S	6164	0.01	3.24	1.28	2.01	5.27	0.45	421	412	35	0.28	7.28	11.71
	23S	6165	0.30	0.99	0.85	0.27	1.02	1.27	433	120	149	0.21	1.29	0.80
	22S	6170	0.24	1.29	1.22	0.17	1.58	0.20	435	129	16	0.10	1.75	7.90
	21S	6172	0.33	6.93	0.39	--	--	--	--	--	--	--	--	--
	20S	6173	0.00	8.97	0.26	--	--	--	--	--	--	--	--	--
	19S	6182	0.29	3.47	2.87	0.78	5.04	1.08	432	176	38	0.13	5.82	4.67
	18S	6183	0.20	2.68	0.90	0.27	1.66	2.68	431	185	298	0.14	1.93	0.62
	17S	6184	0.12	1.21	0.73	0.06	0.49	0.30	435	67	41	0.11	0.55	1.64
	16S	6194	0.01	9.81	0.23	--	--	--	--	--	--	--	--	--
	15S	6202	0.17	1.36	0.73	1.79	3.25	0.85	418	444	116	0.36	5.04	3.82
	13S	6208	0.57	2.18	1.08	0.75	2.74	1.26	433	253	116	0.21	3.49	2.17
	12S	6209	0.36	1.61	1.48	0.52	3.27	0.77	433	220	52	0.14	3.79	4.25
	11S	6211	0.22	1.35	1.13	0.51	3.76	1.22	427	334	108	0.12	4.27	3.08
	10S	6213	0.16	1.33	1.05	0.47	2.29	0.75	434	217	71	0.17	2.76	3.05
	8S	6215	0.05	1.54	1.31	0.32	2.64	0.63	436	201	48	0.11	2.96	4.19
	7S	6217	0.12	1.41	0.96	0.21	0.72	0.28	435	75	29	0.22	0.93	2.59
	6S	6218	0.07	1.32	1.10	0.62	3.90	1.50	432	355	137	0.14	4.52	2.60
	5S	6224	0.38	6.68	0.49	--	--	--	--	--	--	--	--	--
	4S	6227	0.20	2.27	2.22	0.61	3.81	0.70	432	171	32	0.14	4.42	5.44
	3S	6231	0.16	1.34	0.88	0.37	1.78	0.94	435	202	107	0.17	2.15	1.89
	2S	6234	1.15	1.29	0.78	0.29	1.36	1.20	431	174	154	0.18	1.65	1.13
	1S	6235	3.14	1.67	1.22	0.34	1.54	1.02	434	126	84	0.18	1.88	1.51

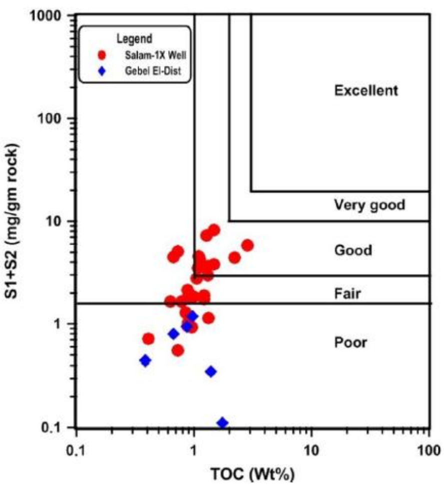

Fig. 5: The Generation potential of Bahariya Formation in the studied rock samples as indicated by TOC and S1 + S2 [14].

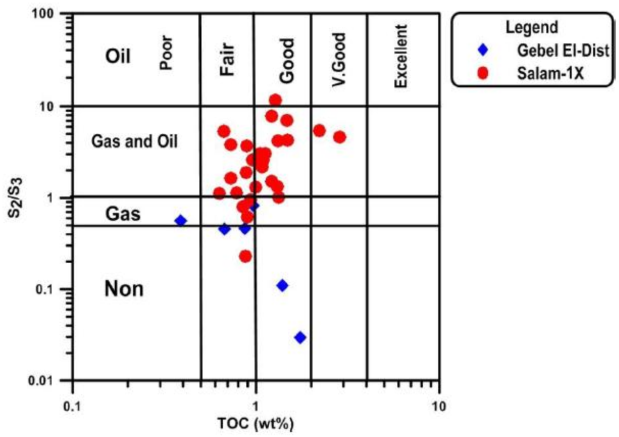

Fig. 6: Cross plot of TOC vs. S2/S3 [23].

generating gas (mainly type III kerogen). Hydrogen index 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 index 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 index above 600 mg/g usually consists of nearly type I or type II kerogen, they have excellent potential to generate oil. In the present study, the hydrogen index "HI" values of the Gebel El-Dist samples range between 4 and 92 mg/g and the oxygen index "OI" range between 98 and 204 mg/g **(Table 1)** which suggest type III kerogen **(Fig. 2a)**. This type of organic matter is derived from terrestrial plant debris and aquatic organic matter **[28]**, while The studied samples of Salam-1X well have "HI" values range from 67 to 447 mg/g and the oxygen index "OI" range from 0 to 424 mg/g **(Table 2),** these data reflect that the main expected kerogen type is type III/II **(Fig. 2b)**.This type of kerogen was derived mainly from mixed organic sources **[28]**. From the relation between TOC% and HI **[29] (Fig. 7)** indicate that Gebel El-Dist section is non-potential source while Salam-1X well is a good potential source. Based on pyrolysis data, kerogen classification diagram constructed using the HI versus OI plot as carried out by **Van Krevelen [30]**, which is used to determine the kerogen type **(Fig. 8)**. The results show that Gebel El-Dist samples are generally plotted under type III kerogen (gas) while Salam-1X samples are plotted in kerogen of type III–II (mainly gas with minor oil). The expected generating hydrocarbon is showing in **(Fig. 9) [18]**. For Gebel El-Dist, it is expected to have gas and/ or oil while for Salam-1X samples it reflects fair oil with some gas.

4.4. Thermal maturation

The generation of petroleum from the organic matter during its burial history is a part of the overall processes of thermal maturation of organic matter **[29]**. 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 maturation **[19]**.

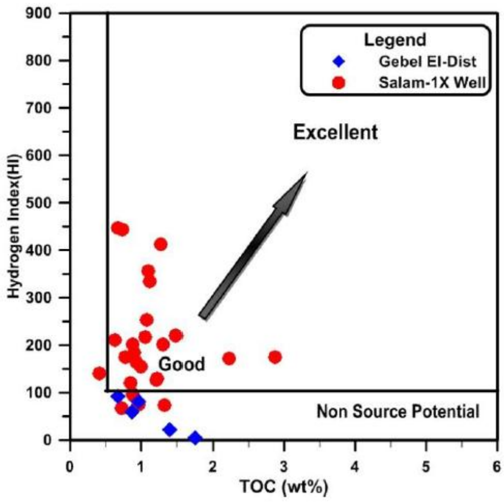

Fig. 7: Hydrogen index versus total organic carbon showing the type of source rocks of the studied sections [29].

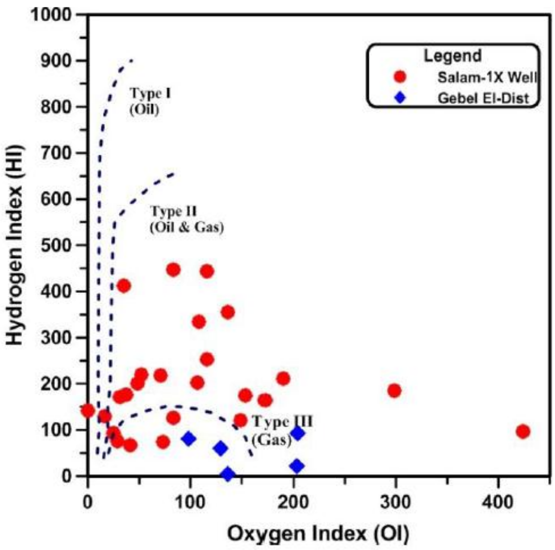

Fig. 8: Modified Van Krevelen type diagram showing type of the organic matter of the Bahariya Formation samples [12].

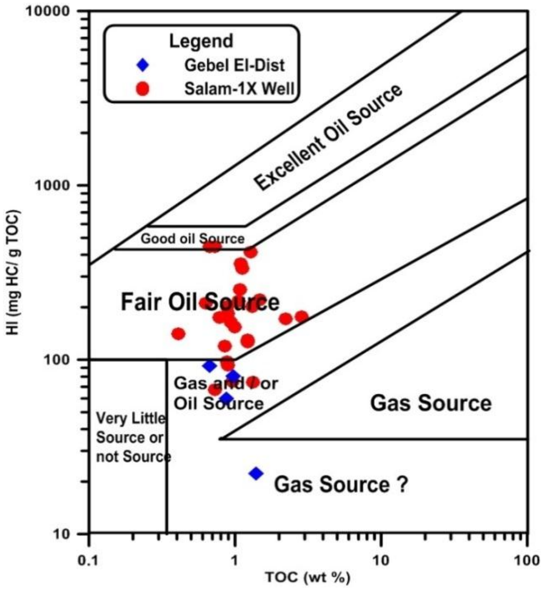

Fig. 9: Source rock characterization using plot of HI vs. TOC for the Bahariya Formation samples [18].

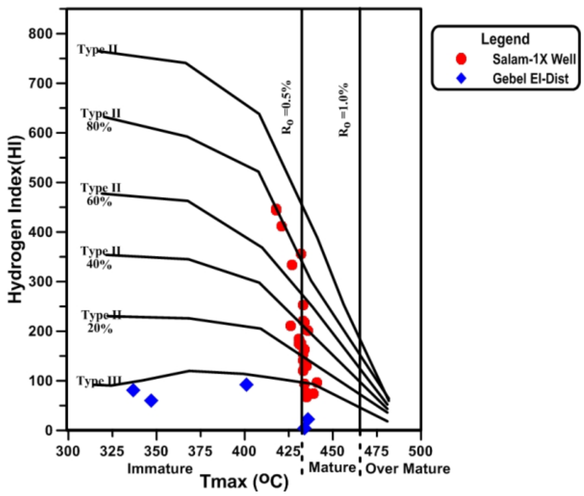

Fig. 10: Relationship between hydrogen index (HI) versus T_{max} [16].

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” **[22,4]. Espitalie et al. [13]** and **Peters [22]** reported that oil generation from source rocks began at "T_{max}" 435–465 °C 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 and ‘‘PI” less than 0.2 and the gas generation from source rocks began at "T_{max}" 470 °C and the production index‘‘PI” more than 0.4.The studied samples of Gebel El-Dist have "T_{max}" values that range from 337°C to 436°C **(Table 1)** indicating that samples lie in immature stage except two samples 3D and 7D lie in marginally mature stage **(Fig. 2a)**. On the other hand, the production index "PI" ranges from 0.12 to 0.45 indicating that the samples lie in between oil generation and gas generation stages. Salam-1X well samples show "T_{max}" values range from 418°C to 441°C **(Table 2)** reflecting that the samples lie in between marginally mature to mature stage**(Fig. 2b)**. Furthermore**,** the production index "PI" ranges from 0.10 to 0.36 indicating that the source rock of this formation are immature to oil generation stage. Based on pyrolysis data; classification diagram was constructed using the HI versus T_{max} plot as carried out by **Hunt [16]** which is used to determine the kerogen type **(Fig. 10)**. The results show that El-Dist samples attain organic matter of type III; while the majority of Salam-1X well samples has varied quantity of Kerogen type III/II.

CONCLUSION:

Based on TOC, Rock–Eval pyrolysis analyses of the Bahariya Formation of the studied sections in the North Western Desert, we concluded that :

1. The Bahariya Formation source rock in Gebel El-Dist section is immature to marginally mature with good capability to produce mainly gas classified as kerogen type III originated mainly from terrestrial plant debris and aquatic organic matter.

2. The Bahariya Formation source rock in Salam-1X well characterized by poor to good organic richness, marginally mature to mature with poor to good hydrocarbon potentiality for generating both oil and gas. The organic matter contains kerogen type III/ II derived mainly from mixed organic sources and has capability of generating mainly gas with minor oil.

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الملخص العربي:

اجريت الدراسة الحالية علي عينات طينيه من تكوين البحريه في جبل الدست بالواحات البحرية و جزء من التكوين في القطاع تحت السطحي لبئر السلام- 1X ممثل بعينات اسطوانية. و قد اجريت التحاليل باستخدام جهازي Rock Eval-6 & LECO SC632 بهدف التعرف علي قدرة هذا التكوين علي انتاج الزيت و الغاز.

و قد أثبتت الدراسة أن قطاع جبل الدست فقير في محتواة العضوي و هو من نوع III و معظمه بقايا نباتيه مستمدة من اليابسه و لم تصل لدرجة النضوج الحراري و هي اكثر احتمالا لتوليد الغاز بينما عينات بئر السلام أغني في محتواها العضوي وهو خليط من نوع III/II و قد وصلت لدرجه النضوج الحراري اللازم لتوليد الزيت و الغاز.