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Thermal Maturity and Hydrocarbon Generation Modelling for the Lower Rudeis Source Rock and Petroleum System Analysis in Garra Area, South Gulf of Suez, Egypt

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Abstract

The Lower Rudeis Formation is an active source rock in the Garra region, which is characterized by a good hydrocarbon generative potential. The Lower Rudeis source rock reached the early mature stage in the Middle Miocene Langhian (15.5 Ma) and went through the mid mature stage at 0.9 Ma.. It was generated from a clay source rock, deposited under sub-oxic to oxic conditions and derived from an organic material composed mainly of terrestrial organic material. The Lower Rudeis source rock went through two phases of hydrocarbon generation and expulsion. The first phase occurred from 6.0 Ma to 3.4 Ma, while the second phase started at 3.4 Ma and continued until the present time, with a transformation ratio estimated of 42%. The oil expulsion increased to 16 mg/gTOC and gas expulsion to 40 mg/gTOC, thus the expelled hydrocarbons are mainly composed of mainly gas and some oil. In contrast to the southern province, the Garra region has a single petroleum system which is charged by pre-Miocene and Miocene, Lowers Rudeis, source rocks along vertical and lateral migration routes and the main Kareem-Rudeis reservoirs that were sealed by the Belayim evaporite. The current study is based on the geological, geochemical, biomarker and stable carbon isotope data, which were analyzed, interpreted and presented as burial, thermal and maturity models using the petroleum systems and basin analysis program (BasinMod software).

Introduction

The introduction should briefly place the study in a broad context and highlight why it is important. It should define the purpose of the work and its significance. The current state of the research field should be reviewed carefully, and key publications cited. Please highlight controversial and diverging hypotheses when necessary. Finally, briefly mention the main aim of the work. As far as possible, keep the introduction comprehensible to scientists outside your particular field of research.

The Gulf of Suez region is considered an important petroleum province in Egypt, as it ranks 7th among the major rift basins in the world (Schlumberger, 1995) [1]. The studied wells are located in the southern part of the Gulf on the eastern side (Fig. 1).

Barakat (1982) [2], Shahin and Shehab (1984) [3], Salah (1992) [4] and Alsharhan and Salah (1994) [5] studied the source rocks and their hydrocarbon potential in the southern province and concluded that the source rocks include the Duwi, Sudr, Thebes and Lower Rudeis formations. The source rocks of syn-rift Miocene contain a mixture of the II and III type of kerogen which indicates the presence of gas and oil-prone. High hydrocarbon potentiality originated from rifting, high geothermal gradient values, development of good reservoirs, such as reefs buildups as well as structure traps resulted from the rotational faulting capped by evaporite rocks. El Nady and Mohamed (2016) [6] recognized that Rudeis source rocks have poor to good generating potential to generate both gas and oil at optimum maturity. Younes and Philip (2005) [7] studied the oils based on a geochemical and a biomarker analysis in the southern province and stated that there are two separated proven petroleum systems attributed to pre-Miocene and Miocene sequences. In Garra area, the petroleum system was not accurately investigated, consequently the authors of the present research attempt to verify whether the petroleum system in Garra area is similar or different from the petroleum systems in southern province.

The current research aims to assess the thermal maturity history in order to determine the mature stages of the Early Miocene Lower Rudeis source rock, and to study the hydrocarbon generation and expulsion evolution. In addition to studying the petroleum systems in Garra area to determining whether there are two petroleum systems, likewise the southern province, or only one petroleum system. For accomplishing such objectives, the authors used the available data of the organic matter from the six wells of the Lower Rudeis Formation and Duwi, Esna and Thebes formations, as well as the geochemical, biomarker and stable carbon isotope data of the oils

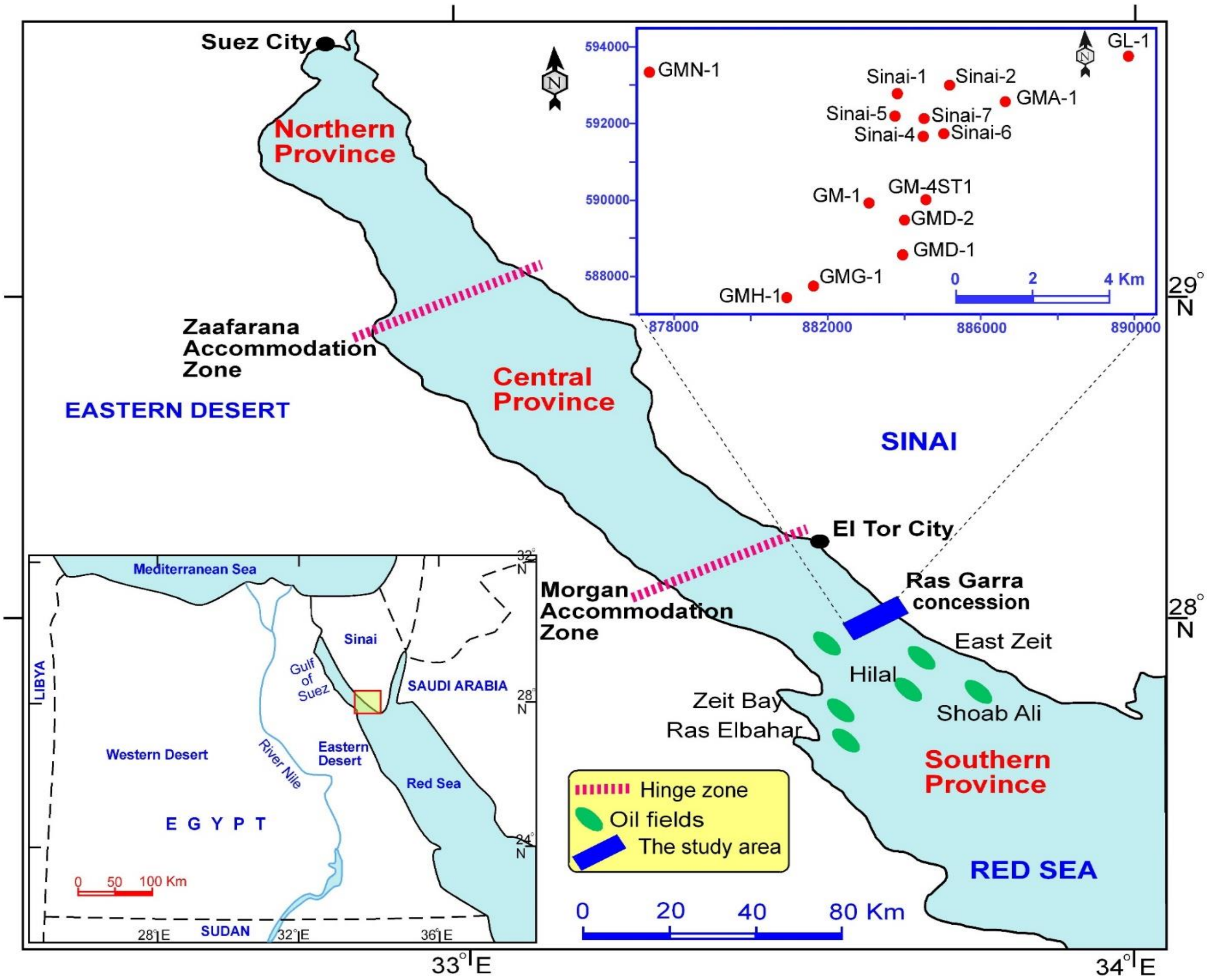

Figure 1 Gulf of Suez map and location of the studied well.

in nine wells (Fig.1). The geochemical and geological data were entered to the BasinMod petroleum systems modeling software program to develop maturity, generation and expulsion models.

Geologic and Tectonic Framework

Garfunkel and Bartov (1977) [8] reported that the Suez rift lies in the northwestern-southeastern direction attributed to the Red Sea rift. The beginning of the Suez rift ranges between 21 to 24 million years (Ma); from the late Oligocene to the early Miocene (Evans, 1990) [9]. In the late Oligocene-early Miocene, the rifting started and it was characterized by magmatic events and high tectonic subsidence (Gandino et al., 1990) [10]. The tensional stresses as well as the elevation of the hot asthenosphere contributed to the Suez rifting. Between 19 and 15 Ma, the maximum development of the axial trough was a result of the tectonic subsidence and crustal expansion (Steckler et al., 1988) [11]. Due to the impact of heating, the sides of the Suez rift started to rise from 20 to 17 Ma (Steckler 1985) [12]. The tectonic movement started along the Aqaba-Dead Sea transform fault at a time of 15 Ma (Bartov et al., 1980) [13]. Sedimentary successions include several major unconformities that occurred in the Paleozoic, Mesozoic (Triassic — Jurassic) and Cenozoic (Oligocene) and Late Miocene (Messinian), due to the various rift episodes in the Gulf of Suez (Dolson et al., 2001) [14].

The main zones of the normal faults surrounded the margins of Suez rift, which is characterized by a fault extended between 40 and 80 km and a fault throw between two and six kilometers. The rift encompasses three provinces with ranging from between fifty and hundred kilometers, depending on the polarity of block faults (Colletta et al., 1988 [15]; Patton et al., 1994 [16]; Moustafa, 1996 [17]). The provinces include Northern Province in the north, which has a south-western dip, Belayim province in the middle, which has a north-eastern dip and the Amal-Zeit province in the south, which has a south-western dip.

The ages, lithologies and stratigraphy of formations were determined on the basis of composite well logs, well reports, unpublished reports and previous studies of many authors. (Abdallah et al. 1963 [18]; EGPC 1964 [19], 1974 [20]; Ghorab 1964 [21]; Issawi 1973 [22]; Moustafa 1976 [23]; Garfunkel and Bartov 1977 [8]; Mazhar et al. 1979 [24]; Beleity 1982 [25] ; Webster 1982 [26]; Allen et al. 1984 [27] ; Fawzy and Abdel Aal 1984 [28]; Saoudi and Khalil 1984 [29]; Sellwood and Netherwood 1984 [30]; Scott and Govean1985 [31]; Barakat et al. 1986 [32], 1988 [33] ; Beleity et al. 1986 [34] ; Montenat et al. 1986 [35] ;

Smale et al. 1988 [36] ; Burchette 1988 [37] ; Richardson and Arthur 1988 [38]; Abd El Shafy 1990 [39]; Darwish 1992 [40]; Hughes et al. 1992 [41]; Rouchy et al. 1995 [42]; Darwish and El-Araby, 1993 [43]; Alsharhan and Salah 1994 [5], 1995 [44], 1997 [45]; Plaziat et al. 1998 [46]; Bosence et al. 1998 [47]; Salah and Alsharhan, 1998 [48]; Peijs et al. 2012 [49]; Rohais et al. 2016 [50]; Elmaadawy, 2020 [51]).

The sedimentary sequences across the Suez rift Basin are divided into three basic sequences, based on the Miocene rift to; pre-rift, syn-rift and post-rift, from the oldest to the youngest, (Fig. 2).

The succession of the pre-rift, in terms of age, ranges from the Precambrian to the Upper Eocene. The pre-rift sequence is 1-km thick, unconformably underlain with the Precambrian crystalline basement. The pre-rift section consists of sandstones, shales, and carbonates that are deposited under the terrestrial and marine environments. In the southern province, the Precambrian basement reached about 200 drilled wells, at depths varying from 1000 to 5000 m. The Nubian Sandstone has Cambrian-Early Cretaceous age, and it is composed of clastics nonconformably overlaying the basement. In the southern province, the thickness of the Nubian Sandstone ranges between 25 and 430 m. In the Garra, Nubian Sandstone has a nonconformable relationship with the underlying basement rocks as well as unconformable relationship with the overlying Matulla Formation. This formation has a Late Cretaceous age deposited under a shoreline condition, and it consists of sandstone, shale and shell banks. In the Ras Garra area, the Matulla Formation has unconformable relationship with the Nubian Sandstones and a conformable relationship with the Duwi Formation. The thickness of Matulla Formation increases towards the northwest, while decreasing towards the southern trend of Ras Garra area. The Duwi Formation dates back to the Campanian (Upper Senonian) age, and it is composed of the brown limestone, chert up to 10–30%, near the base in the Ras Garra. Duwi Formation has a conformable relationship with Paleocene Esna Shale, and it is underlain by the Matulla Formation, which is known locally as Brown limestone or Lacustina Bed. It increases in thickness to the northwest, while decreasing to the south of the area. Esna Shale dates back to the Late Paleocene age, and it is composed of fossiliferous grey shale with sandy pyritic limestones. The Thebes Formation is from the Early Eocene age, and it is made of massive fossiliferous limestone, often sandy, with a chert up to 10–25%. Thebes Formation has an unconformable relationship with the overlaying Nukhul Formation and is underlined by the Late Paleocene Esna Shale.

Syn-rift succession began with the red deposits of Abu Zenima Formation, which occurred at the base of this succession, overlying the Eocene rocks with an angular unconformity relationship. These formations belong to Oligo-Miocene times that were synchronous with the initiation of rifting. The rifting time was associated with Basaltic Oligocene intrusions. This succession is classified into two groups: Gharandal and Ras Malaab. The formations of Nukhul and Rudeis are assigned to the Gharandal Group, while the formations of Ras Malaab include Kareem, Belayim, South Gharib and Zeit.

The age of the Nukhul Formation ranges between the Aquitanian to Burdigalian (Early Miocene). The Nukhul Formation is divided into: Shoab Ali, Garra, and Gharamul members from base to top. Nukhul Formation consists of deep marine shales, anhydrites, sandstones and reefal limestones. Nukhul Formation is unconformably underlain the Lower Rudeis Formation. In the Garra region, Nukhul Formation is classified into the upper rock unit of evaporite as well as the lower unit of clastic. The lower clastic unit consists of a fining-upward sequence, starting with the conglomerates grading upward into the sandstones and shales, while the upper evaporitic unit consists of anhydrite with the marl, calcareous shale and limestone interbeds. The Rudeis Formation dates back to the Burdigalian - Early Langhian age, and it is classified into the Upper and Lower Rudeis, separated and marked by a sharp change in facies change. The Rudeis Formation consists of sandstones interbedded with shale in the upper part, and of shale intercalated with sandstones and limestones towards the base. Kareem Formation is from the Langhian age (Middle-Miocene) and includes Markha/Rahmi and Shagar members from the base to top. The Belayim Formation dates back to the Serravallian (Middle-Late Miocene) age, and consists of Baba, Sidri, Feiran and Hammam Faraun members, from base to top. Whereas the Belayim Formation is composed of anhydrite, halite, reefal carbonate and siliciclastic deposits. The South Gharib Formation dates back to the Serravallian -Tortonian, and it consists of a thick evaporite, thin beds of shale and sandstones, deposited under the shallow under deep marine conditions. Concerning the Garra, it is composed of a thick evaporitic body, thin shale and sand beds. Zeit Formation dates back to the Messinian (Late Miocene) age, and is made up of gypsum, anhydrite and halite beds with interbeds of siltstones and shale, deposited under shallow marine conditions. The post-rift sequence is represented by Post-Zeit deposits of Pliocene-Holocene age consisting of sand, sandstones with interbeds of shales, anhydrites or limestones deposited under shallow marine conditions.

Data and methodology

Petroleum systems and basin modeling

The construction of the burial history, maturity, as well as hydrocarbon generation and expulsion models are conducted by BasinMod program of the petroleum system modeling. Burial history modeling is based on a variety of geological and lithostratigraphic data of the studied wells (Fig.1). The geochemical input data needed for the Lower Rudeis

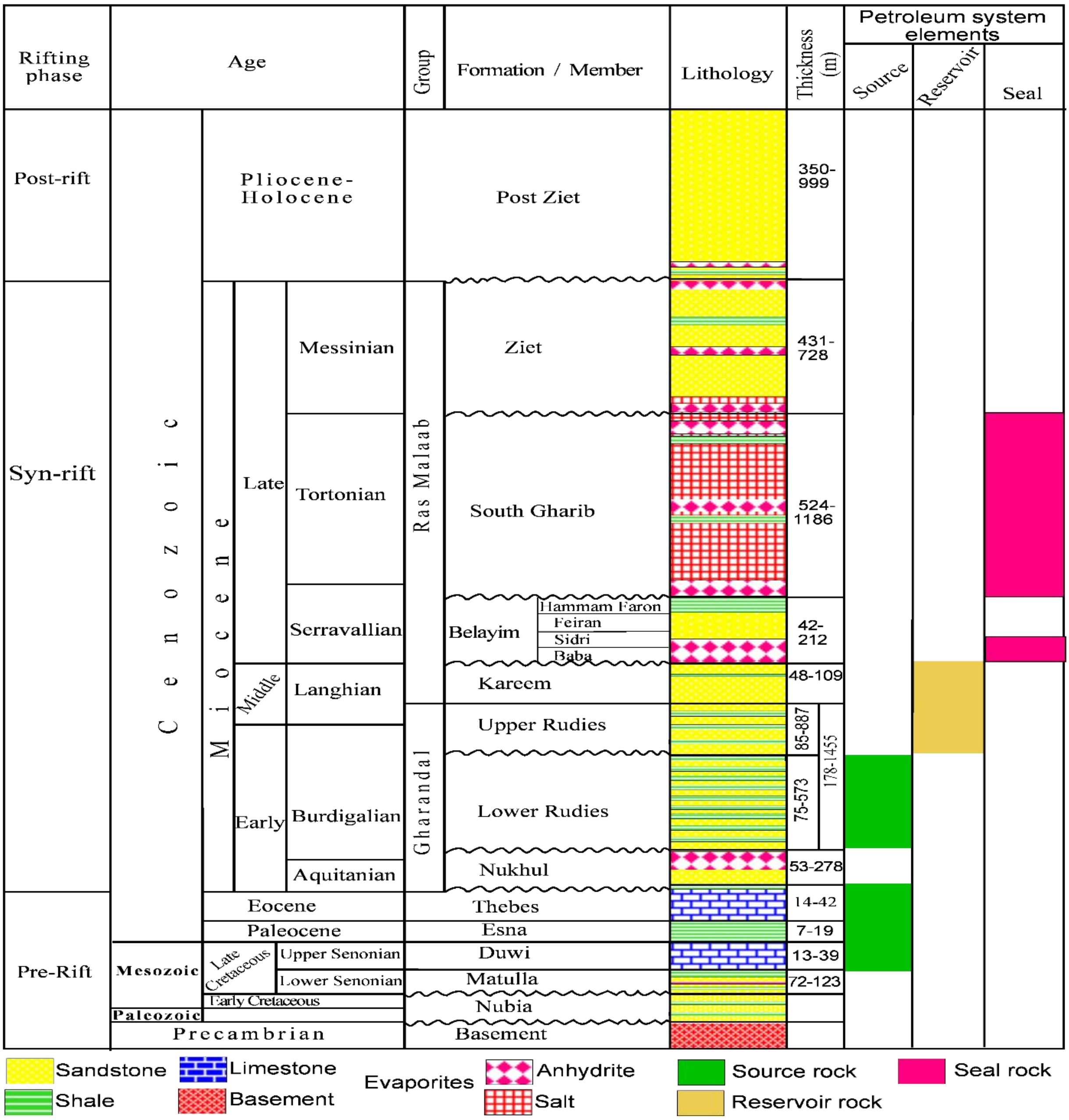

Figure 2 Lithostratigraphic column of the Garra area indicating elements of the petroleum system (Modified after Elmaadawy, 2020).

source rock are the total organic carbon (2%), hydrogen index (250 mg HC/g TOC) and kerogen type III used for the construction of the maturity, generation and expulsion models using the Method of Suzuki et al. (1993) [52]. Hydrocarbon generation is determined by the use of Pepper and Corvi (1995) [53] kinetic model, with a kerogen type III. A threshold of saturation 20% is used to model the proportion of expelled hydrocarbons.

The main data needed for constructing a burial history model include: lithology, formation tops, deposition age, hiatus age, eroded thickness, and reservoir porosity (Allen and Allen 1990) [54]. In the current study, the input data to define the curves of tectonic subsidence of some wells include the beginning age of the events, such as; the formations, erosions and hiatuses shown in table (1). In addition to thicknesses of the formation in meters (m), and lithologies. The burial history of the GM-A1 well was determined in order to reflect the burial history of the study area, because this well contains a complete stratigraphic succession until the basement (Fig.3). Sources for these data include: composite logs, internal company reports, as well as the studies of Rohais et al., (2016) [50] and Evans (1988) [55], which

Table 1 Input data for burial history modeling of wells GM-A1, and GM-G1.

Rifting phase	Formation/event name	Begin age (Ma)	Eroded thickness (m)	lithology	GM-A1 well		GM-G1 well	
					Top depth (m)	Thickness (m)	Top depth (m)	Thickness (m)
Post-rift	Erosion_5	0.8	20					
	Post Zeit	5.3		Sandstones	0	747	0	1021
	Erosion_4	5.5	240					
Syn-rift	Zeit	7.2		Sandstones, evaporites, shales	747	520	1021	728
	South Gharib	11.8		Evaporite	1267	526	1749	870
	Belayim	13.6		Evaporite, shale, sandstone	1793	121	2619	212
	Post-Kareem event	14						
	Kareem	15.8		Shaley Sandstones	1914	99	2831	109
	Upper Rudeis	16		Shaley Sandstones	2013	887	2940	129
	Mid Rudeis event	17						
	Erosion_3	17.6	200					
	Lower Rudeis	19		Sandy Shales	2900	565	3069	495
	Post-Nukhul event	20		Shaley Sandstones				
	Nukhul	22		Sandy Shales, evaporites	3465	78	3564	54
	Early Clysmic event	24						
Pre-rift	Erosion_2	30	18					
	Thebes	50.6		Limestones				
	Esna	62.8		Shales				
	Duwi	83		Limestones				
	Matulla	88.5		Sandy Shales, evaporites				
	Erosion_1	250	250					
	Nubia	540		Shaley Sandstones				
	Basement	570	20	Granite	3543		3618	

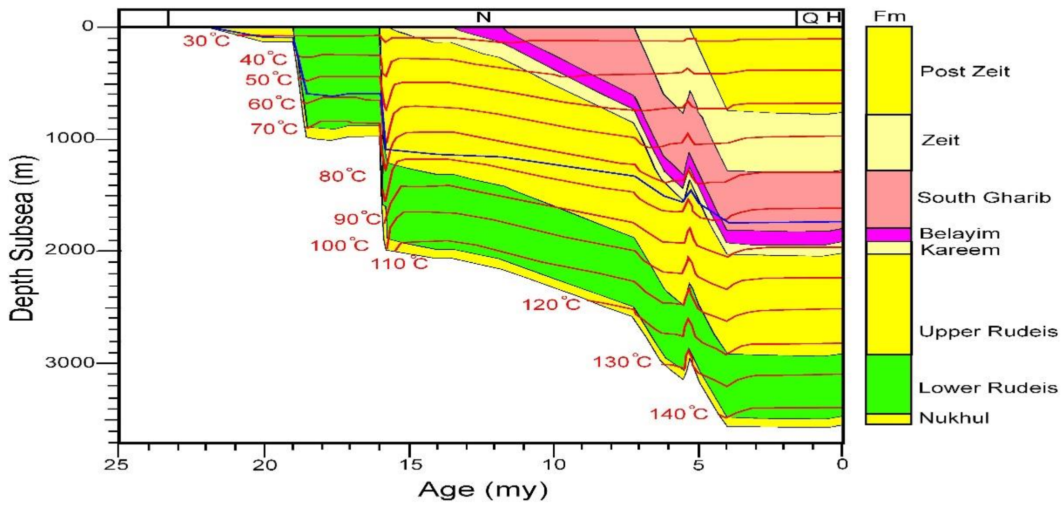

Figure 3 The graph of the burial history showing the curves of tectonic subsidence of GM-A1 well.

are the main source of age for hiatuses, erosions and formations.

The modeling of the petroleum system depends on all the available geological, petrophysical and geological data, including data related to the thermal history modeling, such as; BHT and thermal flow, which are necessary for modeling. In the Garra region, the heat flow during syn-/post rift episodes was

63 and 82 mW/m^2, while it was approximately 54 mW/m^2 during the pre-rift episode. During the post-rift episode, the value reached 63 mW/m^2 due to the prevailed cooling effect during this period (Internal Company Report). In the studied wells, the heat flow has different values, for instance; 74 mW/m^2 (GM-G1 well), 69 mW/m^2 (GM-A1 well) and 63 mW/m^2 in GL-1 well. The measured bottom hole temperatures (BHT) as well as the calculated temperatures in these wells show good agreement, which consequently indicates the validation of the thermal maturity models (Fig.4). Moreover, the model of Javis and McKenzie (1980) [56] is applied in the geothermal calculations. Maturity modeling is performed in order to assess the maturation history as well as to identify the stages of maturity via Suzuki et al. (1993) [52], which is known as LLNL Easy % R_o model.

Geochemical and Biomarker data

The analyses of the geochemical and biomarker data of the oils were analyzed by Gas Chromatography (GC), Gas Chromatography-Mass Spectrometry (GC-MS) and stable carbon isotopes (Tables 2 &3). These data were used to estimate the source rock, characteristics that include the depositional environment, organic matter type and the thermal maturity level of the Lower Rudeis source rocks.

Results and Discussion

Characteristics of the source rock

Based on geochemical and biomarker data, oils were classified into family A oil of GMH-1 well and family B oils for other wells. GMH-1 well oil was obtained from Kareem reservoir of a clay source rock, deposited under sub-oxic to oxic conditions; high energy and non-hypersaline depositional environment, and derived from an organic matter composed mainly of terrestrial organic matter. These conditions are indicated by the heavy isotopic signature (δC^{13} Sat=24.51), high Pr/Ph ratio (1.37), high oleanane and diasteranes content, low amount of tricyclic terpanes, the absence of gammacerane as well as the presence of nor-neohopane and diahopane. The relatively high oleanane (0.24) indicates that the family A oil, was generated from the Tertiary lower Rudeis source rocks and the steranes isomerization and aromatization values indicate that the level of maturity of the oil, reached early mature stage and these results are consistent with the constructed models of the Lower Rudeis source rock, therefore thermal maturity models are validated. In addition, the duration of the mature stages, the burial temperature as well as the depth to maturity are consistent with the calculated vitrinite reflectance values.

The family B oils in Nukhul, Matulla and Kareem-Rudeis reservoirs were generated from shaly source rocks deposited under highly euxinic, anoxic and hypersaline conditions that were indicated by; a light isotopic signature δC^{13} sat, ranging from -27.74 to –30.05); Pr/Ph ratios always less than one (Pr/Ph < 1); low to very low oleanane content (0.04-0.13) and the presence of gammacerane and C35, extended Hopanes more than the C34. The family B oils were generated from both algal and terrestrial organic matter, indicated by high C27αββ steranes. These oils were generated at high maturity level than family A oils that reached mid and late mature stages, which were indicated by the steranes isomerization and aromatization values. The low amount of oleanane (0.13-0.04) suggests that family B oils generated from Late Cretaceous pre-rift source rocks.

Maturity Evolution of the Lower Rudeis source rock

Based on the vitrinite reflectance (VR) values, the source maturity is divided into; the early mature stage ranging from 0.50 to 0.70% Ro; and the mid-mature stage ranging from 0.7 to 1.0% Ro of the oil window. Lower Rudeis source rock only passed early mature as well as mid-mature stages in the GM-A1 and GM-G1 wells (Table 4). Lower Rudeis source rock started the stage of early mature in GM-A1 well at 15.50 Ma, in GM-G1 well at 10.0 Ma (figs. 5a&b) and in the remaining well, the early stage began later such as in wells GM-4ST1 (5.90 Ma) (Fig. 5c), Sinai-1 (6.10 Ma), Siani-7 (3.0 Ma) and in Sian-6 (1.64 Ma) (Fig. 6). The Lower Rudeis only met the stage of mid-mature at 9.0 and 3.2 Ma in two wells of GM-A1 and GM-G1 respectively. The source rock of Lower Rudeis passed the stage of early mature at shallow depths to maturity of 1500 m and 1560 m in wells, while in the other wells, the early mature started at deep depths, reaching approximately ±2250 m. Whereas, the stage of mid-mature began at depths of maturity up to 2320 m and 3200 m in wells GM-A1 and GM-G1 respectively. The burial temperature of the early mature stage has high values of 106 ^{o} C and 112 in wells GM-A1 and GM-G1 respectively, while it has lower values in the remaining wells. The mid-mature stage has high values of 115 ^{o} C and 128 ^{o} C in wells GM-A1 and GM-G1 respectively. The VR ratio of the early mature stage is 0.70 % R_o in GM-A1 and GM-G1 wells, however it has lower values in the other wells. Regarding the stage of mid-mature has values of 0.96 % and 0.78 % $R_{o,}$ respectively. The high maturity parameters reflected high transformation ratio values of 42 % and 18 % in GM-A1 and GM-G1 wells, which only met the stage of mid-mature with high time durations.

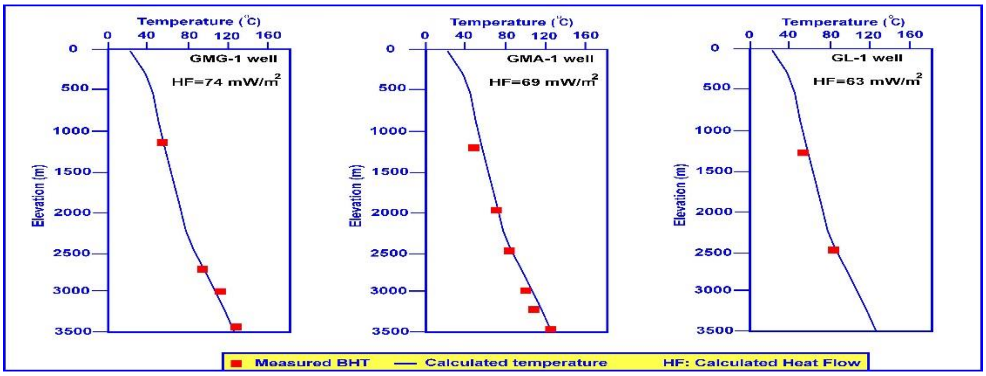

Figure 4 Plotting of measured temperatures (BHT) and the modelled temperatures shows a good fit for the thermal models.

Table 2 The geochemical and biomarker data for oils in Garra region.

Well	**Gl-1**	**GM-D2**	**GM-D2 (RD)**	**GM-D2**	**GM-H1**	**GM-H1**	**Sinai-1**	**Sinai-2**	**Sinai-4**	**Sinai-5**
Reservoir	Nukhul	K-R	K-R	Matulla	Kareem	Matulla	K-R	K-R	K-R	Kareem
Oil Type	B	B	B	B	A	B	B	B	B	B
					Terpanes					
Pr/Ph	0.56	0.85	0.87	0.54	1.37	0.65	0.97	1.00	1.00	0.81
Tri	0.38	0.60	0.53	0.53	0.13	0.82	0.50	0.43	0.38	0.71
Tet	0.06	0.09	0.10	0.07	0.03	0.12	0.16	0.07	0.07	0.12
Trit	6.67	6.36	5.55	7.78	4.00	6.64	3.16	6.50	5.75	6.15
TsTm	0.40	0.73	0.81	0.38	1.71	0.81	0.86	0.74	0.86	0.58
29/30	0.78	0.74	0.70	0.76	0.39	0.66	0.59	0.59	0.54	0.77
29Ts	0.13	0.30	0.26	0.12	0.21	0.25	0.22	0.21	0.22	0.19
C30	0.00	0.09	0.07	0.00	0.09	0.05	0.06	0.05	0.06	0.07
Ole	(+)	0.05	0.04	0.2	0.24	0.04	0.10	0.11	0.13	0.07
Gam	0.28	0.34	0.29	0.31	O.08	0.52	0.23	0.20	0.21	0.28
29Ts/C30	0.00	3.18	3.75	0.00	2.36	4.67	3.71	4.17	3,71	2.75
Lin	0.09	0.08	0.09	0.08	0.00	0.04	0.04	0.04	0.04	0.06
S/S+R	0.57	0.56	0.54	0.57	0.55	0.57	0.55	0.56	0.57	0.81
					Steranes					
Dia	0.39	0.51	0.46	0.31	0.60	0.39	0.55	0.58	0.56	0.47
S/S+R	0.45	0.53	0.53	0.50	0.38	0.57	0.46	0.43	0.45	0.46
Bβ/αα	0.55	0.63	0.62	0.61	0.41	0.67	0.56	0.54	0.54	0.60
C_{27}%	34	35	32	34	34	36	33	32	33	36
C_{28}%	34	34	35	35	38	36	34	35	34	33
C_{29}%	32	31	32	31	39	29	32	32	33	30
C_{27}%/ C_{29}%	1.08	1.13	0.99	1.11	1.18	1.24	1.03	1.00	0.99	1.20
					Aromatics					
MPI	0.80	0.84	0.78	0.83	0.99	0.83	0.91	0.87	0.91	0.97
T/TM	0.82	0.86	0.90	0.88	0.73	0.86	0.78	0.86	0.85	0.86

K-R: Kareem-Rudeis.

Table 3 Stable isotopes analyses of oils

Well	**Reservoir**	**Depth (m)**	**HCS**	**HCA**	**NSO**	**ASPH**
1-Gl-1	Nukhul	1995.5-1998.5	-29.0	-28.6	-28.9	-28.9
2-GMDAL-2	Kareem-Rudeis	2384-2440	-29.5	-28.6	-28.3	-29.1
3-GMDAL-2(RD)	Kareem-Rudeis	2384-2440	-29.4	-28.5	-28.6	-29.0
4-GMDAL-2	Matulla	2962-2980	-30.1	-29.4	-28.9	-29.2
5-GMHAA-1	Kareem	3044-3084	-24.5	-22.6	-22.6	-
6- GMHAA-1	Matulla	3665-3700	-29.8	-29.1	-28.3	-28.9
7-Sinai-1	Kareem-Rudeis	2142-2154	-28.1	-27.6	-28.1	-28.0
8-SINAI-2	Kareem-Rudeis	2017-2040	-27.9	-27.7	-26.7	-28.0
9-SINAI-4	Kareem-Rudeis	2090-2130	-27.7	-27.9	-27.5	-28.0
10-SINAI-5	Kareem	2338-2350	-28.3	-28.6	-28.6	-28.4

Table 4 Lower Rudeis maturity data through the studied wells

Stage	Early mature				Mid-mature				
The studied wells	Time (Ma)	Maturity depth (m)	T (°C)	VR (% Ro)	Time (Ma)	Maturity depth (m)	T (°C)	VR (% Ro)	TR %
GM-A1	15.5	1500	106	0.7	9.0	2320	115	0.96	42
GM-G1	10	1560	112	0.7	3.2	3200	128	0.78	18
GM-4ST1	5.9	2300	102	0.65	—	—	—	—	2.2
Sinai-1	6.1	2280	107	0.66	—	—	—	—	3.0
Sinai-6	1.64	2226	90	0.52	—	—	—	—	2.0
Sinai-7	3.0	2290	95	0.56	—	—	—	—	1.5

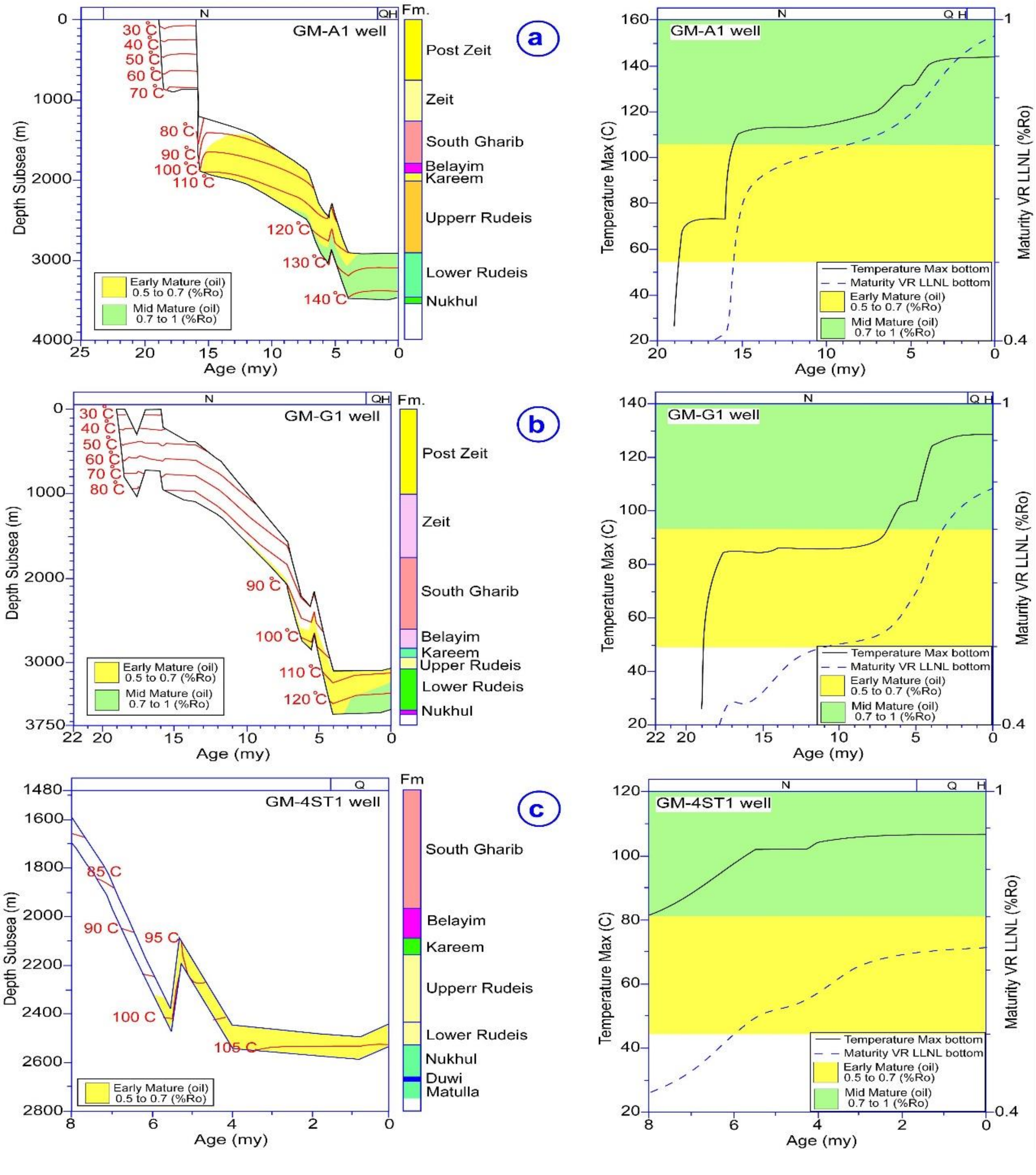

Figure 5 The burial history and maturity models indicate stages of maturity, depth and time to maturity and distribution of temperature of the Lower Rudeis source rock in wells GM-A1 (a), GM-G1 (b) and GM-4ST1 (c).

Hydrocarbon generation and expulsion history

According to Hunt (1995), Lower Rudeis is a good source potential as it has a TOC of 2.0 wt%, passing the early oil generation phase (10–25 % TR) and the main oil generation phase (25–65 % TR). In GM-A1 well, the first generation phase was extended from 6.0 to 3.4 Ma. At 5.5 Ma, the rate of oil generation and gas generation increased to 3.66 and 8.0 mg/gTOC^my

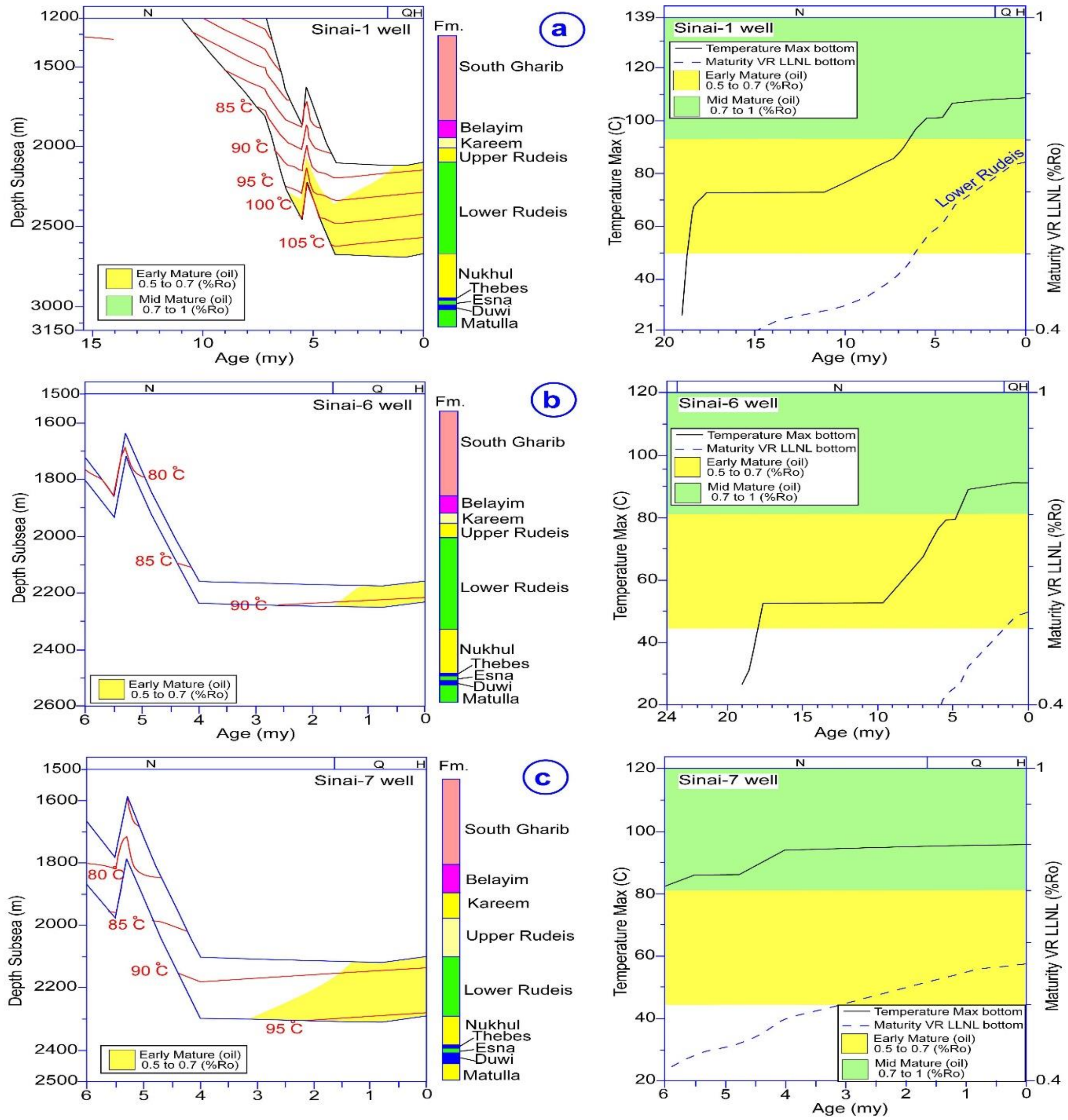

Figure 6 The burial history and maturity models refer to stages of maturity, depth and time to maturity and distribution of temperature of the Lower Rudeis source rock in wells Sinai_1 (a), Sinai_6 (b) and Sinai_7 (c).

respectively (Fig. 7a). From 5.1 to 3.6 Ma, the generation rates of oil and gas have the highest values of 7.7 and 17 mg/gTOC^my, respectively. The second phase started at 3.4 Ma and continued until the present time, with a transformation ratio of 42%, while Oil expulsion increased to 16 mg/gTOC and gas expulsion to 40 mg/gTOC.

In the GM-G1 well, the Lower Rudeis source rock underwent a single hydrocarbon generation and expulsion phase (Fig. 7b). At 4.0 Ma, oil and gas have the highest generation rate of 5.30 and 11.6 mg/gTOC respectively. The transformation ratio was 18%, resulting in the expulsion of trace amounts of oil (2.60 mg/gTOC^my) and (8.30 mg/gTOC^my) of gas.

In GM-4ST1 well, the generation rates of oil and gas are 0.37 mg/gTOC^my and 0.82 mg/gTOC^my, respectively due to a very low transformation ratio of (2.2%) (Fig. 7c), besides that the Lower Rudeis source rock did not undergo any stages of expulsion.

In Sinai wells, the Lower Rudeis source rock did not undergo the onset of the early generation stage as it has a low transformation ratio (TR ≤ 3%), associated with very low generation rates. In Sinai-1well, the transformation ratio is 3% (Fig. 8 a), while it is estimated of less than 2% in Sinai-6 well. (Fig. 8 b) whereas it reached a rate of less than 1.5% in Sinai-7 well (Fig. 8 c).

In Suez rift Basin, the local uplifts and hiatuses were attributed to the Mid-Rudeis event, resulting in stratigraphic and structural traps (Evans 1988). There were two tectonic events formed the main traps related to the structures including the Mid-Rudeis and Post-Kareem events at 17 and 14 Million respectively.

The maturation of the Lower Rudeis source rocks began at 15.53 Ma, and the generation started at 5.10

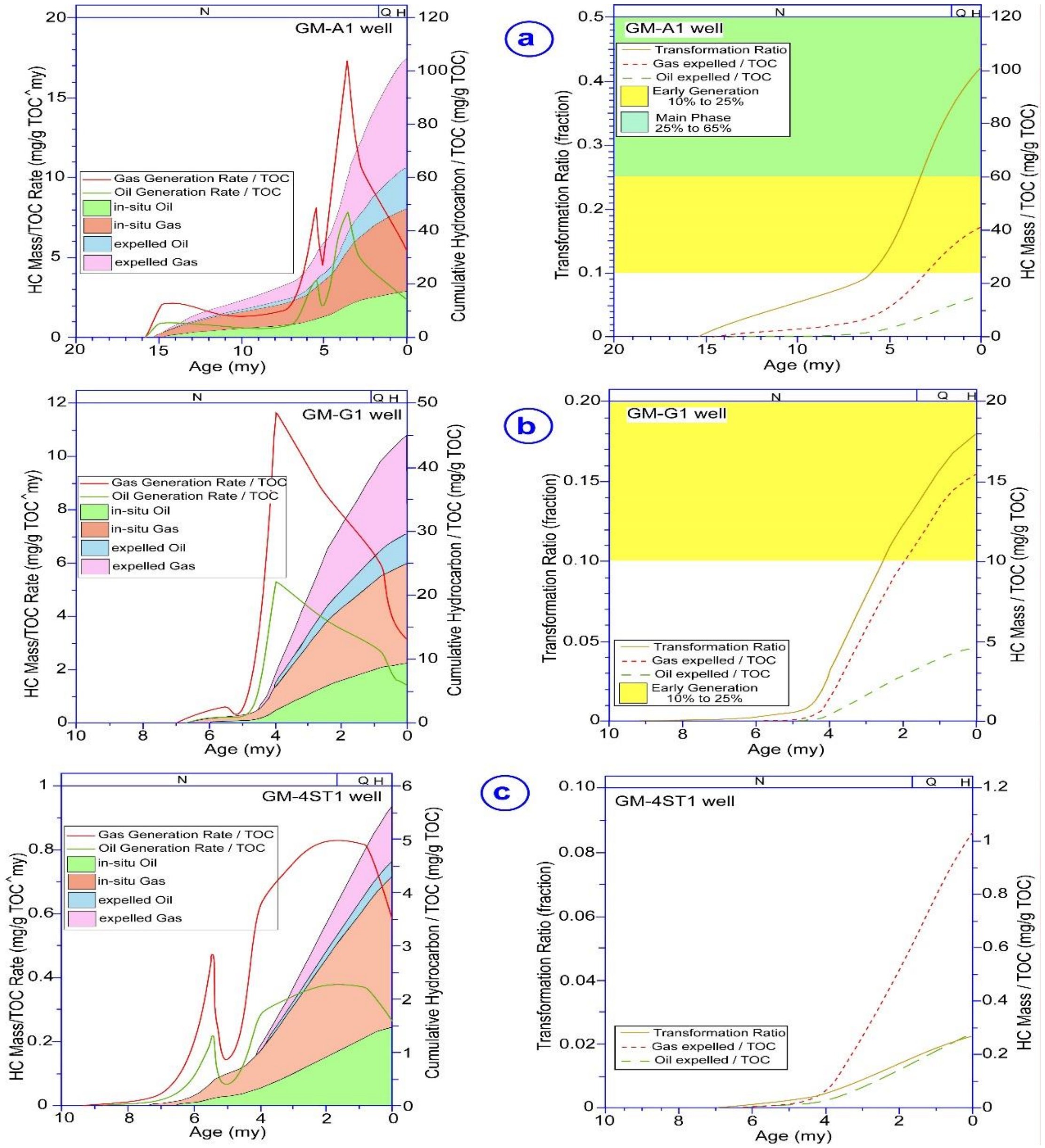

Figure 7 Graphs showing the rates of the generated and expelled oil and gas (left side), in addition to the amounts of expulsion and transformation ratio (right side) for the Lower Rudeis in wells GM-A1(a), GM-G1(b) and GM-4ST1(c).

Ma, which marks the bottom of the early oil generation phase in GM-A1 well. The expelled, migrated and accumulated hydrocarbons were preserved as a result of the deposition of effective seals of the Miocene evaporites. Generation started 5.10 Ma and Miocene evaporites were deposited from 13.60 to 7.20 Ma, preserving the accumulated hydrocarbons under good seals. The timing of trap formation is approximately 17 Ma, which precedes the timing of hydrocarbon generation and expulsion, indicating that the migrated hydrocarbons may be accumulated in the reservoirs of Kareem-Rudeis (Fig.9).

Petroleum system analysis in Garra region

Maturation of the source rock, generation and expulsion of hydrocarbon

The pre-Miocene rocks, including the Duwi, Esna and Thebes formations, as well as the Early Miocene Lower Rudeis Formation, are the source rocks of the petroleum system in the Garra region. The 6-7 % TOC and kerogen type I/II are characterized by the pre-Miocene, indicating very good generating capacity and oil prone. The pre-Miocene source rocks underwent the early and mid-mature stages at 14.3 Ma and 2.4 Ma, at depths of 1400 m and 3007 m, respectively with a vitrinite reflectance (VR percent) of 0.75 % Ro in Sinai-1 well. The average transformation ratio was 26%; with an oil generation rate is 35.90 mg / gTOC^my gas generation rate is 6.72 mg/gTOC^my, with 52.0 mg / g TOC and 17.0 mg / g TOC respectively for oil and gas expulsion.

Lower Rudeis source rock is characterized by 2% TOC and kerogen type III, which mainly indicates a significant generation potential of gas and some oil.

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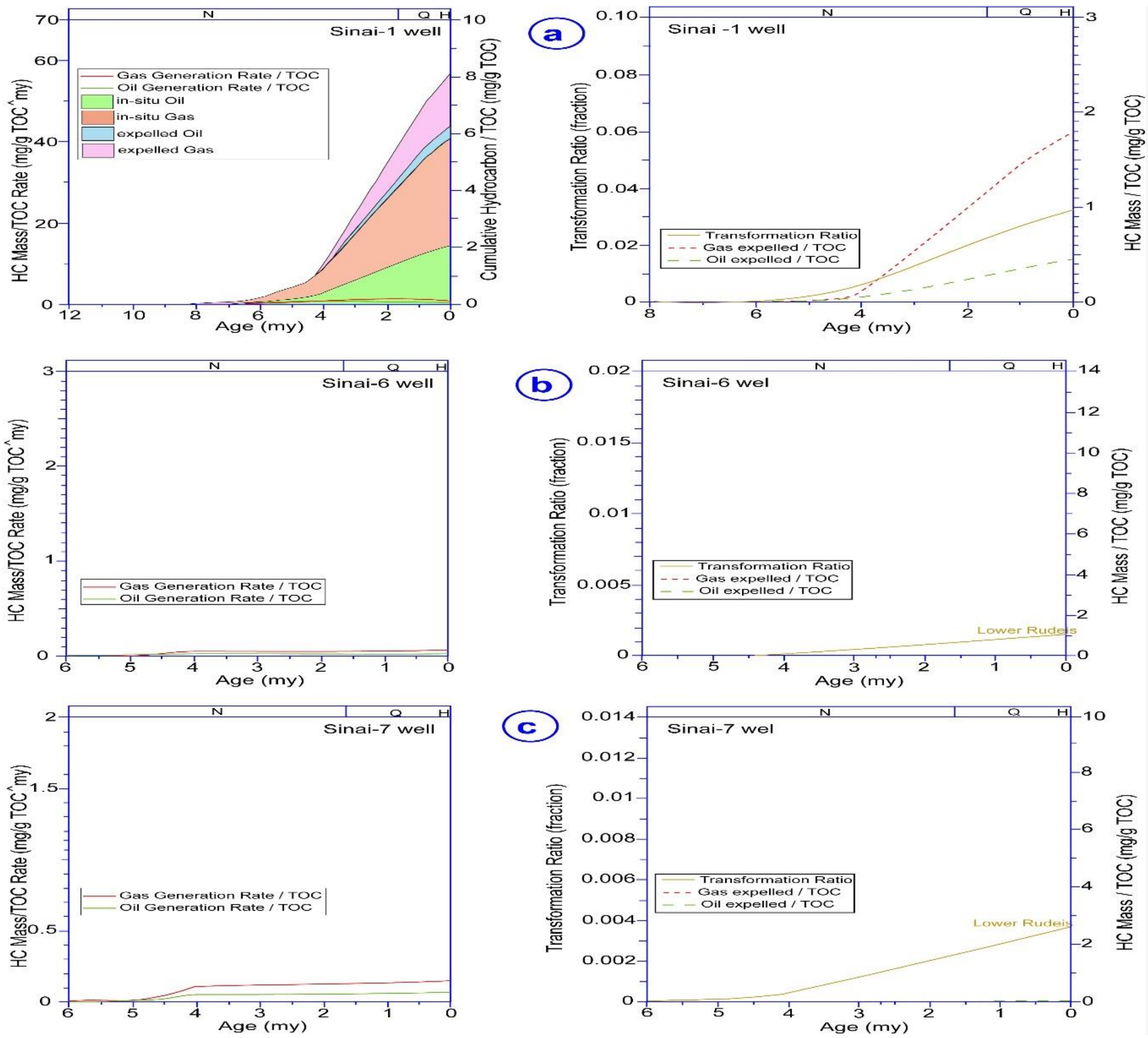

Figure 8 Graphs showing rates of the generated, expelled and generation oil and gas (left side), in addition to the amounts of expulsion and transformation ratio (right side) for the Lower Rudeis in wells Sinai_1 (a), Sinai_6 (b) and Sinai_7 (c).

The Lower Rudeis source rock entered the stage of early mature in 15.5 Ma at a depth of 1500 m, and entered the stage of mid-mature in 0.9 Ma at 2320 m, with VR% estimated of 0.96 % Ro in GMA-1 well. The transformation ratio was 42% with expelled gas 40 and expelled oil 16 mg/g TOC. The amount of oil expelled from the pre-Miocene source rocks was 52 mg/g TOC, and from Lower Rudeis source rock it was 16 mg/g TOC. This indicates that the largest amount of the migrated and accumulated oils are attributed to pre-Miocene source rocks as confirmed by the analysis of geochemical and biomarkers data for oils in producing intervals. Moreover, most of the oils generated from the pre-Miocene source rock are (Type B) oils.

Reservoir and seal rocks

The main producing intervals in the study area are the Kareem and Rudeis formations with an average porosity of 16 % and 19 % respectively whereas the lowest producing intervals for Nukhul and Matulla formations, with an average porosity of 17 % and 18 % respectively. Seals in the Garra region include the local top and lateral sealing rocks of Belayim evaporite. The migration pathway through the Garra area includes vertical migration along fault planes as well as lateral migration along career bed. Based on the data of spill point for the Kareem/Rudeis producing intervals (Table 5), the expelled oil migrated dip laterally from southwest to northeast in the direction of the Sinai shoreline (Fig.9). In Garra, region, a single petroleum system can be identified due to the lack of good effective sealing rocks of the pre-Miocene reservoirs, which form Kareem/Rudeis reservoir that are mainly charged from the pre-Miocene and Lower Rudeis source rocks capped by Miocene evaporites of Belayim Formation (Fig.10).

Table 5 Spill point data for Kareem/Rudeis producing intervals in Garra region.

Well name	Sinai-1	GM-D1	GM-H1	GM-A1	GM-A2
Spill point (subsea, m)	2094	2205	2992	1915	1892

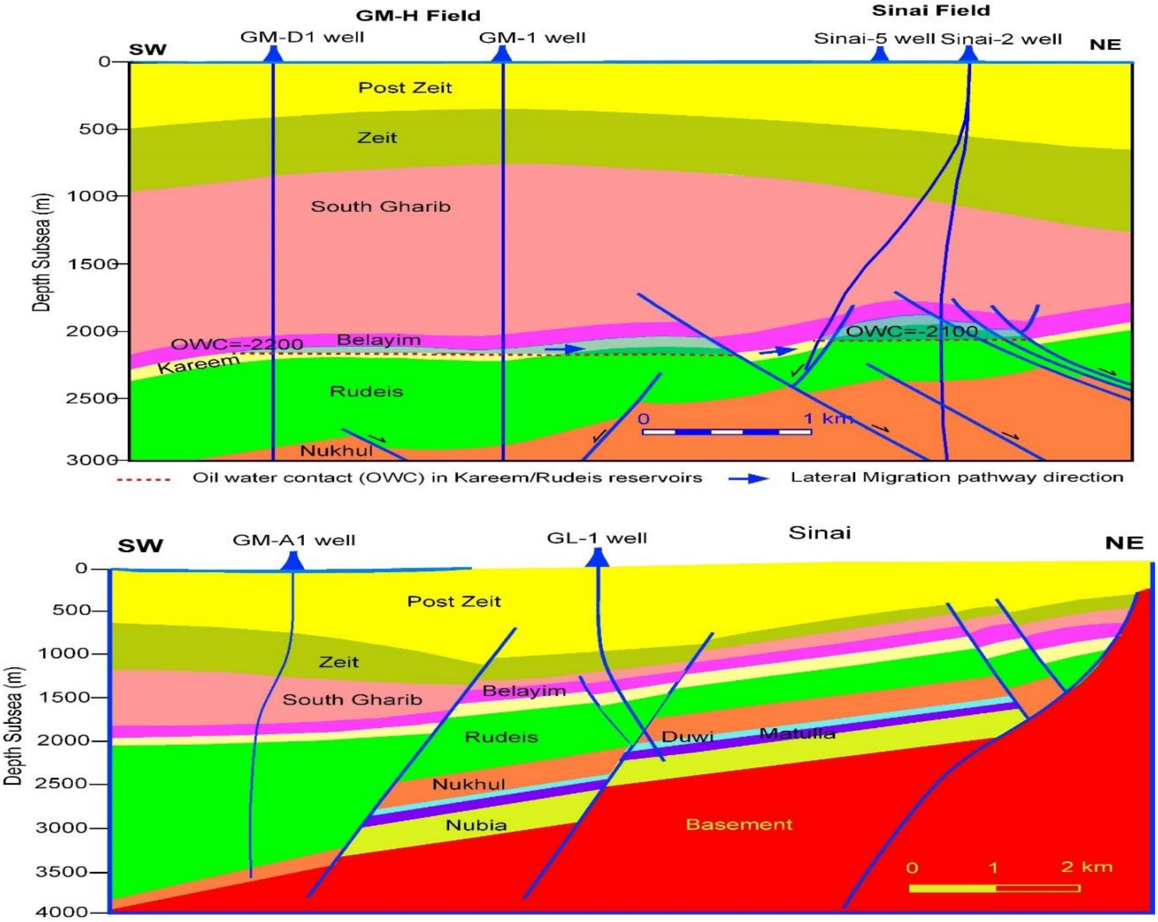

Figure 9 Geological cross-sections in Garra region indicate the direction of hydrocarbon migration to the northeast direction.

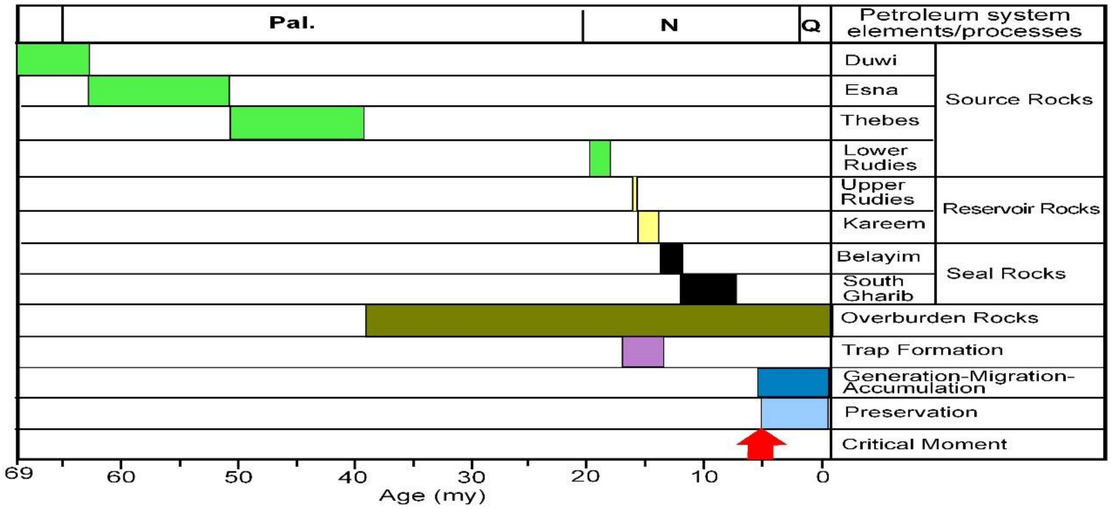

Figure 10 Graph of the events of the petroleum system chart in the Garra concession (Modified after Elmaadawy, 2020).

The development of the petroleum system in Garra region

The development of the petroleum system includes all factors that contribute to the source rock maturity, generation, expulsion as well as migration, and ultimately the accumulation and preservation of hydrocarbons under effective sealing rocks.

The source rock of Lower Rudeis has the maximum thickness of both (2879 &2880 m) overburden, and source rock (537 & 565 m) in GM-G1 and GM-A1 wells, respectively. In addition, they have the longest maturity stages duration and thus entered the mid-mature stage. The pre-Miocene rocks have a maximum overburden thickness (2982 m) in Sinai-1 well, resulting in the longest duration and passing the early stage as well as the mid-mature stage (Fig. 11).

The source rock for Lower Rudeis passed the mid-mature stage in GM-A1 and GM-G1 wells, while only passed the early mature stage in the other wells. With regard to Sinai wells, the stage of early mature began at various depths, such as; (2280 m) in Sinai-1 well;

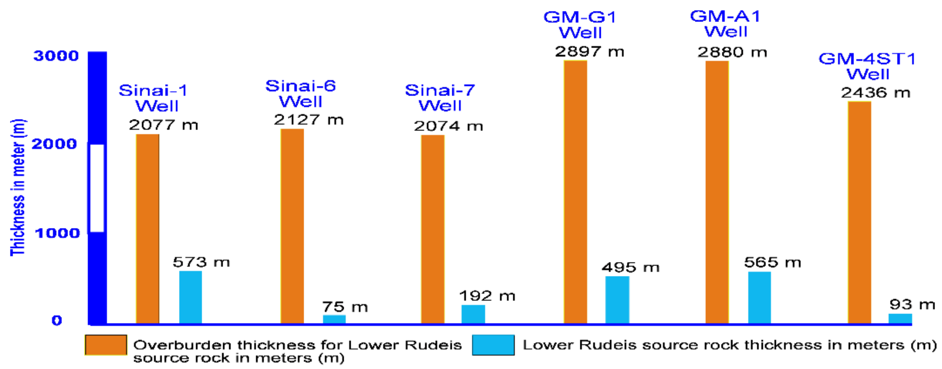

Figure 11 Thicknesses distribution of the Lower Rudeis source rock and overburden.

(2226 m) in Sinai-6 and (2290 m) in Sinai-7, indicating an average critical depth of maturity estimated at ±2265 m for Sinai wells. In regard to Garra Marine wells, the early mature stage occurred at depths of 1500, 2300 and 1560 m in wells GM-A1, GM-4ST1 and GM-G1, respectively. In addition, Lower Rudeis entered the mid stage at 2320, and 3200 m in GM-A1, and GM-G1 wells, respectively with an average critical depth ± 2760 m to mid-mature stage. GM-A1 and GM-G1 wells started the early mature stage at shallow depths of 1500 and 1560 m, respectively, making them enter early and mid-mature stages.

The source rocks of the pre-Miocene underwent the stage of early mature at (1400 m) in Sinai-1, then at deeper depths, such as; (2200 m) in wells GM-4ST1; (2325 m) in Sinai-7 and (2280 m).in Sinai-6. The stage of mid-mature occurred at 3007m in Sinai-1 well, as it encountered the stage of early mature at a very shallow depth. In Garra region, the petroleum system has a critical maturity depth of 1400 m and 1500 m for pre-Miocene and for Lower Rudeis source rocks respectively.

Lower Rudeis entered the mid-mature stage reaching 9.0 Ma in GM-A1 well, resulting in a high transformation ratio of 42%, and in GM-G1 well, which entered the mid-mature stage reaching 3.2 Ma, resulting in a transformation ratio of 18% (Fig.12). At Sinai-1 well, the pre-Miocene rocks only passed the stage of mid-mature. The stages of the source rock of Duwi (2.41 Ma), Esna (2.09 Ma) and Thebes (2.0 Ma), resulted in a transformation ratio of 29%, 25% and 23% respectively. The value of the transformation ratio is mainly controlled by the durations of mid-mature stage.

Tectonic subsidence occurred at a high rate in the deposition of the Upper Rudeis (160 m / Ma) and Lower Rudeis (435 m / Ma) formations during the rift. After these episodes of high tectonic subsidence well Sinai-1, the stage of early mature of the pre-Miocene source rocks started at 14.60 Ma, and in GM-A1 well, the Lower Rudeis rock started the stage of early mature at 15.53 Ma (Elmaadawy, 2020 [51]).

The maturity and hydrocarbon potential of the source rock in the southern province were investigated in previous studies by (Barakat, 1982 [2]; Shahin and Shehab, 1984 [3]; Salah, 1992 [4]; Alsharhan and Salah, 1994 [5]; Meshref et al., 1988 [57]; Rashed, 1990 [58]; Alsharhan, 2003 [59]; Younes, 2003 [60]; Younes and Philp, 2005 [7]; El Nady, 2016 [6]; Elmaadawy, 2020 [51]). In the southern province, two petroleum systems occurred; one petroleum system related to the pre-Miocene succession; and the other petroleum system related to the Miocene succession. Source rocks, including pre-Miocene, represented by the formations of Duwi, Sudr, Esna, Thebes, and Miocene Lower Rudeis and Kareem. These source rocks are characterized by an average TOC of 3.5% with kerogen type I/II, indicating mainly oil and gas prone, and the Miocene source rocks which are characterized by an average TOC of 2.5% with kerogen II/III, indicating mainly gas and oil prone. The high hydrocarbon potential of the southern province is attributed to rifting, the high geothermal gradient, and the development of good reservoirs, such as reefs buildups, and structure traps, resulted from the rotational faulting capped by the evaporites.

Conclusions

Via the construction of the burial / thermal maturity models as well as the generation / expulsion models, a number of parameters were identified, including the mature stages (early or mid), the burial temperature, the times and depths to maturity and the measured vitrinite reflectance. The Miocene source rock of Lower Rudeis, has a good generation potential, which is mainly gas-prone, in addition to kerogen (type III) TOC (2%) and HI (250 mg HC/g TOC).

Lower Rudeis underwent the stage of early mature in all wells, except for GM-A1 and GM-G1 wells, which reached the stage of mid-mature. In regard to both wells, stages of early and mid-mature reached at the shallowest depth (1500 m), accompanied by the longest maturation period, besides the highest value of burial temperature and calculated vitrinite reflectance.

The generation and expulsion in the GM-A1 well, reached peak rates resulting in a maximum transformation ratio of 42%. The maturation process started at 15.5 Ma, that passed the early and mid-mature stages. The gas generation rate was 17 mg/gTOC^my, while the oil generation rate was 7.7 mg/gTOC^my. Most of the expelled hydrocarbons are gas, in addition to some oil. In GM-A1, 40 mg / gTOC is expelled from the gas, and 16 mg / gTOC from

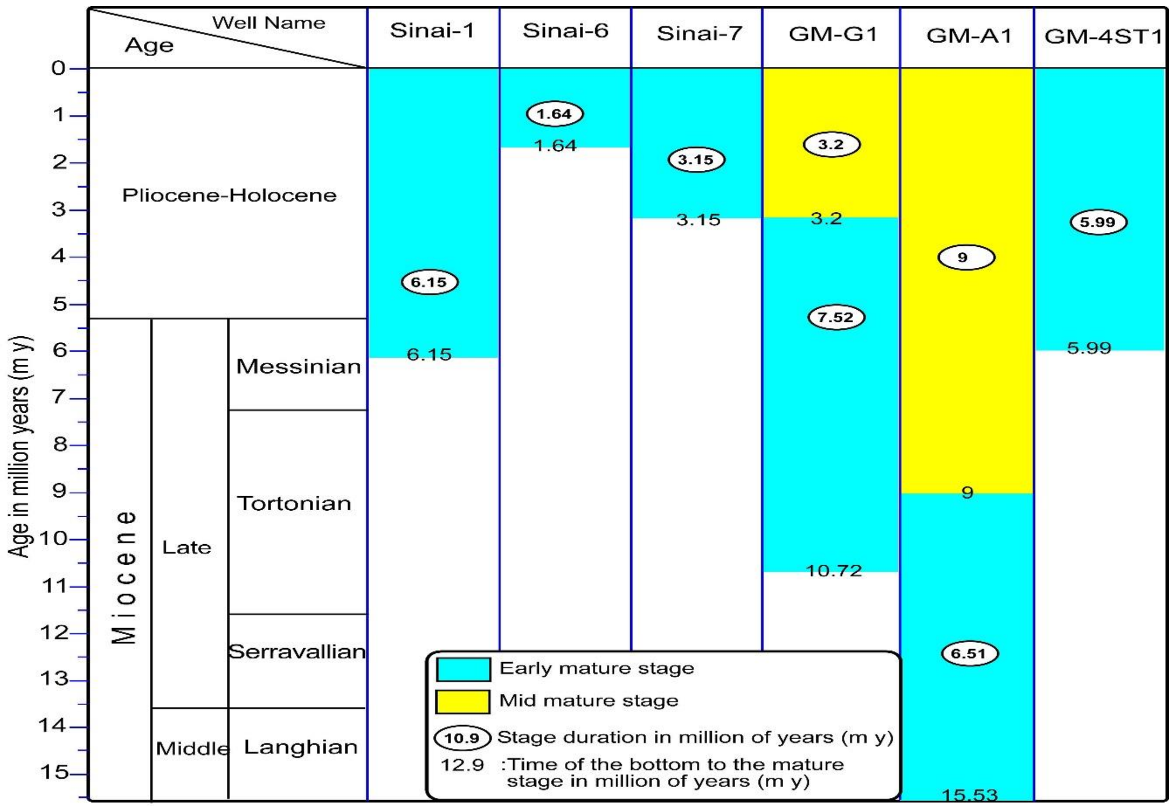

Figure 12 Graph indicating the early and mid-mature stage durations for the source rock of the Lower Rudeis

the oil. The GM-A1 and GM-G1 wells, reached high values of heat flow; 69 and 74 mW/m2 respectively, while the remaining wells reached low values, estimated of 64 mW/m2. Both wells started the early mature stage at 15.5 and 10 Ma respectively, however the other wells started the early mature stage later (Table 3). GM-A1 and GM-G1 wells have the highest overburden thicknesses of 2897 and 2880 m respectively, but the other wells are of lower thicknesses. Therefore, unlike all the other wells, wells GM-A1 and GM-G1 entered the mid-mature stage.

Hydrocarbon tarps were formed as a result of the Mid-Rudeis event at 17 Ma and the maturation process initiated at approximately 15.5 Ma, followed by the deposition of the South Gharib and Belayim seal rocks at 13.60 and 11.8 Ma, respectively. The first phase of generation and expulsion process began at 6.0 Ma, followed by the second phase, similarly like GM-A1 well.

The Garra region includes one petroleum system composed mainly of pre-Miocene source rocks, characterized by a high percentage of TOC (6-7), with a kerogen I/II type. The pre-Miocene rocks underwent the early and mid-mature stages and maturity started at around 14.30 Ma and at nearly 1400 m depth. The hydrocarbons generated are oil, in addition to gas. Lower Rudeis source rock is of a lower potential than pre-Miocene, and the amounts of generated and expelled oil are low, therefore the main source rocks of the petroleum system in the Garra region are of the Pre-Miocene. The main reservoir rocks comprise the Rudeis and Kareem formations, sealed by the Miocene evaporites of Belayim and South Gharib formations. The migration of oil occurred vertically along the fault planes, and laterally in the northeastern direction.

Two petroleum systems were identified in the southern province; one petroleum system attributed to the pre-Miocene rocks, while the other petroleum system attributed to Miocene rocks. One petroleum system was identified in the Garra region, consisting of pre-Miocene and Miocene Lower Rudeis source rocks, charging Kareem-Rudeis reservoirs that is capped by Belayim evaporite. The lateral migration pathway of the hydrocarbons in northeast direction towards Sinai massif, and likewise the direction of the petroleum system in the Garra region.

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Conflicts of interest

There are no conflicts to declare.

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