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Mineralogy and source rock evaluation of the marine Oligo-Miocene sediments in some wells in the Nile Delta and North Sinai, Egypt

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A B S T R A C T

This paper aims to study the mineralogical composition and determine the petroleum potential of source rocks of the Oligocene-Miocene sequence in the Nile Delta and North Sinai districts. The studied interval in the five wells can be divided into five rock units arranged from the top to base; Qawasim, Sidi Salem, Kareem, Rudeis, and Qantara formations.

The bulk rock mineralogy of the samples was investigated using X-Ray Diffraction technique (XRD). The results showed that the sediments of the Nile Delta area are characterized by the abundance of quartz and kaolinite with subordinate amounts of feldspars, calcite, gypsum, dolomite, and muscovite. On the other hand, the data of the bulk rock analysis at the North Sinai wells showed that kaolinite, quartz, feldspar and calcite are the main constituents associated with minor amounts of dolomite, gypsum, mica, zeolite, and ankerite.

Based on the organic geochemical investigations (TOC and Rock-Eval pyrolysis analyses), all studied formations in both areas are thermally immature but in the Nile delta area, Qawasim, Sidi Salem and Qantara formations (El-Temsah-2 Well) are organically-rich and have a good petroleum potential (kerogen Type II—oil-prone), while Rudeis Formation is a poor petroleum potential source rock (kerogen Type III—gas-prone). In the North Sinai area, Qantara Formation has a poor petroleum potential (kerogen Type III—gas-prone) and Sidi Salem Formation (Bardawil-1 Well) is a good petroleum potential source rock (kerogen Type II—oil-prone).

1. Introduction

The Miocene succession in Egypt represents about 12% of the total land surface (Ball, 1952). Lying unconformably on the older rocks, they extend from near Cairo westwards across the northern part of the Western Desert into Libya. They are forming a plateau rising gradually to south and reaching height over 200 m. Also, they occur in hills to the east of Cairo, as well as, along both sides of the Gulf of Suez and near the Red Sea coast in both Egypt and Sudan (El-Heiny, 1979).

Numerous studies have investigated the petroleum potential and hydrocarbon characteristics of many localities in Egypt (Rohrback, 1983; Mostafa, 1993; Mostafa et al., 1993, 1998; Bakr and Wilkes, 2002; El-Gayar et al., 2002; Hegazi et al., 2004; Barakat et al., 2005; El-Shahat et al., 2009; El Diasty and Peters, 2014; and El Diasty et al., 2015). Both Miocene and pre-Miocene sediments are sufficiently mature to generate oil; Eocene and Lower Miocene source rocks correlate closely with produced crude oils which appear to be related to a single, widespread source rock (Rohrback, 1983).

This work studies five wells, three of them are located at the northeastern of the Nile Delta: the Boughaz-1 Well was drilled to a total depth of about 3540.9 m by Continental Delta Oil Company (lat. 31° 09′ 24.6″ N, long. 32° 40′ 47.55″ E), the San El-Hagar-1 Well was drilled to a total depth of about 3772 m by Continental Delta Oil Company (lat. 30° 29′ 13″ N, long. 31° 50′ 53″ E), and the El-Temsah-2 Well was drilled to a total depth of about 4689 m by Mobil exploration Egypt Inc. Company (lat. 31° 47′ 7.38″ N, long. 32° 10′ 26.68″ E). While the last two wells are located at the northwest Sinai region, the Malha-1 Well was drilled to a total depth of about

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2198 m by Egyptian Petroleum Company (E.G.P.C) (lat. 30° 59′ 12″ N, long. 33° 20′ 32″ E) and the Bardawil-1 Well was drilled to a total depth of about 4490 m by (E.G.P.C) (lat. 31° 08′ 14″ N, long. 33° 07′ 35″ E). All of these are onshore wells except the El-Temsah-2 Well (offshore) (Fig. 1).

This study aims to determine the bulk mineralogical composition for the subsurface Oligo-Miocene sequence in two localities (Nile Delta and North Sinai), and the source rocks evaluation in terms of petroleum potential and thermal maturity.

2. Lithostratigraphy

The Oligo-Miocene sequence in this study was represented by five rock units arranged for the top to base as follows: Qawasim, Sidi Salem, Kareem, Rudeis and Qantara formations. The litho- and biostratigraphy of these rock units in the five wells are previously discussed by Faris et al., (in press), and their lithostratigraphy are shown in Fig. 2.

3. Materials and methods

Twenty eight cutting samples were selected from the five studied wells in the Nile Delta and North Sinai areas. These samples were analyzed by using a BRUKER D8 Advance model X-ray diffractometer (XRD) in Geochemistry Research Laboratories of Istanbul Technical University (ITU/JAL), Istanbul, Turkey. Using a Rigaku Rad-1 X-ray powdered diffractometer with energy ranging from 30 kV to 10 m A. Small pieces of sample were dried and finally powdered with agate mortar and pestle. The mineralogical investigation was carried out on the bulk rock, and then slides are scanned at a scan speed of 1° 2θ“/minute at a range from 2° 2θ to 72° 2θ. Minerals were identified by their characteristic reflections (Moore and Reynolds, 1989). It was operated with scanning rate 0.1° 2θ/sec., 1 × 104 CPS, time constant 1, slit 0.3 using Ni filtered Cu K-∝ radiation. Samples were interpreted using X,Pert HighScore Plus program, version: 2.2b (2.2.2), licensed to: I.T.U. Istanbul Technical University, Faculty of Chemistry and Metallurgy, Maslak (License No. 92000060).

The organic geochemical analyses of Total Organic Carbon (TOC) and Rock-Eval pyrolysis were performed in 19 samples (13) from the Nile Delta area (Boughaz-1, San El-Hagar-1 and El-Temsah-2 wells) and (6) samples from the North Sinai area (Malha-1 and Bardawil-1 wells). These analyses were conducted at TPAO (Turkish Petroleum Corporation) Research Center's Organic Geochemistry Laboratories (Ankara, Turkey) using a RockEval-6 device (including TOC determinations), IFP 160000 (French Institute of Petroleum) standard on 100 mg pulverized rock samples which were heated to 600 °C in the helium atmosphere, in order to determine the amount of organic matter, the petroleum generation potential as well as the thermal maturity.

4. Results and discussion

4.1. Mineralogical composition

All samples were analyzed by XRD and a semi-quantitative determination of the minerals was conducted based on measuring peak height ratio (Carver, 1971). The mineral identification was carried out based on the discussion of Moore and Reynolds (1989). The (001) and (002) reflections of kaolinite are 7.16 Å and 3.58 Å, respectively. Non-clay minerals were identified by their maximum reflections as follows: quartz (3.34 Å), calcite (3.04 Å), halite (2.82 Å), feldspar (3.26 Å) and dolomite (2.89 Å). In addition, barite was identified using 3.44 Å and 3.1 Å peaks, but it was disregarded from semiquantitative calculations as it is a contamination from drilling mud. The results of mineralogical analysis are given in Table 1.

In this study, the sediments of the Nile Delta area are mostly

Fig. 1. Location map of the studied wells.

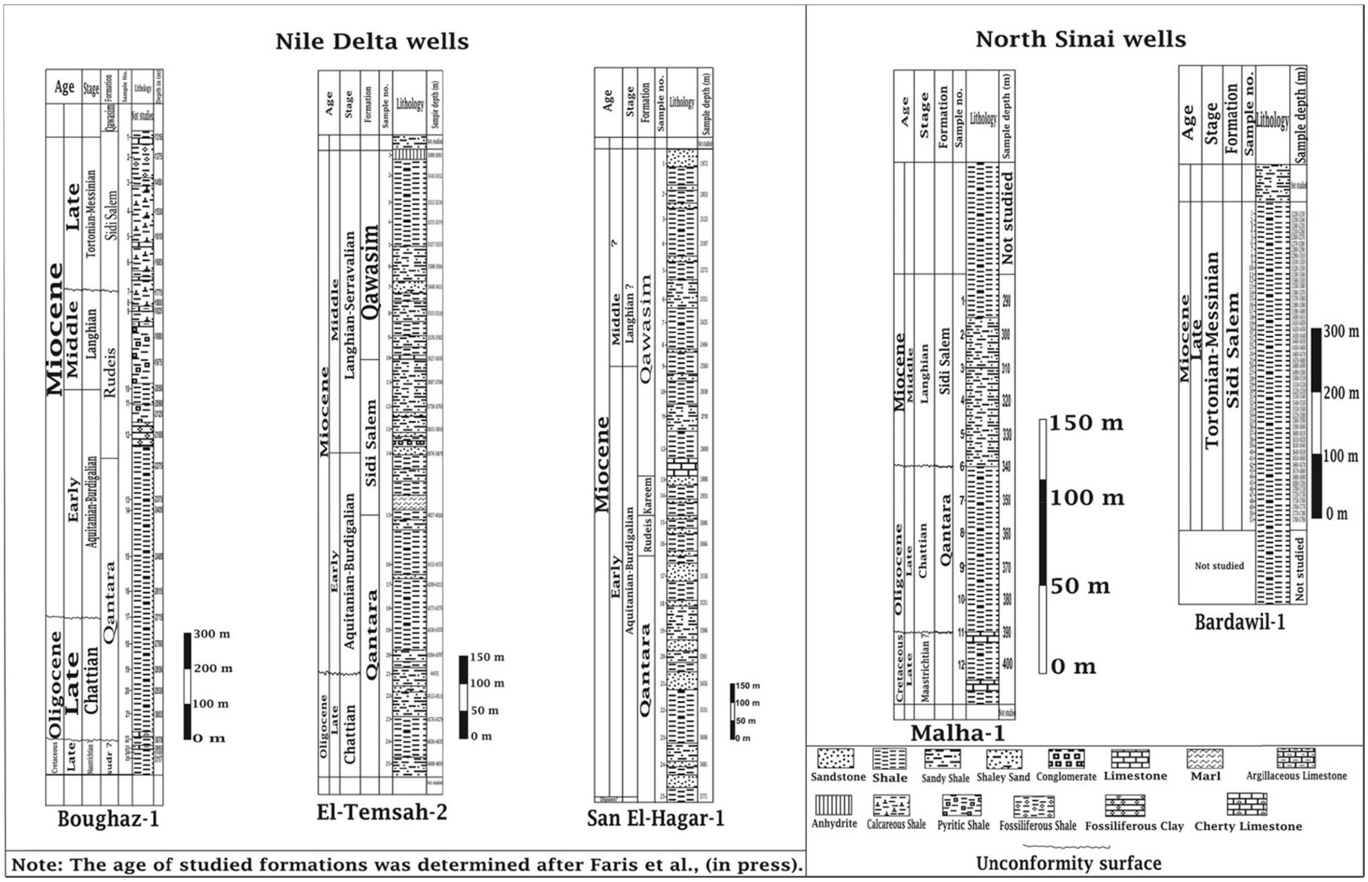

Fig. 2. Lithostratigraphy of the studied wells in the Nile Delta and North Sinai areas.

clastics and composed mainly of sandstone and shales. Mineralogical analyses were carried out on (18) samples selected from the subsurface different rock units in the Nile Delta wells (Boughaz-1, El-Temsah-2 and San El-Hagar-1; Table 1).

Generally, the bulk rock mineralogy indicates the abundance of quartz, kaolinite and few feldspars. Calcite frequently occurs with small amounts of gypsum. Dolomite and muscovite are present in minor amounts. The vertical distribution of these minerals along different rock units are shown in Figs. 3–5. Kaolinite is the only principal clay mineral identified in the Nile Delta wells. In this area, Miocene sediments contain relatively high kaolinite content (Table 1).

Whereas the mineralogical analyses carried out in 10 bulk rock samples selected from different rock units in the North Sinai wells (Bardawil-1 and Malha-1) showed that kaolinite, quartz, feldspar and calcite are the main constituents beside other minor minerals such as, dolomite, and rarely gypsum, mica, zeolite and ankerite (Table 1). The XRD patterns for the analyzed samples are shown in Figs. 6–7.

Kaolinite and illite are the main clay minerals recorded in the North Sinai studied wells. Both wells (Bardawil-1 and Malha-1) contain relatively high kaolinite content than the illite. In general, the middle and upper Miocene sediments of the Sidi Salem Formation in these wells are more calcareous than the other formations (Table 1).

Generally, the Miocene sediments of the three studied wells in the Nile Delta area (Boughaz-1, El-Temsah-2 and San El-hagar-1), are dominated by kaolinite and quartz more than the two wells in the North Sinai area (Bardawil-1 and Malha-1). The upper-middle Miocene sediments in the Boughaz-1 Well contain high calcite content than other wells due to the high abundance of calcareous nannofossils (Faris et al., in press). However, the lower-middle Miocene sediments in the all studied wells contain relatively high carbonate content than the upper Miocene.

During the early and middle Miocene, sea-level rose worldwide (Haq et al., 1987), and as a result of this eustatic rise of sea-level marine waters transgressed far to the south in the Gulf of Suez region. Shelf sands and carbonates were deposited (Harms and Wray, 1990). On the other hand, the relatively low carbonate contents obtained from the upper Miocene sediments are related to high terrigenous influxes and to the syn-and post-depositional dissolution of readily dissolved planktonic organisms. During the upper Miocene, the sedimentation begins with sandy shelf condition and becoming increasingly fine-grained.

The predominance of carbonates deposited in the Early-Middle Miocene in the studied wells indicates that they laid down in the inner shelf leading the reduction of terrigenous influx allowed calcareous organisms to flourish and resulting in the carbonate production.

El Shahat and El Sherbini (1984), studied the clay mineralogy of the Tertiary and Quaternary subsurface sediments in Damanhour S-1 Well, west Nile Delta. They mentioned that kaolinite and montmorillonite are the main clay minerals present and concluded that these clays are detrital in origin. Gheith and El Sherbini (1986) studied the mineralogical composition of the subsurface sediments in the northern part of the Nile Delta. They stated that the sediments of the Abu Madi and Qawasim formations are made up of quartz, calcite, plagioclase and K-feldspars with montmorillonite

Table 1
X-ray diffraction analysis of bulk rock mineralogy of the sediments studied in the Nile Delta and North Sinai wells.

Area	Well name	Age	Formation	Sample depth (m)	Bulk rock mineralogy %											
					Clay minerals		Quartz	Feldspar		Carbonate			Mica		Zeolite	Evaporite
					Kaolinite	Illite		Albite	Anorthite	Dolomite	Calcite	Ankerite	Muscovite	Biotite		Gypsum
Nile Delta	Boughaz-1	Late Miocene	Sidi Salem	1610	42		19		32		8					
				1685	49		31				21					
		Middle Miocene		1800	57		25				19					
			Rudeis	1825	11		8			24	29		23		2	4
		Early/Middle Miocene		2050	29		42	13	15							
		Early Miocene	Qantara	2375	20		65	12			3					
				2405	36		30				4		30			
				2485	20		44	33			3					
	El-Temsah-2	Middle Miocene	Qawasim	3448–3455			27	19					41		2	11
				3515–3618	30		57			10					4	
		Early/Middle Miocene	Sidi Salem	3876-3879	11		72	6	9	2						
		Early Miocene		4027–4030	43		33	17		3	5					
			Qantara	4152–4155	32		24	26		10	9					
	San El-Hagar-1	Early Miocene	Qawasim	2800	36		29	30			4					
			Kareem	2931	25		15	15		1	24		20			
			Rudeis	3066	61		29				3		7			
			Qantara	3156	25		50	15			10					
				3681	18		64	14			4					
North Sinai	Bardawil-1	Late Miocene	Sidi Salem	1230–1240	7	19	10	18	33					12		
				1420–1430	28		31	22			19					
				1760–1770	15	37	15	13	18							3
				1770–1780	34		30	21			11					5
				1780–1790	24		11	19					31		8	7
	Malha-1	Middle Miocene	Sidi Salem	300	13	33	24	8			16	6				
				320	17		14		11	33	12		13			
		LateOligocene	Qantara	350	23		26	13			8	2	26			1
				380	30		19	15			9		27			
		Late Cretaceous	Sudr ?	400	31		64				5					

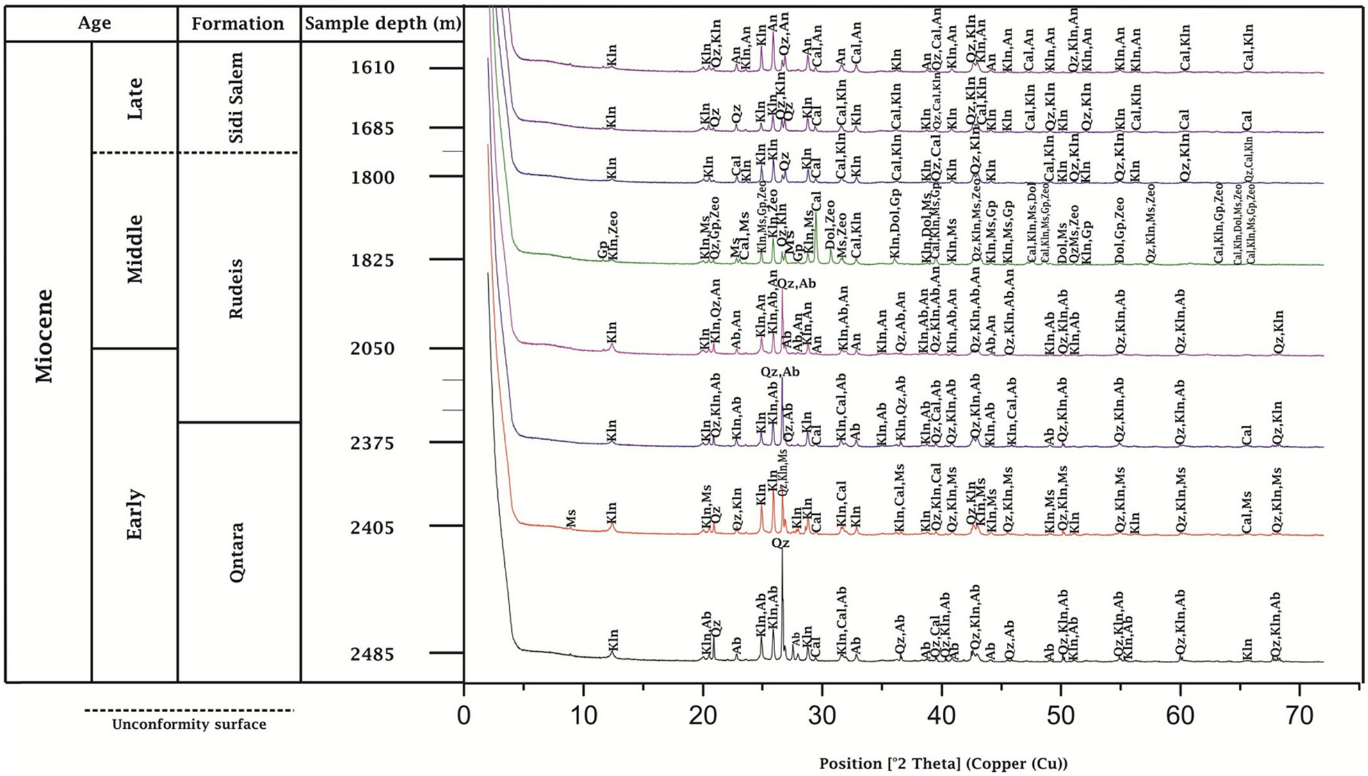

Fig. 3. XRD patterns for the analyzed samples of the Boughaz-1 Well. Abbreviations; albite:Ab; ankerite: Ank; anorthite: An; biotite: Bt; calcite: Cal; dolomite: Dol; gypsum: Gp; illite: Ilt; kaolinite: Kln; muscovite: Ms; quartz: Qz; and zeolite: Zeo.

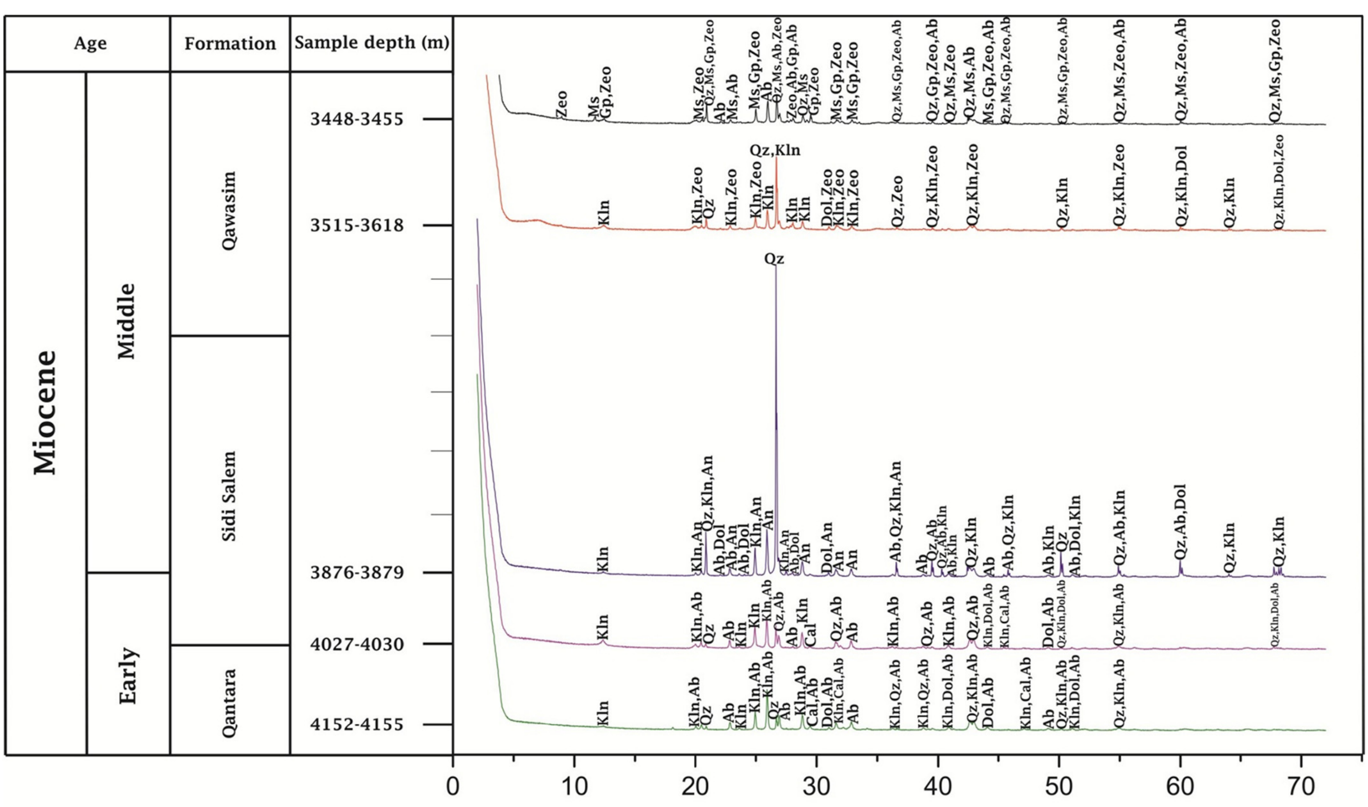

Fig. 4. XRD patterns for the analyzed samples of the El Temsah-2 Well.

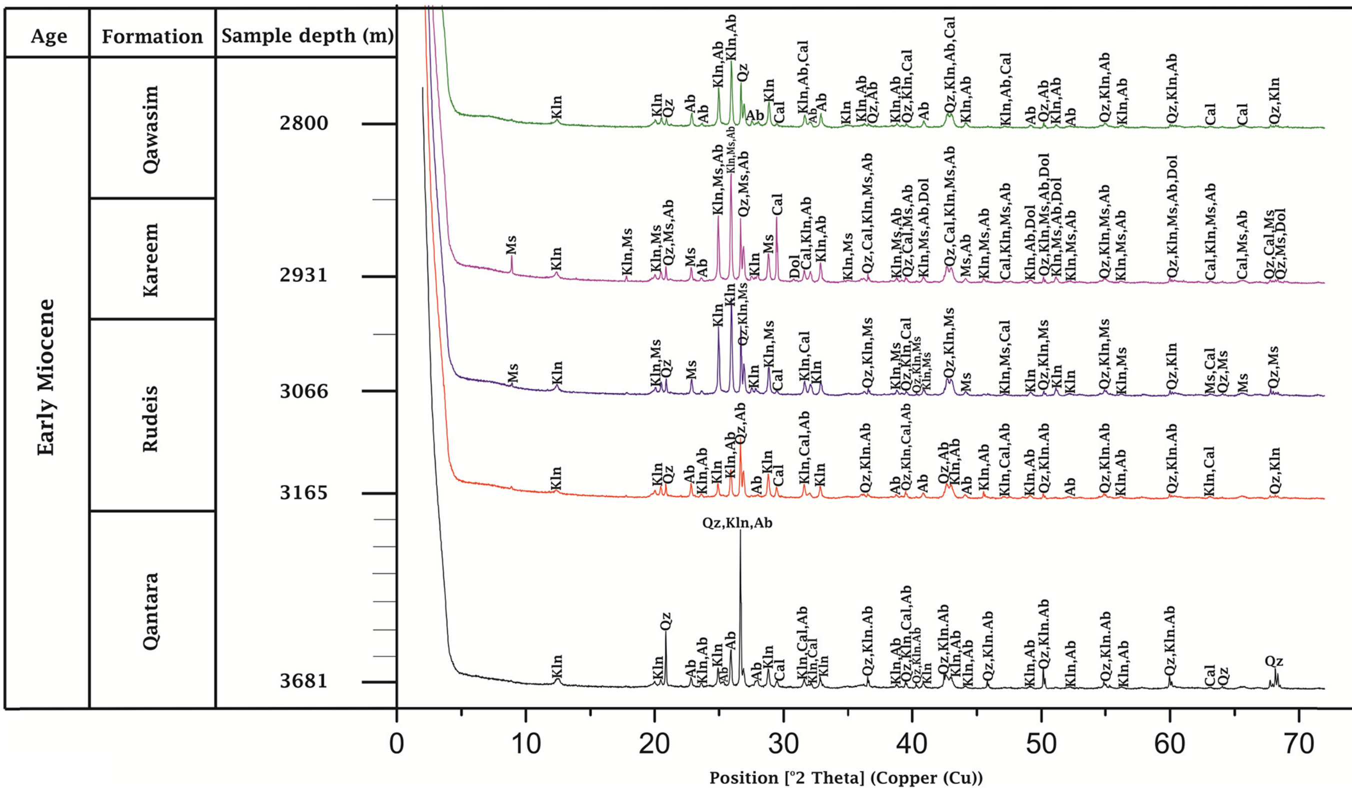

Fig. 5. XRD patterns for the analyzed samples of the San El-Hagar-1 Well.

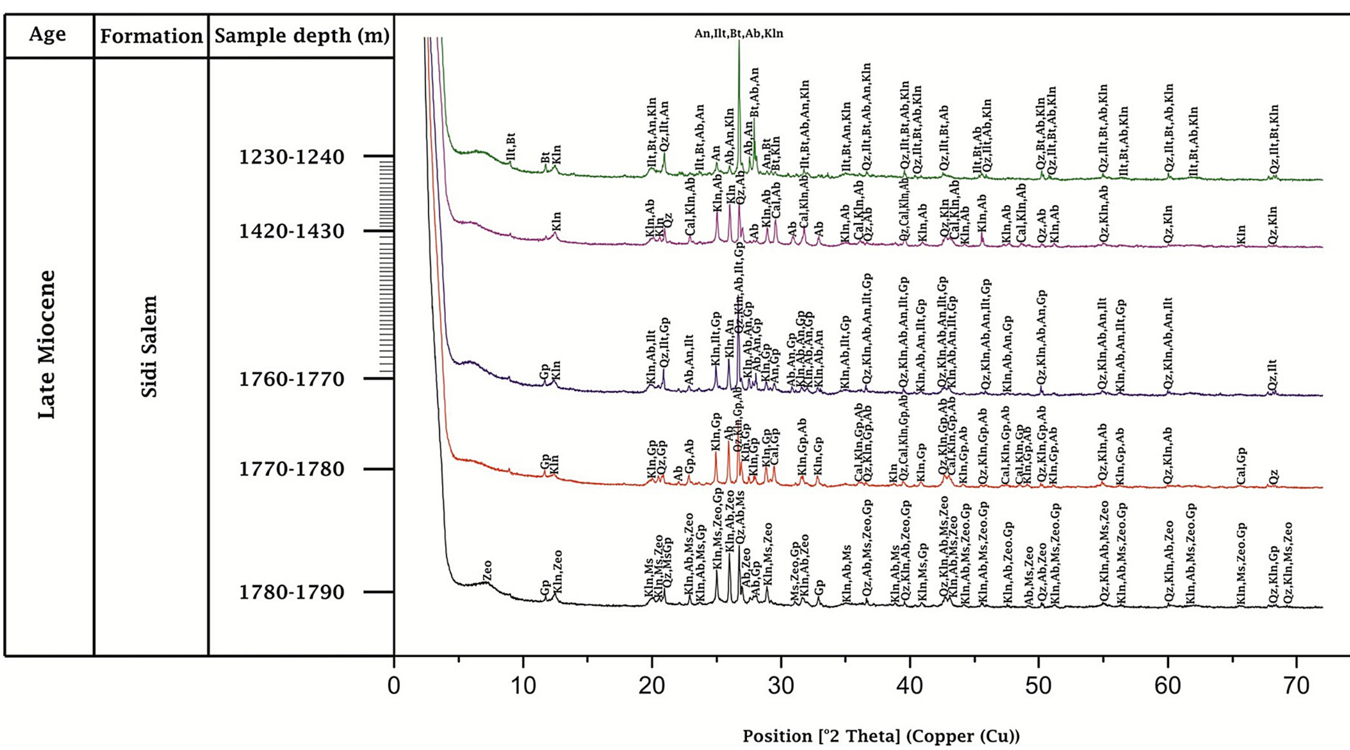

Fig. 6. XRD patterns for the analyzed samples of the Bardawil-1 Well.

and kaolinite clay minerals and concluded that these minerals were possibly derived from different source rocks, either exposed sediments (carbonates and sandstones) or basic igneous rocks.

The clay mineral assemblages identified in the Miocene sediments of the studied areas (the Nile Delta and the North Sinai) are made up mainly of kaolinite and some few content of illite (North

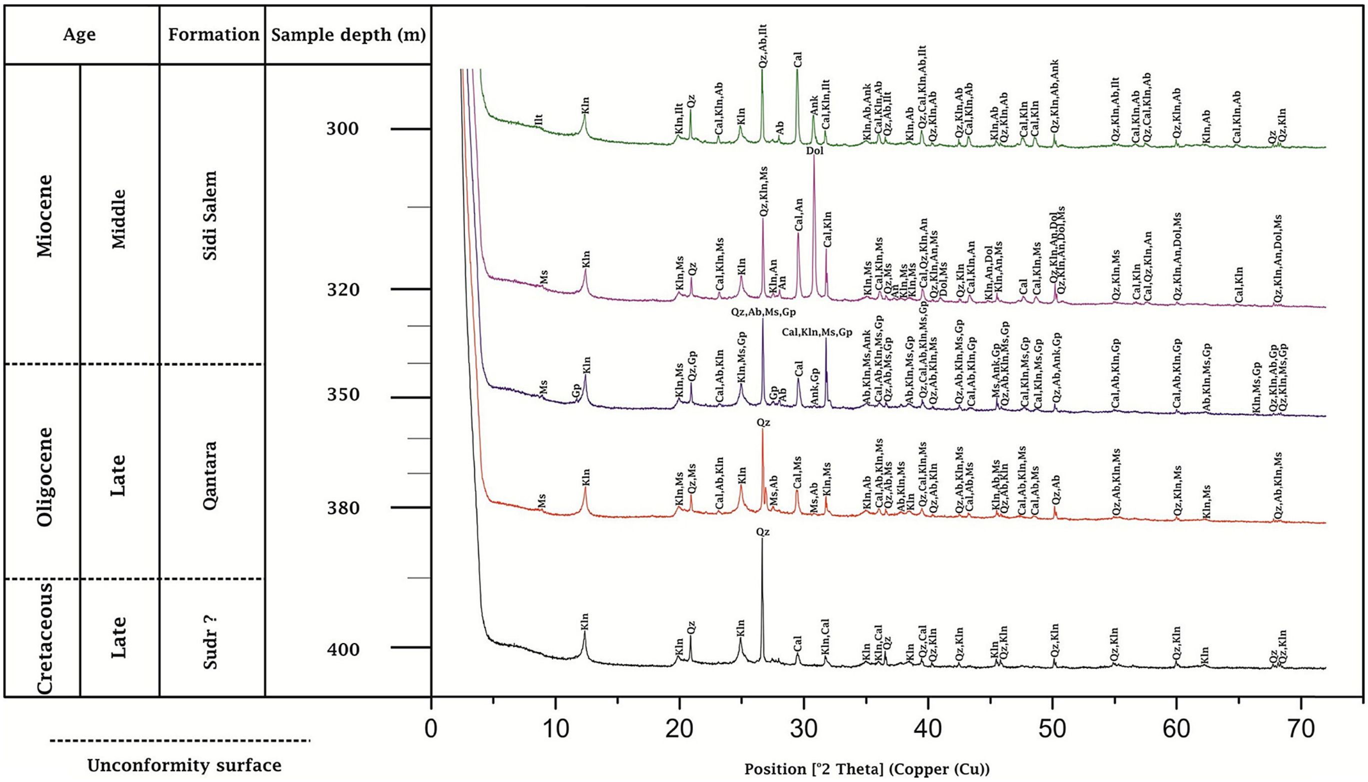

Fig. 7. XRD patterns for the analyzed samples of the Malha-1 Well.

Sinai only). The presence of kaolinite suggests a climatic warming trend during the lower to middle Miocene (Wolfe and Poore, 1982).

Kaolinite has been accepted for a long time as a product of chemical weathering of feldspars or their detrital weathering products under tropical to subtropical humid climatic conditions (Hendriks, 1985; Chamley, 1989; Hallam et al., 1991). It is worth to mention that the mineralogical composition obtained in the studied wells suggests that the detrital input was especially intense at the Miocene, probably because of the abundance of detrital kaolinite associated with significant amount of detrital quartz and feldspar.

4.2. Source rock evaluation

The studied materials represent 19 cutting samples of shale collected from the five studied wells, 13 of them belonging to the Nile Delta area and the other 6 samples belonging to the North Sinai area. The organic geochemical results of TOC and Rock-Eval pyrolysis are summarized in Table 2.

The thermal maturity was evaluated based on the Tmax measurements from Rock-Eval pyrolysis. The amount of kerogen is determined as the total organic carbon (TOC) and it can be described as poor, fair, good, very good, or excellent depending on the weight percentage of TOC. Generally, a poor source rock has TOC values below 0.5 (wt %) while a fair source ranges from 0.5 to 1 (wt %), the good source rock has TOC values ranging from 1 to 2 (wt %), the very good source rock has TOC values ranging from 2 to 4 (wt %) and the excellent source rock has TOC values more than > 4 (wt %) (Peters, 1986).

The results of the present analyses in Table 2 from the Nile Delta area show the values of TOC ranging from 0.66 to 3.52 wt %, indicating that the formations of this area have fair to very good source rock potentials. Qawasim and Sidi Salem formations varied from fair to very good source rocks (0.69–2.66 wt % & 0.66–2.95 wt %, respectively), Rudeis Formation has a good source rock potential (1.22–1.34 wt %), while Qantara Formation presents the highest value of TOC (El-Temsah-2 Well); it varies from good to very good source rock (1.33–3.52 wt %), (Fig. 8 A). On the other hand, North Sinai area has values of TOC ranging from 0.36 to 3.38 wt %, indicating that its formations are poor to very good source rock potentials. Sidi Salem Formation (Bardawil-1 Well) presents the highest value of TOC (3.38 wt %), while Qantara Formation varied from a fair to good source rocks (0.83–1.64 wt %) (Fig. 8 A).

According to the Rock-Eval pyrolysis analysis; (S1): the free hydrocarbons present in the sample before analysis, it can be thought of as a residual hydrocarbon phase.

From Table 2; the values of S1 in the Nile Delta area ranged from 0.03 (Sidi Salem Formation, Boughaz-1 Well) to 13.85 (Qantara Formation, El-Temsah-2 Well) mg/g of rock.

Whereas in the North Sinai area, S1 values ranged from 0.05 (Sidi Salem Formation, Malha-1 Well) to 12.89 (Sidi Salem Formation, Bardawil-1 Well) mg/g of rock.

While the quantity of petroleum in mg/g of rock released by the kerogen cracking during pyrolysis is (S2) (whereas S2 is the sum of hydrocarbons and non-hydrocarbons produced by cracking of kerogen) it can be used in determining the type of source rock potential, a poor source rock has S2 values below 2.5, a fair source ranges from 2.5 to 5, a good source rock has S2 values ranging from 5 to 10 and a very good source rock ranging from 10 to 15 (mg HC/g Rock) (Peters, 1986).

From Table 2; the Nile Delta formations are considered to be a poor to very good source rock potentials based on S2 values ranging from 0.44 to 13.33 (mg HC/g Rock). Qawasim Formation ranged from a poor to good source rock (0.44–8.28 mg HC/g Rock), Sidi Salem Formation varies from a poor to very god source rock (0.49–12.69 mg HC/g Rock), Rudeis Formation ranged from 1.51 to

Table 2
Total Organic Carbon and Rock-Eval pyrolysis data for the analyzed samples in the Nile Delta and North Sinai areas.

Area	Well nname	Age	Formation	Sample no.	Sample depth (m)	Lithology	TOC wt%	S1	S2	S3	Tmax	HI	OI	PI	Thermal maturity	Kerogen type
Nile Delta	Boughaz-1 Well	Late Miocene	Sidi Salem	1	1316	Grey shale	0.69	0.03	0.49	1.41	449	71	204	0.06	Mature	III
		Early/Middle Miocene	Rudeis	2	2050	Grey shale	1.22	0.29	1.51	3.73	426	124	306	0.16	Immature	III
		Late Oligocene	Qantara	3	2790	Dark grey shale	1.33	0.82	2.25	2.27	428	169	171	0.27	Immature	II/III
	San El-Hagar-1 Well	Middle Miocene	Qawasim	4	2425	Grey shale	0.66	0.07	0.44	1.44	428	67	218	0.15	Immature	III
		Early Miocene		5	2800	Dark grey shale	1.19	0.16	0.84	3.55	427	71	298	0.16	Immature	III
			Rudeis	6	3066	Slightly glauconitic shale	1.34	1.87	2.42	2.76	426	181	206	0.44	Immature	III
			Qantara	7	3531	Grey shale	1.34	2.19	1.62	3.32	421	121	248	0.57	Immature	II/III
				8	3771	Blocky shale	1.92	4.68	5.06	2.37	413	264	123	0.48	Immature	II/III
	El-Temsah-2 Well	Middle Miocene	Qawasim	9	3145	Dark grey shale	2.95	11.73	8.28	1.32	294	281	45	0.59	Immature	II
				10	3327	Grey shale with few sand	2.83	9.41	6.75	1.16	305	239	41	0.58	Immature	II
		Early/Middle Miocene	Sidi Salim	11	4027	Grey shale	2.66	7.55	12.69	1.69	399	477	64	0.37	Immature	II
		Early Miocene	Qntara	12	4273	Grey shale	3.52	13.85	13.33	1.79	408	379	51	0.51	Immature	II
		Late Oligocene		13	4576	Grey shale with few sand	3.36	10.94	10.19	2.26	431	303	67	0.52	Immature	II
North Sinai	Malha-1 Well	Middle Miocene	Sidi Salem	1	290	Grey Shale	0.36	0.05	0.14	1.31	412	39	364	0.28	Immature	III
				2	330	Sandy Shale	0.64	0.06	0.36	2.78	424	56	434	0.13	Immature	III
		Late Oligocene	Qantara	3	360	Dark Grey Shale	1.64	0.22	1.17	2.83	433	71	173	0.16	Immature	III
		Late Cretaceous/Late Oligocene		4	390	Calcareous Shale	0.83	0.12	0.61	2.89	420	73	348	0.16	Immature	III
	Bardawil-1 Well	Late Miocene	Sidi Salem	5	1290	Grey Shale	2.87	6.86	9.75	2.89	430	340	101	0.41	Immature	II
				6	1570	Grey Shale	3.38	12.89	9.64	1.77	428	285	52	0.57	Immature	II

S1: quantity of free hydrocarbons in mg/g of rock; S2: quantity of petroleum in mg/g of rock released by the kerogen cracking during pyrolysis; S3: amount of oxygen in mg CO_2/g of rock; Tmax: temperature in °C that occurs the maximum petroleum generation rate; HI: Hydrogen index, HI = (S2/TOC) × 100, mg S2/g TOC; OI: Oxygen index, OI = (S3/TOC) × 100, mg CO_2/g TOC; PI: Production index, PI = S1/(S1 + S2).

2.42 mg HC/g Rock (poor source rock) and Qantara Formation has the highest value of S2 (13.33 mg HC/g Rock, El-Temsah-2 Well), it varies from a poor to very god source rock (1.62–13.33 mg HC/g Rock), (Fig. 8 B).

The North Sinai formations are considered to be a poor to good source rock potentials ranging from 0.14 to 9.75 (mg HC/g Rock). Sidi Salem Formation varies from a poor (Malha-1 Well) to good (Bardawil-1 Well) source rock (0.14–9.75 mg HC/g Rock) and Qantara Formation has values ranged from (0.61–1.17 mg HC/g Rock) it is a poor source rock (Fig. 8 B).

S3 values are relatively high in both two areas, ranging from 1.16 to 3.73 (Rudeis Formation in the San El-Hagar-1 Well) mg CO2/g Rock in the Nile Delta and from 1.31 to 2.89 mg CO2/g Rock in the North Sinai (Table 2), resulting in high oxygen index characterizing a Type III kerogen, related to the land plant input.

The mature source rock has Tmax values above 435 °C (Peters and Cassa, 1994). As shown in Table 2 the Tmax values in the Nile Delta area ranged from (294–449 °C), all formations are immature (not exceed 435 °C) except Sidi Salem Formation varies from an immature to mature source rock has Tmax 399–449 °C (449 °C this high value is probably affected by the low detection limit of the equipment) (Fig. 8 C). In the North Sinai, Tmax values ranged from (412–433 °C), all formations are immature (not exceed 435 °C) (Fig. 8 C).

(Fig. 9 A–C); the relationships between TOC versus Rock-Eval S2, HI versus Tmax and Hydrogen Index (HI) versus Oxygen Index (OI) (modified Van Krevlen diagram, Espitalié, 1986), all these relationships show what kerogen type is associated with the present formations. From Fig. 9 the Nile Delta formations varied in kerogen types from II (Oil-prone), II-III (Oil-gas-prone) to III (Gas-prone). From these interpretation we can concluded that Qawasim, Sidi Salem and Qantara formations (El-Temsah-2 Well) are characterized by organic-rich shales with good petroleum generation potential (Type II) source rocks (Fig. 9 C), while Rudeis Formation is of Type III, organic-poor and low petroleum generation potential (mostly gas-prone) source rock but all formations are thermally still immature for petroleum production.

Also from (Fig. 9 A–C) the North Sinai formations have two kerogen types (II and III) (Oil- and Gas-prone), Sidi Salem Formation (El-Temsah-2 Well) is characterized by organic-rich shales with good petroleum generation potential (Type II) source rocks, while Sidi Salem (Malha-I Well) and Qantara formations are of Type III, organic-poor and low petroleum generation potential (mostly gas-prone) source rock, also as in the Nile Delta all formations are thermally immature for petroleum production.

Early Miocene-Oligocene shales and mudstones are the principal source rocks in the Nile Delta (Shaaban et al., 2006). The Miocene source rocks in in Abu Madi/El Qar'a Gas Field, Nile Delta, reached late mature stage at middle to upper Miocene age and the gas window in upper Miocene to lower Pliocene. Accordingly, the hydrocarbon generation (oil and gas) started in middle to upper Miocene and peak hydrocarbon generation occurred during lower Pliocene (Keshta et al., 2014). In the North Sinai the Oligo-Miocene fine clastics, could yield oil and/or gas and are mature enough in the deep kitchens to generate hydrocarbon (Alsharhan and Salah, 1996).

5. Conclusions

In this work, the Oligo-Miocene sequence was studied in the five wells to determine mineralogical composition and petroleum potential of source rocks. Three of them are located at the northeastern of the Nile Delta (Boughaz-1, El-Temsah-2 and San El-Hagar-1) and the others two wells are located at the northwest Sinai region, Egypt (Bardawil-1 and Malha-1).

The mineralogical composition of 28 clastic and non-clastic samples selected from the Nile Delta and North Sinai areas were obtained using X-Ray Diffraction technique (XRD) with a semi-quantitative determination of the minerals based on measuring peak height ratio.

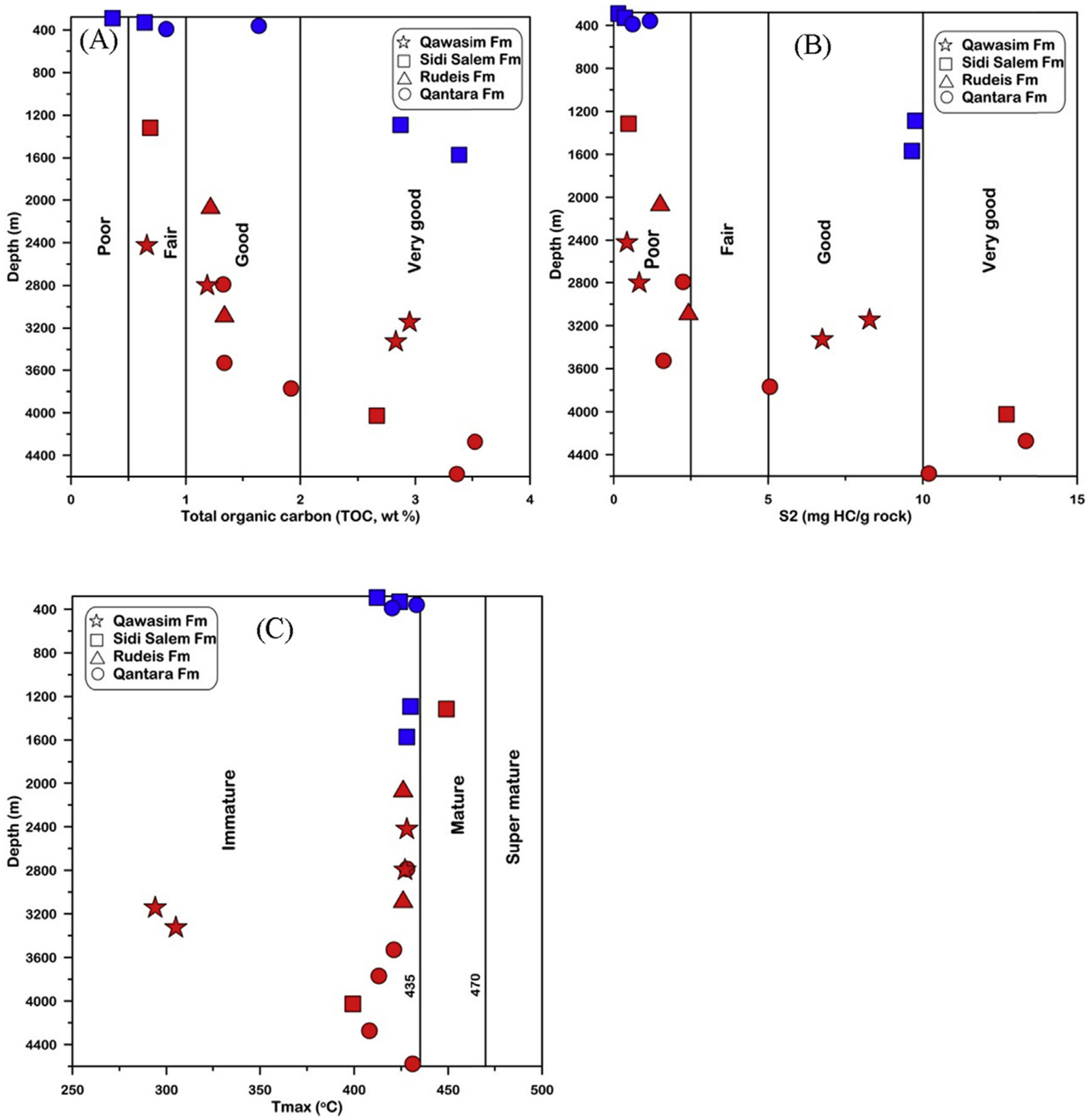

Fig. 8. (A) Plot of TOC versus depth, (B) Plot of S2 versus depth, (C) Plot of Tmax versus depth, for the analyzed samples of the Qawasim, Sidi Salem Rudeis and Qantara formations in the studied wells (Nile Delta area: Red color; North Sinai area: Blue color). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

The sediments of the Nile Delta area are mostly clastics and composed mainly of sandstone and shales. The bulk rock mineralogy of the wells in this area indicates the abundance of quartz and kaolinite with minor amount of feldspars, calcite gypsum, dolomite, and muscovite. The data of the bulk rock analysis for the North Sinai area showed that kaolinite, quartz, feldspar and calcite are the main constituents beside other minor minerals such as, dolomite, gypsum, mica, zeolite, and ankerite.

Generally, the Miocene sediments of the three studied wells in the Nile Delta area are dominated by kaolinite and quartz more than the two wells in the North Sinai area. The lower-middle Miocene sediments in the all studied wells contain relatively high carbonate content than those of the upper Miocene. The predominance of carbonates deposited in the Early-Middle Miocene indicates that they laid down in the inner shelf leading to the reduction of terrigenous influx allowed calcareous organisms to flourish and resulting in the carbonate production.

Organic geochemical investigations based on TOC and Rock-Eval pyrolysis analyses were carried out on 19 cuttings samples collected from the shales of different studied formations in the both Nile Delta (13 samples) and North Sinai wells (6 samples) to evaluates the petroleum potential of source rocks in the Oligo-Miocene succession in these two areas. The Rock-Eval pyrolysis and TOC results indicated that all the studied formations in both two areas, depending on temperature, are immature source rocks. In the Nile delta area, Qawasim, Sidi salem and Qantara formations (El-Temsah-2 Well) are organically-rich and have a good petroleum potential (kerogen Type II—oil-prone), while Sidi Salem (Boughaz-1 Well), Rudeis and Qawasim (San El-Hagar-1 Well) formations are a poor petroleum potential (kerogen Type III - gas-prone) and Qantara Formation (Boughaz-1 and San El-Hagar-1 wells) has a moderate petroleum potential (Mixed kerogen Type II/III—oil-gas-prone). On the other hand, Qantara Formation in the North Sinai area has poor petroleum potential (kerogen Type III - gas-prone)

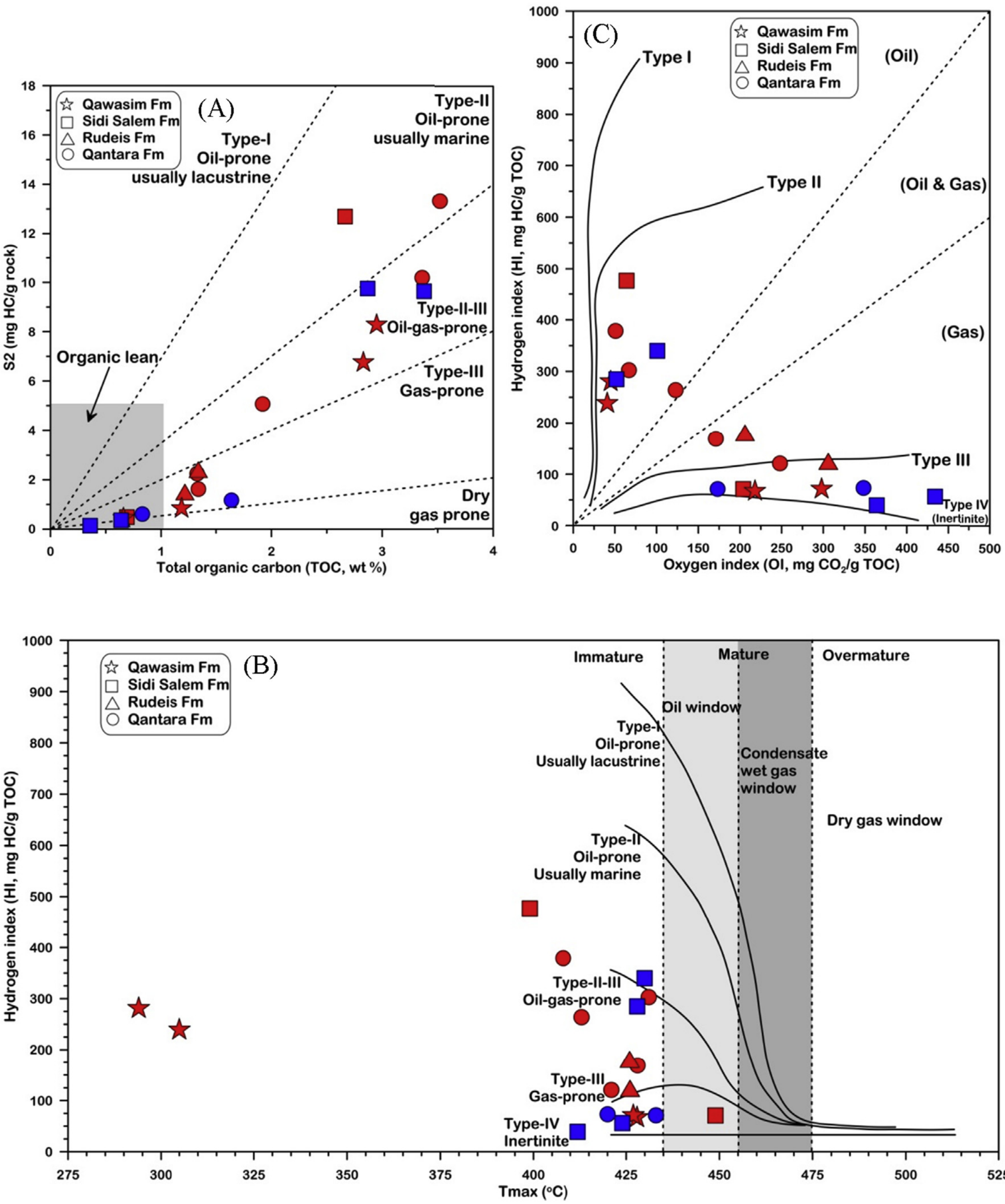

Fig. 9. (A) Plot of S2 versus TOC (El Diasty et al., 2015), (B) Plot of HI versus Tmax (El Diasty et al., 2015), (C) Plot of HI versus OI (Modified Van Krevlen diagram, Espitalié, 1986), for the analyzed samples of the Qawasim, Sidi Salem Rudeis and Qantara formations in the studied wells (Nile Delta area: Red color; North Sinai area: Blue color). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

and Sidi Salem Formation (Bardawil-1 Well) is a good petroleum potential source rock (kerogen Type II—oil-prone).

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