

Analysis of the Petroleum System Elements of Amana Oil Field, East Abu Gharadig Basin, Western Desert, Egypt

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Article Info

Received 6 Mar. 2022

Revised 31 Mar. 2022

Accepted 17 Apr. 2022

Keywords

Petroleum System ; Amana oil Field; Abu Gharadig Basin; source rocks; reservoirs types, hydrocarbon traps; Western Desert; Egypt.

Abstract

The petroleum system elements that include source rocks, paths of hydrocarbon migration, reservoirs types, hydrocarbon traps, and seal rocks are essential in characterizing the hydrocarbon accumulation in the sedimentary basins. However, each part of these elements may be of different age and formed in different environment but these elements must meet in space and time in one petroleum system. The available well log and core data for some wells in the Amana oil field were used to perform a comprehensive petrophysical evaluation of the Abu Roach G Member. The evaluation of petroleum system elements in the Amana field shows that the source rock is the Middle Jurassic Khatatba Formation, which was deposited in a transitional environment. It comprises an oil and gas-prone organic matter (type II/III kerogen), that is believed to have entered the oil window defined by 0.6% vitrinite reflectance (Ro). The Interpretation of the available log data was used to evaluate the penetrated rock units in Amana field. The middle zone of the Abu Roach G Member which is sealed laterally at the top by shale intercalations in the Abu Roach G Member and by the Abu Roach F massive carbonates in other areas.

1 Introduction

The petroleum system concept describes the dynamic hydrocarbon system that operates in a limited geologic space and time scale (Perrodon and Masse, 1984). All of the factors that affect hydrocarbon generation, migration, and accumulation are parts of a larger system known as a hydrocarbon machine (Magoon et al. 1994). Darwish et al. (2004), Dolson et al. (2001 & 2002), Zein el Din et al. (1990), and Moretti et al. (2010) investigated Egypt's western desert's petroleum potential. The primary goals of this work are to apply petroleum system theory to the Amana oil field in order to analyse the main elements and hydrocarbon machine existence in the area, source rock evaluation and migration on a basin-scale, while trap and seal will be presented in field-scale. The occurrence of

hydrocarbons in the Western Desert is heavily influenced by tectonic events and depositional environments that have created numerous reservoirs and seals. Most fields in the northern Western Desert are related to Late Cretaceous-Eocene structures and are located in or near early depo-centers that later became kitchen areas (Abu El Naga, 1984). The Abu Gharadig basin structure has been identified as a major rift basin with numerous localized highs in NE-SW oriented plunging anticlines that are thought to be fault-controlled folding (Schlumberger, 1995). The primary source rocks are the Middle Jurassic Khatatba Formation (Fm) and the Upper Cretaceous (Turonian) Abu Roash "F" Member (Shahin et al., 1986). While the Bahariya, Kharita, and Abu Roash formations act as reservoir rocks, the Abu Roach G Member (Late

Cenomanian) is considered the main reservoir in the East Bahariya concretion. It is made up of alternated layers of shale, limestone and some streaks of sandstone (Abu-Hashish et al., 2022). The Abu Roash and Khoman formations act as seal rocks. The Abu Gharadig basin contains a variety of traps, including structural, stratigraphic, and combination traps (Younes, 2012 & Abu-

Hashish et al., 2019). The Amana oil field is located in the East Bahariya concession in the Abu Gharadig basin's easternmost trough between Latitudes 29° 33' 17" N and 29° 33' 54" N and Longitudes 29° 24' 40" E and 29° 26' 40" E (Fig. 1).

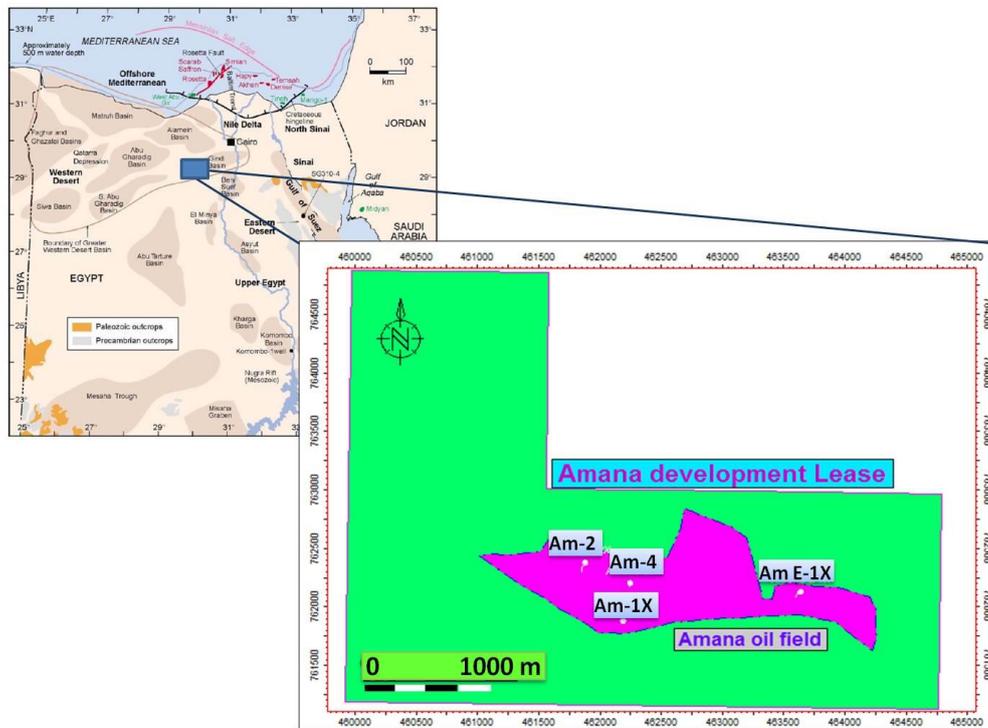


Figure 1 Location map of Amana field in Abu Gharadig basin.

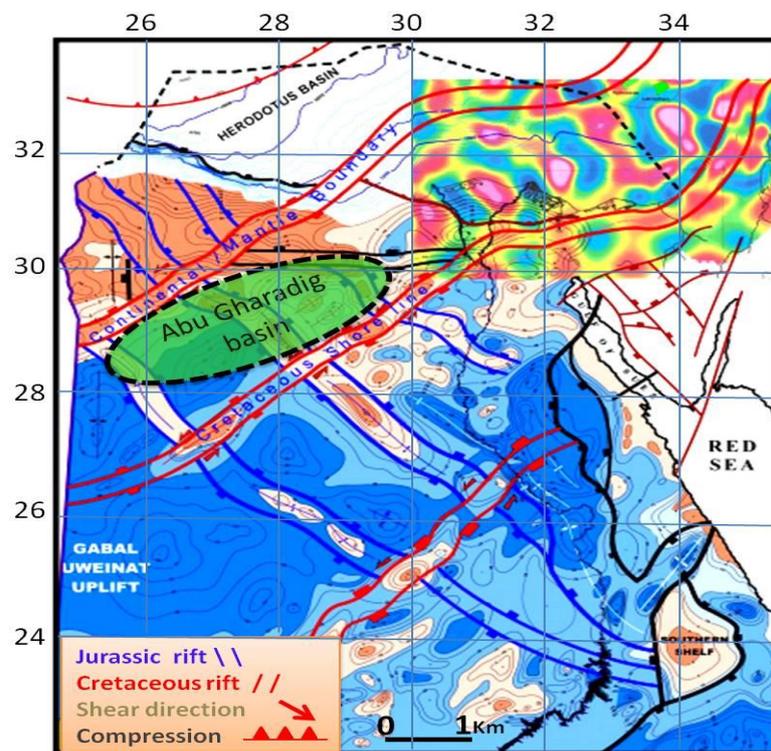


Figure 2 Tectonic framework of Egypt (modified after Meshref, 1988).

2 Geologic settings

Two major tectonic features influenced Egypt: the NW-SE trending during the Jurassic period and the NE-SW trending during the Cretaceous period (Fig. 2). The Abu Gharadig Basin is a multi-cyclic, E-W elongated structurally controlled basin with an oval shape. It originated as a result of deep crustal extensional tectonics that affected the northern part of Egypt during the Mesozoic times (Bayoumi et al., 1989). It could have formed during the Jurassic period, as a pull apart basin between the two right-lateral wrench faults. The area is highly deformed by folding and faulting activities, especially by the most pronounced structural feature "the Syrian Arc fold system" which started, with the end of the Cenomanian, and was intensively active during Turonian- Santonian time interval and was culminated with local rejuvenation during the Eocene. This major system is resulted in series of anticlines and synclines (Pivnik et al., 2007). The northern margin of the Abu Gharadig basin is marked by a major border fault zone which up-throws basement to about 10,000 feet forming Sharib-Sheiba ridge, and the southern boundary is called Sitra platform (Enayet, 2002). The tectonic activity reached its maximum peak during the Upper Cretaceous to Eocene interval (Schlumberger, 1995). The Abu Gharadig basin was subjected to various tectonic events, which resulted in various tectonic trends seen in the basin (Meshref et al., 1988), which were explained by a convergent wrench model as follows: A N-S to NNW-SSE trending structures of Precambrian age,

- 1) E-W trending (Y-trends) structures of Paleozoic to Jurassic age,
- 2) W-NW trending (R-trends) structures of Late Jurassic to Early Cretaceous, and
- 3) E-NE trending (P-trends) structures of Late Cretaceous to Eocene age.

During the Jurassic and Cretaceous periods, extensional deformation influenced the Abu Gharadig basin, which has half graben geometry with a northward tilt. The basin architecture shows the effect of three fault trends: namely WNW-ESE, NE-SW, and E-W (Moustafa, 2008). The Amana field locally shows almost the regional structural

regime that had been mentioned above, where the major fault trends are WNW-ESE and E-W (Fig. 3). Abu Gharadig basin was affected by extensional deformation during Jurassic and Cretaceous time and acquired half graben geometry with a northward tilt, the basin architecture shows the effect of three fault trends: namely WNW-ESE, NE-SW, and E-W (Moustafa, 2008). Amana field locally shows almost the regional structural regime, where the major fault trends are WNW-ESE and E-W.

East Bahariya concession comprises two distinct geological regions; The Southern Platform area, which is dominated by a basement high representing the eastern extension of Bahariya- Diyur high, the basement, is penetrated shallower than 3 km. The Northern Basinal area, which is represented by Mubarak Sub-basin, which is the eastern extension of Abu Gharadig basin where we study. The stratigraphic succession in the northern part of the Western Desert ranges from Cambrian to Holocene. The stratum were made up of various lithologies with total thickness that reaches more than 4km in the Abu Gharadig Basin (Younes, 2003). Said (1962) subdivided this sedimentary cover into three main units from top to base:

- A Clastic- Carbonate unit (Late Eocene- Holocene).
- A Carbonate dominated unit (Late Cretaceous- Middle Eocene).
- A Clastic dominated unit (Cambrian- OEarly Cretaceous).

The Abu Gharadig Basin's generalised stratigraphic column (Fig. 4) shows a depositional gap between the Paleozoic and Jurassic formations due to a lack of Triassic sediments, which can be interpreted as this area being folded above sea level at the end of the Paleozoic time, and the folding continuing, or being renewed, during the lower Cretaceous Aptian - Albian time. (Said, 1962). The whole section that had been penetrated through Amana wells started from Miocene Moghra Fm. (on the surface) to Cenomanian Bahariya Formation at the total depth.

3 Materials and Techniques

Different sources of data were used to accomplish this work; 2D seismic data was used to configure the main structural features in Amana oil field. Petrophysical evaluation was done using a complete set of wireline log data for four wells in Amana oil field. The log data include Gamma ray, neutron, density, sonic and resistivity logs. Geochemical analyses were conducted for some rock samples to deduce the source rock properties. Tech log, Petrel and basin Mode softwares were adopted for data analysis and presentation.

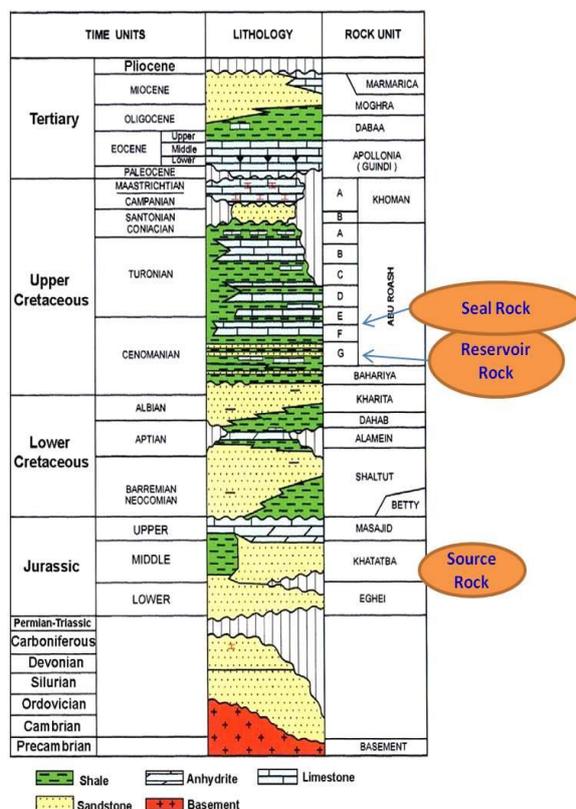


Figure 4 Generalized stratigraphic column of Abu Gharadig Basin (modified after Schlumberger, 1995).

4 Results and Discussion

4.1 Source Rock Assessment

When applying the petroleum system theory, the first and most important element that should be considered is the evaluation of source rocks. Source rock is referred to as the kitchen area because organic matter is subjected to high temperature (that can reach over 100 degrees Celsius) and high pressure for a significant period of geologic time in order to generate hydrocarbons (Karpenko, 2014). The Khatatba Formation is the main

source rock in the study area. It is composed of a thick carbonaceous shale sequence (Halim et al., 1996), with some porous sandstone interbeds (which is oil bearing in the Razzaq oil Field), coal seams and limestone streaks. The Khatatba Formation grades into the lateral equivalent Masajid Formation, which is mostly made up of platform and carbonates, including oolitic, reefal, and dolomitic limestones, with cherty intervals (Schlumberger, 1995). The Khatatba Formation was

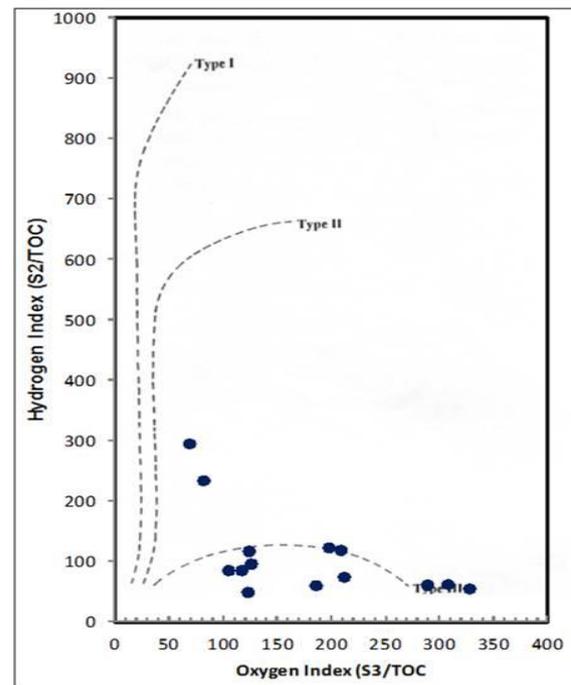


Figure 5 Van Krevelen diagram for Khatatba Fm.

deposited in continental to inner-middle shelf environments. The Khatatba source rock is marginally mature, has mixed marine and terrestrial organic sources, and was deposited in a clay-rich transitional marine environment under oxidizing-reducing shallow marine and/or deltaic environment with mixed organic sources (El Nady, 2014).

4.1.1 Source Rock Quantitative Analysis

The TOC Analyzer instrument was used to determine the organic carbon amount by combusting samples (100 gm of the rock) at 1350°C in an oxygenated atmosphere. Moisture and particulate matter are filtered out, and a solid-state infrared detector then measures the CO₂ gas, according to the carbon weight percent, the quantity of organic matter is determined as a function of carbon atoms. The (TOC) of Middle Jurassic Khatatba Formation ranges between 3.14 and 5.9 wt. % (Table 1). Based on those results the Khatatba Formation is classified as a

good source for hydrocarbon generation. There are also few beds yielded poor, fair and excellent TOC values that reach over 33.1 wt. % which may be due to the presence of coal beds (Abu Bakr et al., 2008). The samples yielded TOC values of more than 0.5 wt. % were selected to determine the quality of this organic matter as a function of kerogen type and kerogen maturity using Rock Eval Pyrolysis. Van Krevelen Diagram was used to detect the kerogen type (Van Krevelen, 1961) (Fig. 5). The gas chromatography (GC) analysis of the oil recovered from the Abu Roash "G" Member sandstone suggests a predominantly terrestrial organic source, which is matching with the Khatatba Formation (mixed type II and type III kerogen), this oil is well matched with the north Western Desert Jurassic source rocks (Fig. 6).

4.1.2 Kerogen Thermal Maturity

Thermal maturity is the transformation of organic matter that motivates a source rock to generate hydrocarbon. It varies according to the in situ conditions such as the

closeness of basement rock and the function of burial depth and variation of temperature gradient in the kitchen area. With increasing maturity, organic matter was initially transferred to petroleum with complex compounds starting from oil, wet gas and finally dry gas. Vitrinite is a macerals formed through thermal alteration of lignin and cellulose in plant cell walls; it is found in most of kerogen types, and has an ability of reflectance; this reflectance varies in its intensity according to the degree of exposure to the heat (thermal maturity). Vitrinite reflectance was first used for determination of the rank of thermal maturity of coals. Vitrinite reflectance is the diagnostic tool for assessing the maturity. The amount of the reflected light by the vitrinite macerals is the main key for the thermal maturity determination.

Reflectivity was measured using a microscope equipped with an oil immersion objective lens and a photometer (R). Measurements of vitrinite reflectance were meticulously calibrated against glass or mineral-reflectance

Table 01 TOC and Pyrolysis Analysis of Khatatba Formation.

Sample no.	TOC	S1	S2	S3	T max	S2/TOC	S3/TOC	S1/(S1+S2)
	wt. %	mg/g	mg/g	mg/g	Deg. C	HI	OI	PI
1	2.33	0.5	6.88	1.61	435	295	69	0.07
2	2.31	0.34	5.41	1.9	433	234	82	0.06
3	1.03	0.09	1.23	2.15	431	119	209	0.07
4	1.21	0.11	1.42	1.5	435	117	124	0.07
5	1	0.07	0.85	1.17	432	85	117	0.08
6	0.98	0.07	0.94	1.23	432	96	126	0.07
7	1.01	0.1	1.24	2	432	123	198	0.07
8	0.7	0.06	0.42	1.3	434	60	186	0.13
9	1.05	0.09	0.89	1.1	434	85	105	0.09
10	0.77	0.07	0.57	1.63	427	74	212	0.11
11	0.71	0.09	0.44	2.19	366	62	308	0.17

12	0.89	0.09	0.54	2.57	415	61	289	0.14
13	0.8	0.09	0.44	2.62	324	55	328	0.17
14	0.82	0.06	0.4	1.01	367	49	123	0.13

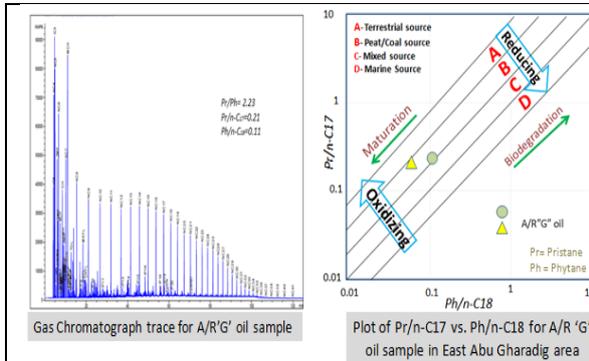


Figure 6 GC trace and Pristane/ Phytane plot for Abu Roash G Oil sample.

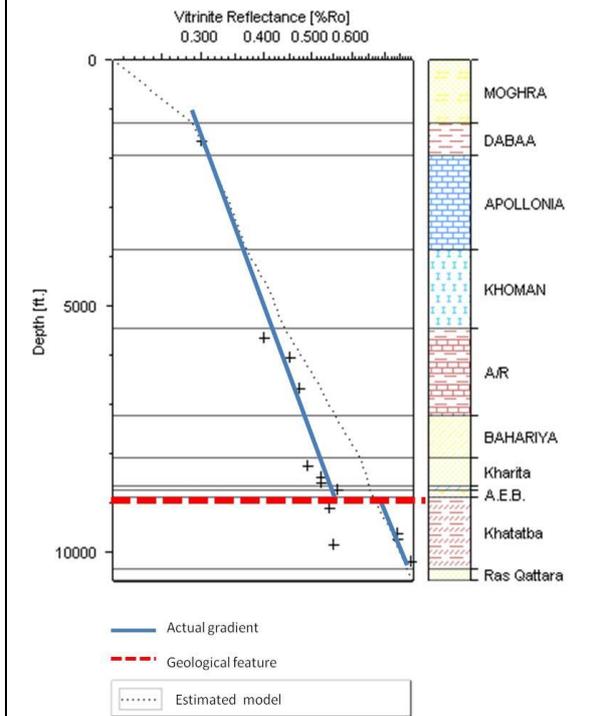
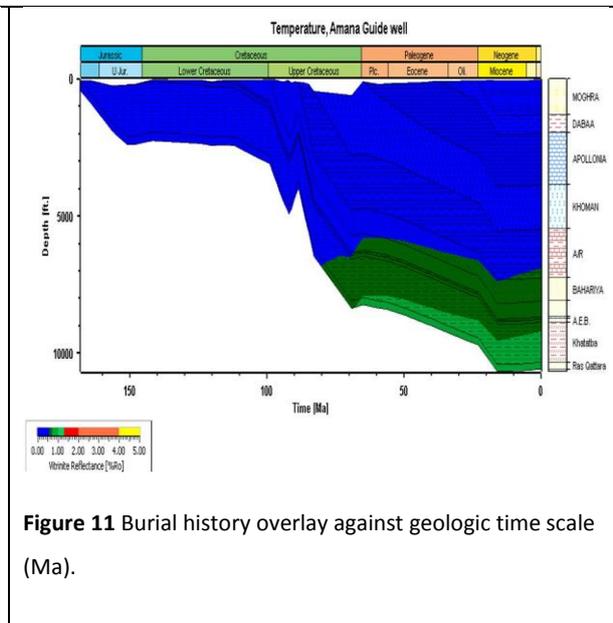
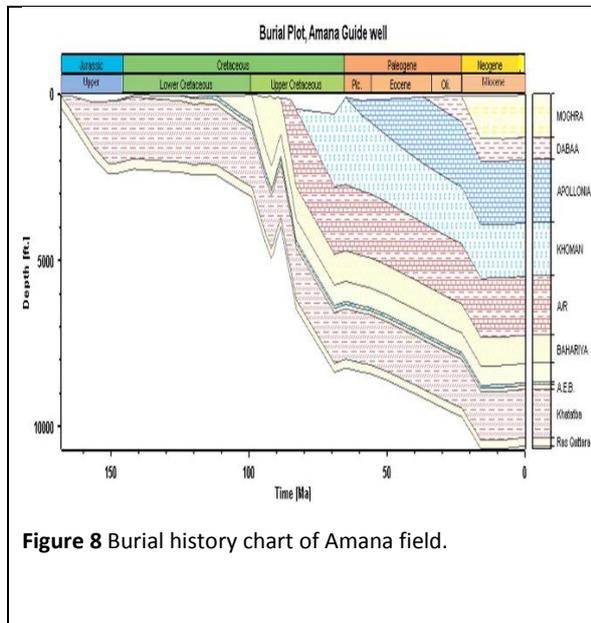


Figure 9 Temperature gradient versus depth in Amana field.

Figure 0 Maturity level and Vitrinite Reflectance gradient.



Figure 10 Burial history with temperature gradient overlay.



standards; these values represent the percentage of light reflected in oil (Ro). High maturation values (more than 1.5% - 0.8%) generally indicate the presence of predominantly dry and wet gas, while the values ranging between 0.8% - 0.6% indicate predominantly oil and (Ro) less than 0.6% points to immature kerogen. A geochemical analysis were performed for some cutting samples against the Khatatba Formation in the study area; that analysis showed values of Vitrinite Reflectance with average value 0.6% Ro (Table 2). The constructed maturity profile from the Ro values shows that, the Khatatba Formation already skipped the oil window stage. A gap in maturation gradient around the depth of 9000 feet was noticed in the maturity profile, which may be due to unconformity surface above Khatatba Formation. Below this depth, the organic matter reached the maturity level while above still immature (Fig. 7). The evaluation of source rock in the Amana area is primarily based on kerogen conducting burial history records, which explain the sequence of all layers and their thicknesses versus time (Fig. 8).

The burial history chart shows a significant break during the deposition of both the Abu Roash G Member and the Bahariya Formation (Cenomanian age). This break can be interpreted as the presence of a major fault in the area where the guide well is located, resulting in a missing section of over 800 feet and the massive break in the curves 90 million years ago. To complete the picture about the source rock potentiality of the Khatatba Formation,

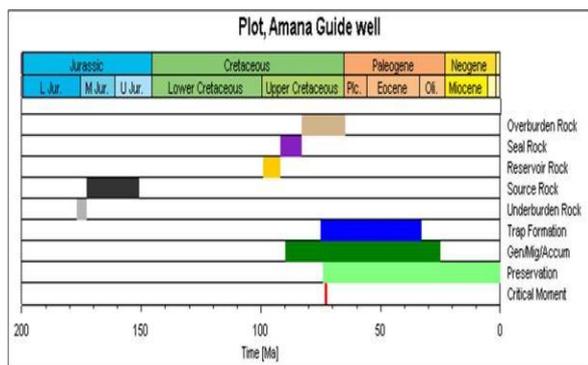
the temperature gradient by which the oil window has been estimated should be taken in consideration (Fig. 9). The temperature gradient is the process of following up the change of temperature values as a function of depth. It was acquired in the guide well of Amana field and has been compiled with the burial history chart in order for recording the temperature gradient versus geologic time to take a note about the proportionality of the temperature gradient with the time (Ma : million years ago) (Fig. 10). Based on one-dimensional modelling and combining vitrinite reflectance data with burial history, it can be observed that the shallower part of the section (Moghra, Dabaa, Apollonia, Khoman, and Abu Roash formations) has a low degree of thermal maturity, with vitrinite reflectance Ro less than 0.5 percent. The middle section (Bahariya, Kharita, Alam Elbueb, and upper zone of Khatatba formation) has a Ro value ranging from 0.6 to 1%, the lower section has a Ro value greater than 1%. (Fig. 11). The built model obtained by employing the Easy percent Ro algorithm (Sweeney and Burnham, 1990).

Table 2 Vitrinite Reflectance measurements against Khatatba Fm.

Formation	No. of Measurements	Average Vitrinite Reflectance (RO%)
Khatatba Fm.	22	0.54
	3	0.74
	1	0.74
	19	0.55
	7	0.79

4.2 Expulsion

The Basin modelling indicates that oil production from the Jurassic Khatatba source rock began around 90 million years ago, during the Middle to Late Santonian age (Abu Roash Formation deposition) (Lotfy et al., 2020). However, the expulsion did not begin until 75 million years ago, during the Campanian period (base Khoman deposition). During the deposition of the Miocene Moghra Formation, oil extraction ceased 25 million years ago (Fig. 12).

**Figure 12** Event chart for the petroleum system in Amana area

4.3 Reservoir Rocks

The main reservoir rock in the study area is the Abu Roash "G" Member, the lowest member of the Abu Roash Formation (Abu-Hashish and Said, 2016), it is made up of interbedded carbonates and clastics that deposited in an inner neritic environment during the Cenomanian period's continuation of regional transgression. Based on their relative positions within the Abu Roash "G" Member, the sandstone and/or siltstone beds in the Abu Roash "G" Member are developed in three petrophysically distinct sub-divisions (upper, middle, and lower beds) (Fig. 13).

Because of its high productivity in comparison to the other reservoirs, the Middle zone is the most important. (Table 3). The average gross thickness of Abu Roach G Member is around 45 feet. While the net pay thickness in the Amana field ranges from 20 to 30 feet.

Grain Size has a strong impact to the reservoir efficiency (Lacey et al., 2017) where the coarser the grain size, the higher the reservoir quality (Ogolo et al., 2015). The well log tools (particularly the Gamma Ray log) show an obvious coarsening upward (Fig. 14). The lower part of the zone is composed primarily of siltstone and silty sandstone, showing high Gamma Ray readings, then grading upward to fine sandstone with moderate Gamma Ray readings, while the upper part of the pay-zone is made up of coarse and clean sandstone with low Gamma Ray readings; indicating that the Middle Abu Roash "G" bed is a mouth bar geo-form in a neritic zone. The log response of the Middle Abu Roash "G" bed has a strong correlation with the proximal and distal Mouth Bar ideal log motifs, as predicted by Sam Boggs' model (Sam Boggs et al., 2006). Because of the grain size variation and coarsening upward of the pay-zone, the first recovery and the production efforts were concentrated on the upper part of this reservoir. The fine-grained reservoir rock shows difficulties in the fluid flow through it and causes several problems in the pumping tools during production stage. The Petrophysical properties of the Abu Roash "G" reservoir in Amana Field was evaluated using both well log tools and core analysis data. It has a very good porosity ranging from 5% to 25%.

Some geologists use the porosity cut-off to distinguish between gross and net thicknesses, while others use the permeability cut-off, but a more rigorous approach to net thickness determination is based on a detailed analysis of the rock properties, including effective porosity, permeability, facies, and fluid saturation (Gaynor and Sneider, 1992; Worthington and Cosentino, 2005). The net to gross is a relation compiling the gross thickness and net thickness in one function obtained from dividing the net thickness by the gross thickness as a decimal fraction or percentage. For more detailed description of Abu Roash "G" reservoir, the gross and net thicknesses were calculated

Table 0 Petrophysical parameters in Amana wells.

Well	Zone	V shale	Φ_t	Φ_{eff}	S_w	S_o	Thickness ft		N/G
							Gross	net	
Amana-1	Middle	0.10	0.23	0.20	0.25	0.75	200	28	0.14
Amana-2	Middle	0.03	0.22	0.21	0.35	0.65	130	15	0.13
Amana-4	Middle	0.02	0.24	0.23	0.29	0.71	112	18	0.15
Amana E-1	Middle	0.06	0.20	0.18	0.39	0.61	390	19	0.05

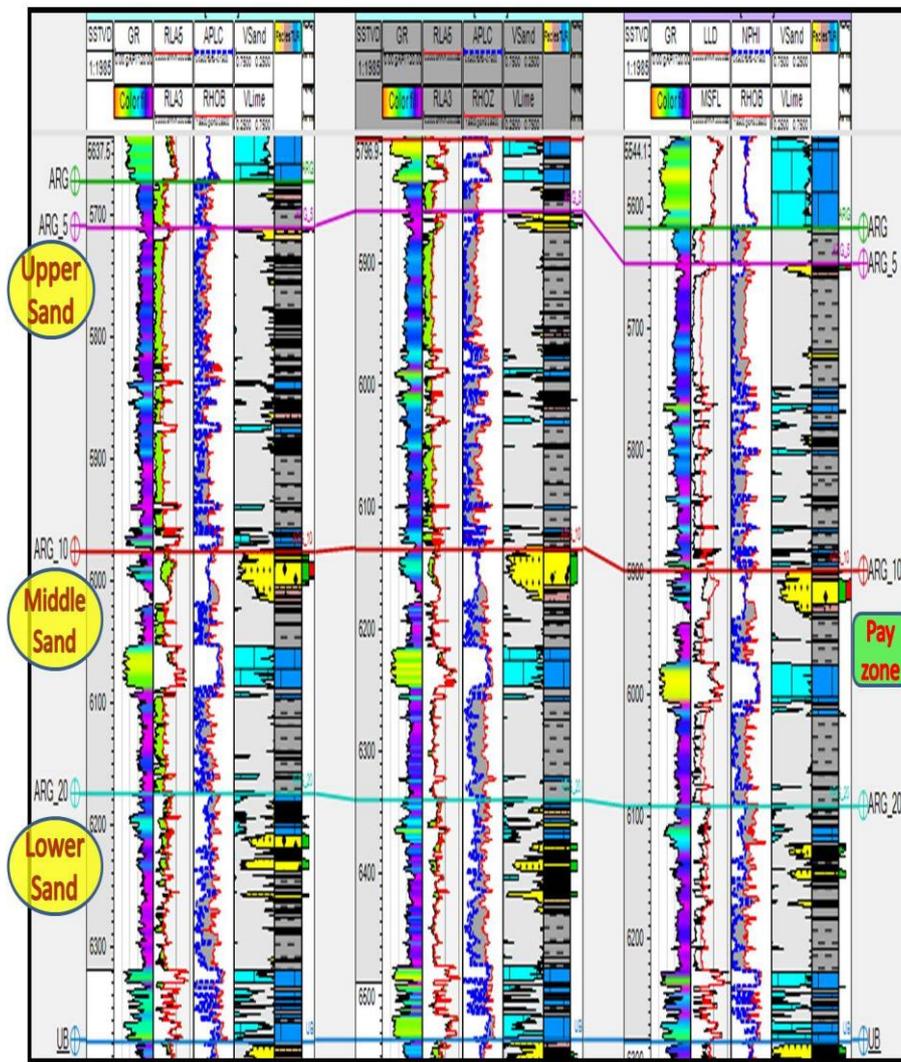


Figure 13 Abu Roash "G" Member with three sub-divisions in Amana wells

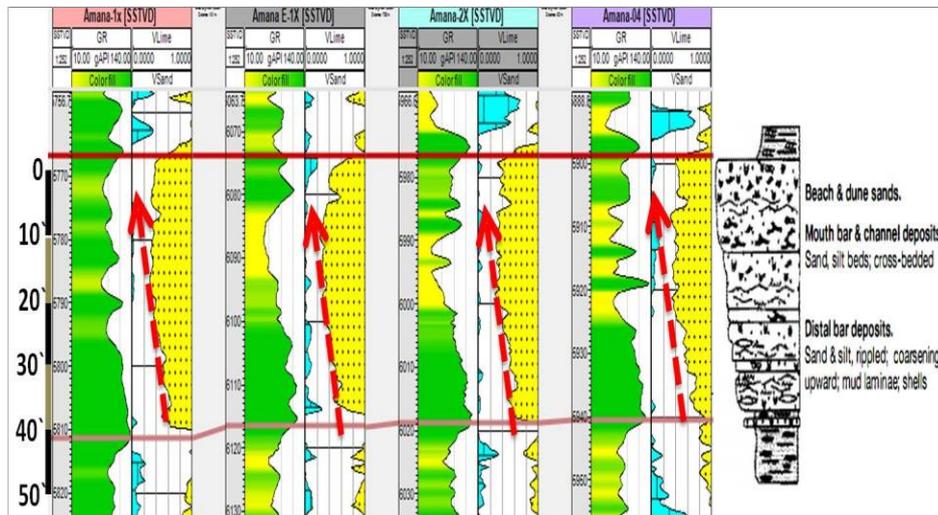


Figure 14 Middle Abu Roash G Sand responses.

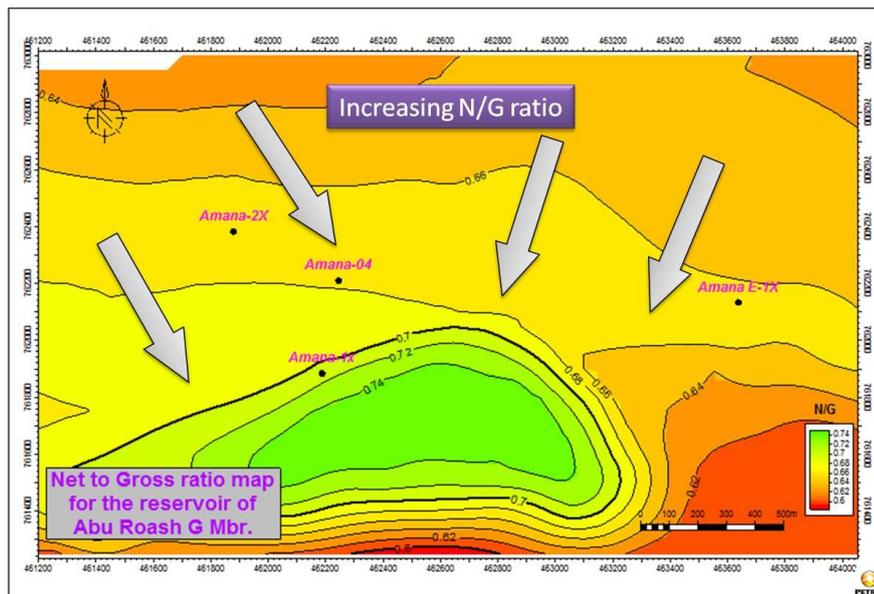


Figure 15 Net/Gross map for M. Abu Roash "G" Member in Amana field.

and mapped through the study area it increases towards the central part as the arrows pointed (Fig. 15), thus, it is highly recommended to increase the drilling activities in the central part of Amana area.

6797	1.2	16.05
6810	1.82	16.82
6822	0.39	13.34

Table 04 Core Analysis results in Amana – 1X well

Depth ft.	Permeability (mD)	Porosity %	Lithology
6533	241.99	24.17	Sandstone, medium to fine grained, silty in part, high argillaceous, with pyrite.
6540	325.12	24.97	
6543	188.74	24.12	
6558	167.25	23.74	
6565	112.98	23.47	
6580	62.34	22.94	
6787	7.16	19.96	
6790	2.42	18.34	
6793	2.64	18.86	

Permeability is the property that describes the ease of the fluid movement through the connected pore spaces in the rock, Well logs allow us a rough predicted value of permeability, but because of the spatial variability of reservoir permeability, estimation of permeability is very difficult. Abu Roash G Member attain an average permeability from 100 mD to 300 mD (Table 4). A relation between the porosity and permeability was created using the core analysis data, the proportional relation exists between them with a correlation coefficient equal to 0.83 (Fig. 16). The resulted equation of the relationship is:

$$\ln K = 24.27\Phi + 0.28.$$

4.4 Top and Lateral Seal and Entrapment

Source and reservoir rocks are not enough to keep the petroleum in place, but such a seal should be present to prevent oil from escape. The seal is mainly impermeable rock, called cap rock because of occurrence above the reservoir bed. This existence prevents the upward oil seepage only, and it is necessary to prevent the lateral escape also, lateral seal should be existed. Top seal is easily determined in the field by the lithologic column, but lateral seal is determined by whether the beds dip normally in a faulted reservoir or by the juxtaposition of impermeable bed against the reservoir, as in the present case. The Middle Abu Roash "G" sand bed is overlain by a thick section of shale (about 300 ft.). As the reservoir is faulted, the key risk is the lateral seal, i.e. does the fault leak the fluid or seal it? The maximum fault cut among Amana field does not exceed 300 ft., thus, the Middle Abu Roash "G" reservoir in the up thrown side of the major fault is juxtaposed against Abu Roash "G" shale and Abu Roash "F" carbonate in the down thrown side, suggesting good lateral sealing conditions for the Middle Abu Roash "G" reservoir. The lateral hydrocarbon migration could not be exist through this system. The hydrocarbon may exist without escaping and could not be economically produced because of the absence of trap The Amana block shows a suitable petroleum trap of structural type developed by two normal faults resulting in a horst structure (Fig. 17).

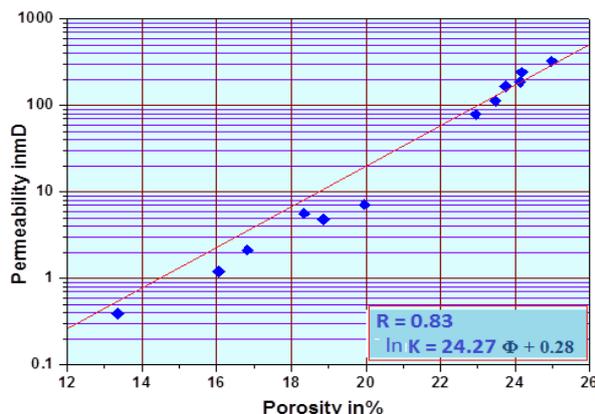


Figure 16 Porosity vs. permeability for Abu Roash "G" Member in Amana -1X field.

4.5 Timing

All of the above-mentioned petroleum system elements should be combined in a time-domain manner. According to geochemical analysis and basin modelling, oil generation from Khatatba source rock began during the Late Cretaceous (Santonian) age, oil expulsion from source rock did not begin until the Campanian age, after the deposition of Abu Roash. during Khoman Formation deposition, this migration had been stopped 25 million years ago during the Miocene time while, the main structural features in Amana area appear to have had their maximum development during late Cretaceous, and show additional rejuvenation during Tertiary (Fig. 18). The timing of oil generation and expulsion relative to the structure trap formation should be favorable for Amana structure.

4.6 Level of Certainty

The well matching between Khatatba source rock and the produced oil in Amana field, this petroleum system is classified as a "known petroleum system" with three levels of certainty: known, hypothetical, or speculative. The petroleum system nomenclature begins with the name of the source rock, then moves on to the name of the major reservoir rock, and finally to the symbol expressing the level of certainty. The produced hydrocarbon from the Amana oil field is referred to as the Khatatba source rock, while the main reservoir bed is the middle Abu Roash G bed, with a confirmed relationship between the produced oil and the Khatatba origin, thus, the present petroleum system could be named as:

the Khatatba-Abu Roash G (!) petroleum system.

where: Khatatba: source rock Abu Roash G: main reservoir rock (!): known level of certainty

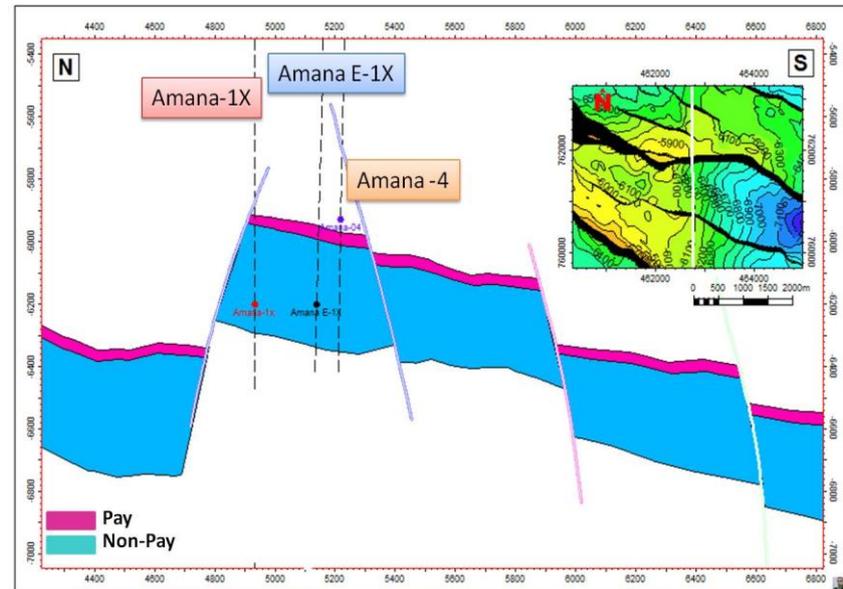


Figure 17 Structural cross section among Amana wells.

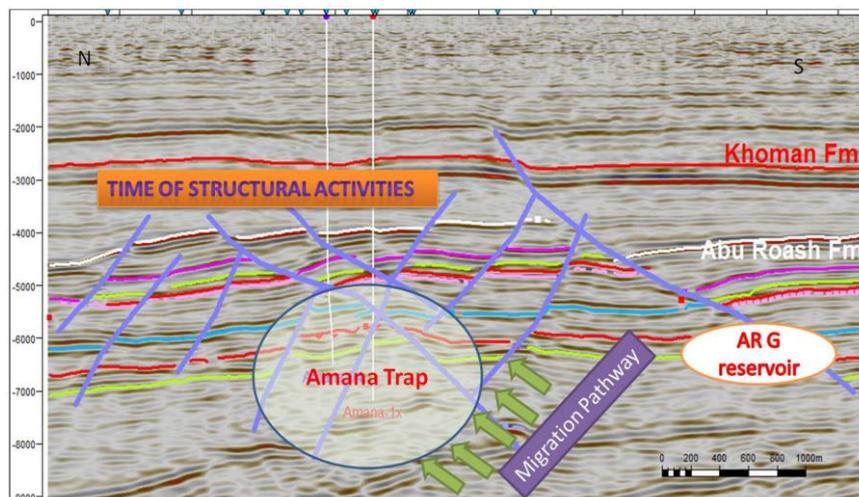


Figure 18 Seismic section with Petroleum system elements in Amana field.

Conclusions

The Middle Jurassic Khatatba Formation, which acts as a source rock in the study area, consists of mixed unstructured lipids and terrestrial organic matter. It contains a significant quantity of oil-prone organic matter (type II kerogen), with gas-prone organic matter (type III kerogen) and believed that it had entered the oil window (defined by 0.6% Ro). The reservoir rock in Amana field was determined based on the petrophysical analysis and formation evaluation that assigned to the middle sandstone zone in Abu Roash G Member that had been top and laterally sealed by the intercalations of shale included in Abu Roash G Member itself and overlain by Abu Roash F massive carbonates. The trap in Amana Field is of

structural type was formed during the Late Cretaceous time with a Horst style resulted from the two boundary E-W trend normal faults from north and south of the field and bounded from east and west sides by the normal dipping which was very favorable for collecting the hydrocarbon in the reservoir. While the time of oil generation from Khatatba source rock has started during Santonian age. The oil expulsion has commenced during the deposition of Khoman Formation in Campanian (Late Cretaceous age). The geochemical correlation between Khatatba source rock and the produced oil from Amana oil field indicates that the migration has been stopped 25 million years ago in the Miocene time.

Funding sources

This research received no external funding.

Conflicts of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Acknowledgements

The authors wish to express their thanks and gratitude to the EGPC (The Egyptian General petroleum Corporation) and Qarun Petroleum Company for permission and release the data for this research.

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