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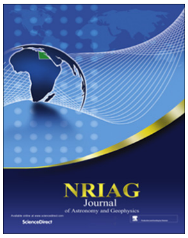

Geothermal studies in oilfield districts of Eastern Margin of the Gulf of Suez, Egypt

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Abstract Results of geothermal studies carried out at 149 onshore oil wells have been used in evaluation of temperature gradient and heat flow values of the eastern shore of the Gulf of Suez. The investigations included temperature logs in boreholes, calculation of amplitude temperature, geothermal gradients and heat flow. The results obtained indicate that geothermal gradient values are in the ranges of 0.02–0.044 °C/m and regionally averaged mean heat flow values are found to fall in the interval of 45–120 mW/m^2. Temperature gradients and heat flow values change from low values eastward to high values toward the axial of Gulf of Suez rift. The result of this research work has been highly successful in identifying new geothermal resources eastward of the Gulf of Suez. Additionally, this study shows that the areas with relatively higher temperature gradients have lower oil window, mature earlier, than those with low gradient values. Thus, high temperature gradients cause to expedite the formation of oil at relatively shallow depths and narrow oil windows. On the other hand, low temperature gradient makes the oil window to be quite broad when locate at high depths.

1. Introduction

Unlike most of countries, there is no sufficient information on the thermal status of Egypt. However, the tectonic position of Egypt in the northeastern corner of the African continent suggests that it may possess significant geothermal resources, especially along its eastern margin (Morgan et al., 1985). Egypt is bounded to the east by what has been interpreted as spreading center in the Red Sea and Gulf of Suez (McKenzie et al., 1970) and indicates that the potential for development

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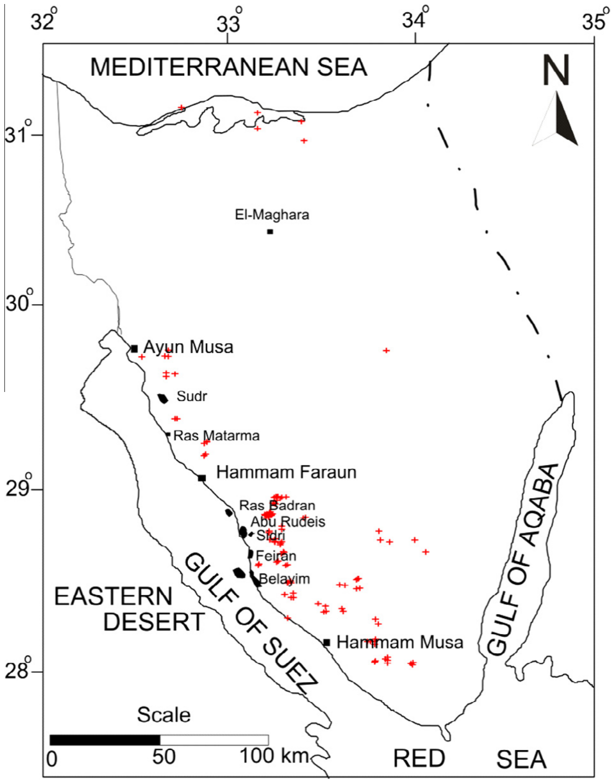

Fig. 1 Location map of the Gulf of Suez region, showing the locations of the hot springs on the eastern margin of the Gulf. Locations of the oil wells used in the geothermal studies are plotted as red crosses.

of geothermal resources is located along the Red Sea and Gulf of Suez coasts. Consequently, the Gulf of Suez region is one of the most interesting geothermal areas in Egypt because of its spring's high temperatures. The hot springs at the eastern coast of the Gulf of Suez include Ayun Musa (37 °C), Ain Hammam Faraun (70 °C) and Hammam Musa (48 °C) (Sturchio et al., 1996). These springs are probably of tectonic or non-volcanic origin associated with the opening of the Red Sea–Gulf of Suez rifts (Boulos, 1990). Geothermal studies were carried out at the eastern margin of the Gulf of Suez, where the distributed bottom-hole temperature records of deep offshore and onshore oil wells are shown (Fig. 1). The main objective of this study is to evaluate new localities for geothermal energy resources which are used for the development of the area. Based on these temperature logs data, the temperature gradients and heat flow characteristics of the eastern side of the Gulf of Suez were calculated. Geothermal parameters, including amplitude of temperature (*A*), mean surface temperature (*MST*), Geothermal gradient (*GG*), regression coefficient (R^2), thermal conductivity (*K*) and heat flow (*Q*), were calculated. Additionally, we studied the impact of the temperature gradients on the rate and extent of hydrocarbon maturation that consider the prime interest of valuation of oil fields.

Many geothermal explorations were conducted in Egypt using thermal gradient/heat flow and groundwater temperature/chemistry techniques as well as geophysical tools. Morgan and Swanberg (1979) showed high heat flow values, up to 175 mW m^{-2}, approximately three times the normal values, in the eastern Egypt, and the heat flow appears to increase toward the Red Sea coast. Also, Morgan et al. (1983) discovered a regional thermal high and a local thermal anomaly along the eastern margin of Egypt. El-Nouby (1990) studied

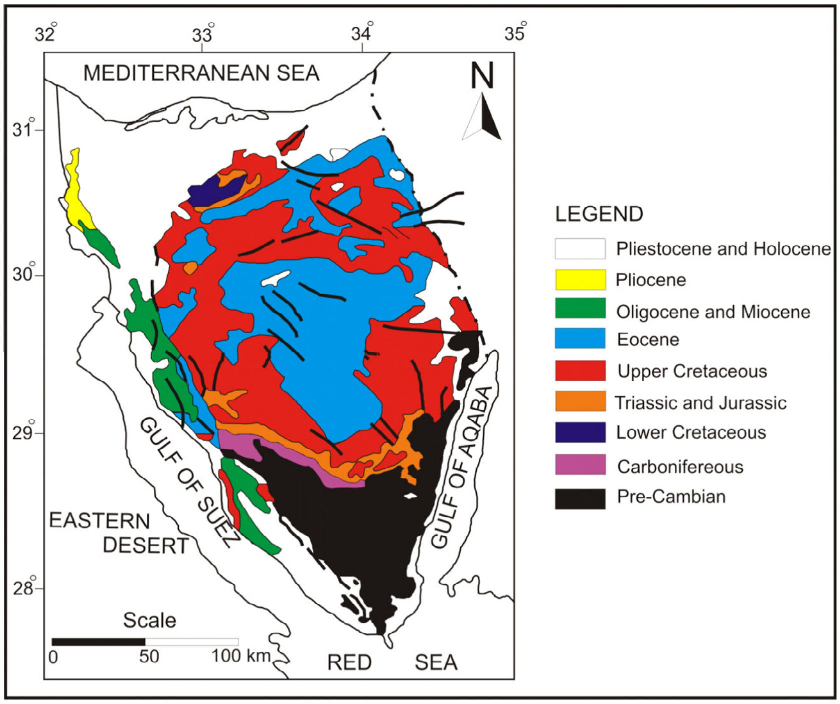

Fig. 2 Main surface geologic setting of Sinai Peninsula (Omara, 1972 and Kora, 1995). Heavy lines indicate the major faults in Sinai Peninsula.

the potassium deposits within the Middle Miocene evaporate at the Gulf of Suez. He showed that the radioactivity and the isothermal maps have the same trend which coincides with the major structure at the area. Abdel Zaher et al. (2011a) evaluated potential geothermal resources in the Gulf of Suez region using both bottom-hole temperature data and geophysical data. Also, Abdel Zaher et al. (2011b) developed a conceptual and numerical model of the geothermal system at Hammam Faraun area and demonstrated that Hammam Faraun hot spring originates from a high heat flow and deep ground water circulation in the subsurface reservoirs that are controlled by faults. Abdel Zaher et al. (2012) and listed stable isotopes of ^{18}O and Deuterium of thermal water samples that were collected from hot springs of Ayun Musa, Hammam Faraun and Hammam Musa. He suggested that recharge to the hot springs may not be entirely from the Gulf of Suez water, but possibly from the meteoric water that comes from areas of higher altitude surrounding the hot springs.

2. Geological setting

Sinai, a triangular peninsula in Egypt, lies between the Mediterranean Sea to the north and the Red Sea to the south, forming a land bridge from Africa to Southwest Asia. Sinai Peninsula is characterized by significant variation from the geological and topographical settings where the igneous and metamorphic mountains form the southern tip of the peninsula (Fig. 2). The basement rocks (Precambrian) occupy the southern part of the studying area, along the Gulf of Suez and Gulf of Aqaba, whereas the central part of Sinai Peninsula is occupied by Mesozoic to Tertiary sediments. Northward, the topography comprises low alluvial plains which are broken by large uplifted Mesozoic domes and anticlines (Syrian arc). Further northward, these "Syrian Arc" structures sink seaward due to Tertiary down-to-the-basin normal faults and are hidden under the Quaternary coastal plain and continental deposits. During the Tertiary opening of the Red Sea, volcanism in the western and central Sinai resulted in many basaltic bodies, mostly doleritic sills, plugs and flows (Meneisy, 1990).

The stratigraphic record of the Gulf of Suez shows that the Gulf existed as a shallow embayment of the Tethys as early as the Carboniferous, and that a landmass lay at its southern end until the late Cretaceous. Predominantly clastic sediments that characterize its early history change to calcareous marine sediments in the Cenomanian. Intensive faulting and subsidence, associated with volcanic and intrusive activities, evident from the late Cretaceous, reached a maximum toward the end of the Oligocene, and continued through the Miocene into the Pleistocene; hot springs are still active at present (Abdel-Gawad, 1970). Tawfik et al. (1992) obtained a direct

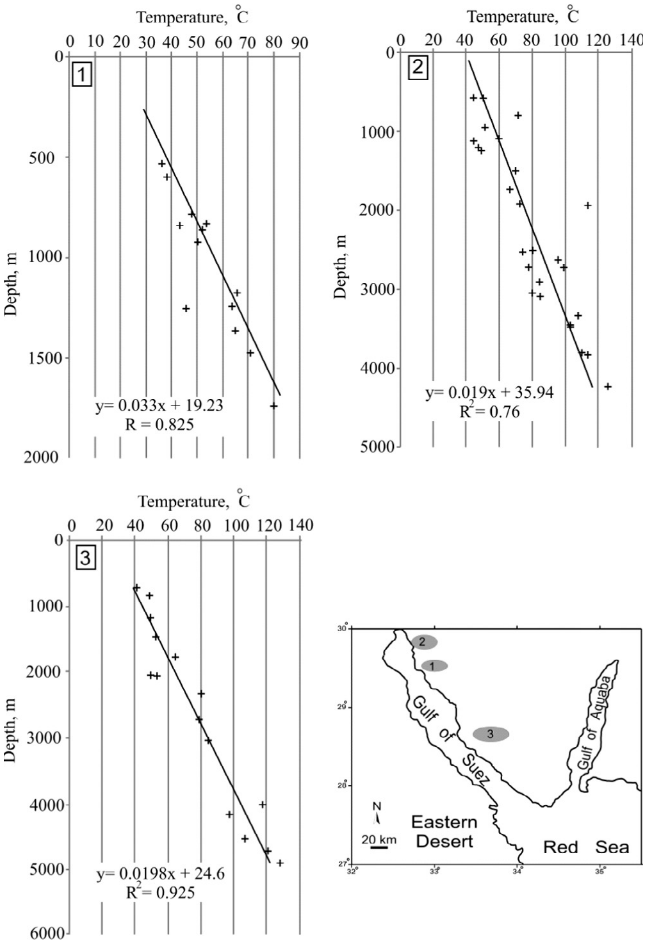

Fig. 3 Examples of temperature gradient measurements for wells 1, 2 and 3 displayed in the attached map; the temperature-versus-depth relationship was plotted by a least squares regression analysis technique.

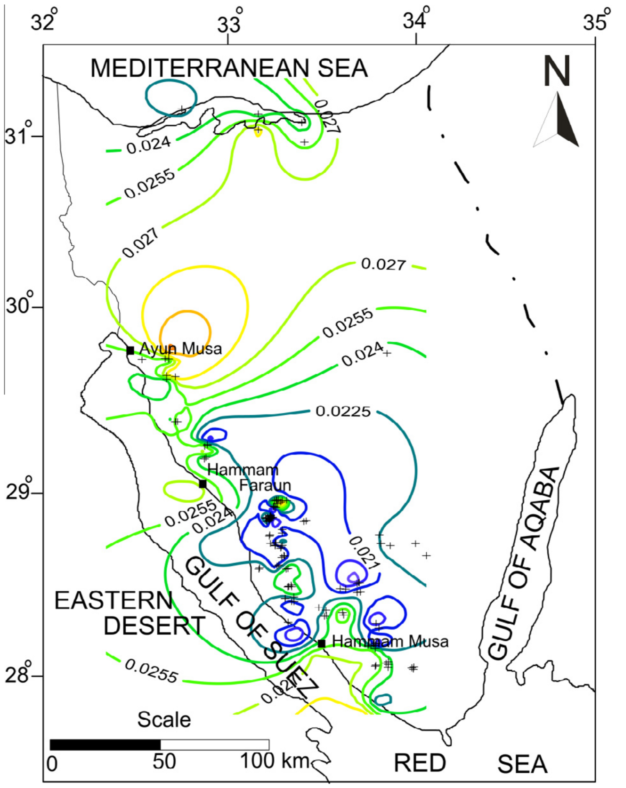

Fig. 4 Temperature gradient values of the eastern margin of the Gulf of Suez. High values are encountered westward and around the vicinity of hot springs. Locations of the oil wells used in the geothermal studies are plotted as crosses on the map.

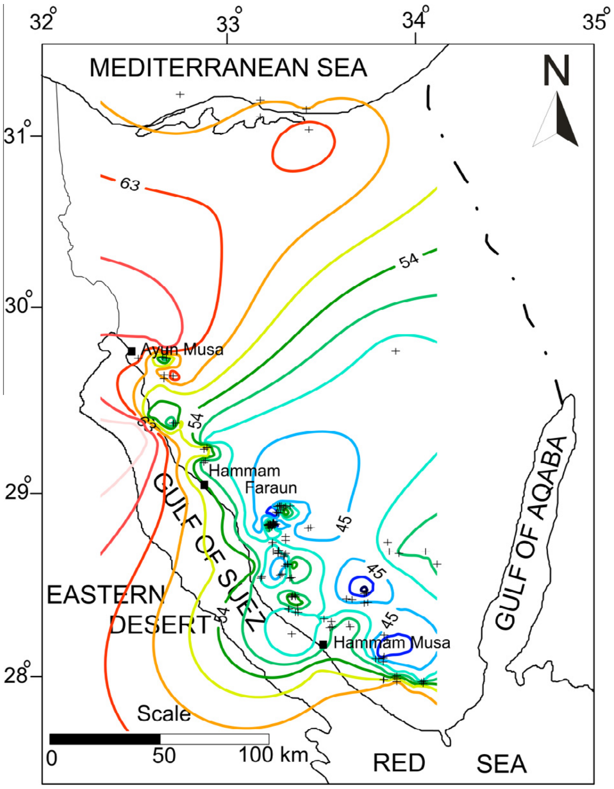

Fig. 5 Heat flow values of the eastern margin of the Gulf of Suez measured by combining sets of temperature-gradient and thermal-conductivity data. Locations of the oil wells used in the geothermal studies are plotted as crosses on the map.

relation appears to exist between the geothermal trends in the Gulf of Suez and the pre Miocene relief. The hot trends indicate high pre Miocene blocks while the cold trends indicate deeper pre Miocene blocks. Besides, Miocene salt distribution accounts for most of the cold trends in the Gulf of Suez. Meshref (1990) shows that the major troughs along the rift axis associated with high temperature gradient are reaching 20 °F per 30 m, or more. This is explained by the axis of rift usually associated with thin crust and up welling of hot mantle material by convection. El-Nouby (1990) studied the potassium deposits within the Middle Miocene evaporate at the Gulf of Suez. He shows that the radioactivity and the isothermal maps of Behar NE area (Gulf of Suez) have the same trend which coincides with the major structure at the area.

3. Geothermal studies

Geothermal studies were conducted on the basis of the collected bottom-hole temperature logs of 149 onshore deep oil wells at the eastern margin of the Gulf of Suez, with depths ranging from 2000 to 4500 m. These measurements were carried out by oil companies, including the Egyptian General Petroleum Company (EGPC), the Gulf of Suez Petroleum Company (GUPCO), and British Petroleum Company (BPC). Often, temperature measurements influenced by the ceasing process due to the cooling effect of drill fluid circulation. Various methods have been adopted to correct the logged BHT to real formation temperatures. These methods have been reviewed by Beck and Balling (1988). Information about the time since circulation of the drilling fluid was stopped and the length of time of circulationis required for doing correction. Unfortunately, this information is not available whereas the BHT logs are not corrected from the cooling of fluid circulation. Nevertheless, the areas that have geothermal potentiality are expected to be higher than they are.

Thermal gradient/heat flow technique was used to estimate the main geothermal parameters such as amplitude of temperature, geothermal gradient, and heat flow. The Amplitude of temperature is defined as the amount of temperature displacement that equals the difference between the bottom-hole temperature and surface temperature. Temperature gradients were computed for linear sections of the temperature-versus-depth data by least squares regression analyses (Fig. 3). The main gradient at each well location was measured assuming the mean annual surface temperature of 26.7 °C (Morga et al., 1983). In some wells there is a big difference in temperature between the surface and the first record which leads to produce high value of temperature gradient. This huge difference may be due to the blanketing effect of the overburden that allows sediments to heat by conduction causing to increase the pressure and temperature of the deeper parts of the earth. Thus, the value of the surface temperature was not taken into account for calculating the temperature gradient in some sites.

High temperature gradients were encountered on the margin of the Gulf of Suez and decrease eastward and northward. The maximum gradients were recorded near the Hammam Faraun and Hammam Musa areas (0.045 °C/m); such a geothermal gradient may be the highest recorded in geothermal exploration in Egypt (Fig. 4). Heat flow values were determined by combining sets of temperature gradient and thermal conductivity data using the formula $Q = K(dt/dz)$, where Q is heat flow, K is thermal conductivity, and t is the temperature at depth z. Preliminary heat flow values ranging from 50 to 115 mW m^{-2} have been computed for the eastern margin of the Gulf of Suez (Fig. 5) with a reasonably good geographical distribution, and a limited number of thermal conductivity determinations were obtained from different studies such as El-Nouby and Ahmed (2007), Morga et al. (1983), Swenberg et al. (1983), Morgan and Swanberg (1979), and Clark (1966).

4. Results and discussion

Table 1 shows the geothermal parameters that estimated at different locations on the Eastern margin of the Gulf of Suez. Data obtained from the Ayun Musa coal exploration borehole No. 15 indicate a linear gradient of approximately 32 °C/km between 405 and 450 m. These high geothermal gradients are due to the presence of coal seams and extensive structure which affected the area. Data obtained from six oil wells drilled at Ras Misalla oil field show normal to high geothermal gradient and heat flow.

Abu El-Darag oil field is located directly to the north of Sudr oil field and to the south from Misalla oil field. It is the

Table 1 Main geothermal parameters of some oil well data at the eastern margin of the Gulf of Suez. Where; (*A*) amplitude temperature, (*MST*) main surface temperature, (*GG*) temperature gradients, (R^2) correlation coefficient, (*K*) thermal conductivity, and (*Q*) heat flow.

Well name	*A* (°C)	*MST* (°C)	*GG* (°C/m)	R^2	*K* ($W{\cdot}m^{-1}{\cdot}K^{-1}$)	*Q* (mW/m^2)
Ayun Musa B.H.No.15	17	29	0.032	0.98	2.4	77
Misalla E-1	27	26	0.027	0.99	2.6	70.8
Misalla S-1	41	26	0.026	0.99	2.6	67.6
w-78-1	67	26	0.024	0.98	2.6	62
Darag-1	82	26	0.025	0.99	2.6	65
Darag-17-1	94	26	0.026	0.99	2.9	75.4
N. Darag-1	51	26	0.029	0.99	2.6	75.4
N. Darag-2	40	26	0.025	0.99	2.6	65
N. Darag-3	37	26	0.025	0.99	2.6	65
Sudr-1	42	24	0.032	0.91	2.6	82
Sudr-3	40	24	0.032	0.91	2.6	83.2
Sudr-8	14	24	0.023	0.91	2.2	51.3
Sudr-25	10	24	0.039	0.91	2.2	86.7
Sudr-32	32	24	0.027	0.91	2.2	60
Sudr-33	40	24	0.035	0.91	2.2	75.7
Sudr-34	26	24	0.028	0.91	2.2	61.6
Sudr-38	28	24	0.032	0.91	2.2	70.8
Sudr-39	29	24	0.035	0.91	2.2	77
Sudr-40	19	24	0.023	0.91	2.2	50.6
N-Sudr-3	43	26	0.029	0.99	2.6	75.4
Ras Matarma-1	69	24	0.032	0.99	2.2	70.4
Ras Matarma-2	35	24	0.031	0.99	2.1	65
Ras Matarma-3	34	24	0.030	0.99	2.1	63
Asl-1	40	24	0.032	0.99	2.1	63
Asl-2	36	24	0.030	0.99	2.1	63
Fin-780-1	11	26	0.028	0.99	2.9	81.2
Nebwi-81-1	59	26	0.019	0.99	2.2	41.8
Lagia-5	47	26	0.027	0.99	2.6	70.2
Wadi Gharandal-1	11	26	0.027	0.91	2.6	70
Wadi Gharandal-2	3	26	0.026	0.91	2.1	55
Conco - C2-A-1	67	26	0.023	0.98	2.6	60
Conco - C2-B-1	101	26	0.026	0.95	2.6	68
Conco - C3-A-1	115	26.9	0.027	0.98	2.2	59.4
Conco - C4-NA-1	73	26	0.023	0.94	2.6	60
Conco - C4-NA-2	95	26	0.029	0.99	2.6	74.4
Conco - C4-NA-8	88	26	0.027	0.99	2.6	70.2
Gebel Tanka-1	24	26	0.027	0.99	2.6	68
Gebel Tanka-2	19	26	0.027	0.99	2.6	70
Gebel Tanka-3	4	26	0.026	0.99	2.2	57
Wadi Mutalla-1	14	26	0.028	0.92	2.6	73
Wadi Mutalla-2	14	26	0.027	0.92	2.6	70
Wadi Mutalla-3	17	26	0.026	0.92	2.6	68

same geological structure in Ayun Musa and Misalla oil fields. Data from five oil wells represent Abu El-Darag oil field with depths ranging between 1500 and 3300 m. Studies carried out on the lithostratigraphic units under Abu El-Darag area show that Coal seams and Carboniferous shale are recorded within Middle Jurassic deposits. In oil wells NDR-2 and NDR-3 trace of lignite occurrence. This proves that coal seams in the area occurred as lances which are similar to coal seams at Ayun Musa areas. Sudr, Matarma and Asl oil fields are located directly to the south of Abu El Darag oil field and to the north from Nebwi oil field. Data obtained from 26 oil wells drilled at Sudr, Matarma and Asl oil fields with depths ranging between 133 and 1741 m., were used. Results of studies show two zones of high geothermal gradient. The first zone is located at south-eastern part of the area (about 32 °C/km), where well Sudr 22 is located. The second high geothermal gradient zone is located at the northwestern part. It is higher than the first zone (about 35 °C/km.). In this area well Sudr 15 is located with the temperature at surface of 55 °C.

Geothermal parameters were calculated in Lagia concession which contains Nebwi, Lagia and Wadi Gharandal oil fields (Table 1). Also data obtained from 6 oil wells drilled at Conco oil field, located to the south from Wadi Gharandal oil field and to the north from Gebel Tanka oil field, penetrated depths ranging between 2900 and 4200 m. These data were used to evaluate the geothermal parameter characteristic for Conco oil field. To the south of the previous oil field Wadi Mutalla oil field and Hammam faraun hot spring are located. The spring issues from 12 small individual outlets occupy a groove of about 50 m length, 4 m width and 2 m depth. The

Table 2 Temperature gradients (*GG*), depth for the oil ceiling (*Doc*), the depth to oil floor (*Dof*) and oil window of oil well data at the eastern margin of the Gulf of Suez.

Well name	*GG* (°C/100 m)	*Doc* (m)	*Dof* (m)	Oil window
Ayun Musa B.H.No.15	3.2	2403	3853	1450
Misalla E-1	2.7	2848	4566	1718
Misalla S-1	2.6	2957	4742	1785
w-78-1	2.4	3204	5137	1933
Darag-1	2.5	3076	4932	1856
Darag-17-1	2.6	2957	4742	1785
N. Darag-1	2.9	2651	4251	1600
N. Darag-2	2.5	3076	4932	1856
N. Darag-3	2.5	3076	4932	1856
Sudr-1	3.2	2403	3853	1450
Sudr-3	3.2	2403	3853	1450
Sudr-8	2.3	3343	5360	2017
Sudr-25	3.9	1971	3161	1190
Sudr-32	2.7	2848	4566	1718
Sudr-33	3.5	2197	3522	1325
Sudr-34	2.8	2746	4403	1365
Sudr-38	3.2	2403	3853	1450
Sudr-39	3.5	2197	3522	1325
Sudr-40	2.3	3343	5360	2017
N-Sudr-3	2.9	2651	4251	1600
Ras Matarma-1	3.2	2403	3853	1450
Ras Matarma-2	3.1	2480	3977	1497
Ras Matarma-3	3	2563	4110	1547
Asl-1	3.2	2403	3853	1450
Asl-2	3	2563	4110	1547
Fin-780-1	2.8	2746	4403	1657
Nebwi-81-1	1.9	4047	6489	2442
Lagia-5	2.7	2848	4566	1718
Wadi Gharandal-1	2.7	2848	4566	1718
Wadi Gharandal-2	2.6	2957	4742	1785
Conco – C2-A-1	2.3	3343	5360	2017
Conco – C2-B-1	2.6	2957	4742	1785
Conco – C3-A-1	2.7	2848	4566	1718
Conco – C4-NA-1	2.3	3343	5360	2017
Conco – C4-NA-2	2.9	2651	4251	1600
Conco – C4-NA-8	2.7	2848	4566	1718
Gebel Tanka-1	2.7	2848	4566	1718
Gebel Tanka-2	2.7	2848	4566	1718
Gebel Tanka-3	2.6	2957	4742	1785
Wadi Mutalla-1	2.8	2746	4403	1657
Wadi Mutalla -2	2.7	2848	4566	1718
Wadi Mutalla -3	2.6	2957	4742	1785

spring flows from faulted dolomitic limestone. Water temperature has been individually measured by different workers at different periods and was found to be 75 °C (1961), 60–70 °C (1966), 72 °C (1971), 70 °C (20 May 1981) and 72 °C (24 May 1984). A borehole 100 m north of the hot spring was drilled on May 1981 in limestone to the depth of 80 m and the temperature inside the bore hole was measured at 5 m intervals using a resistance (Thermistor) thermometer whose resistance varies significantly with temperature. High temperature gradient and heat flow were encountered in Hammam Faraun area (48 mk/m and 115 mW/m^2).

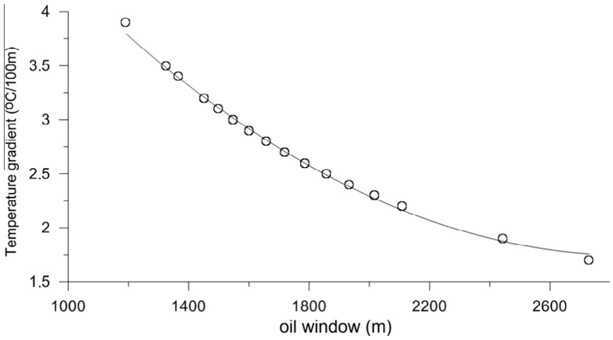

Fig. 6 Oil window variation with temperature gradient for representative wells in the Eastern margin of the Gulf of Suez. High temperature gradients corresponding with shallow oil windows. While, low temperature gradient indicates high depth of oil window.

The maturation of hydrocarbon source rocks depends on a range of factors, including the primary rock type and its original content of organic matter; the history and depth of sedimentation; duration of sedimentation; and the local temperature gradient. The subsurface temperature range in which oil forms and expelled from the source rocks is defined as oil window. Below the minimum temperature (60–120 °C at 2–4 km depth range) liquid hydrocarbons are generated and preserved in the form of kerogen, and above the maximum temperature (100–200 °C at 3–6 km depth range) the oil is converted into natural gas through the process of thermal cracking.

The oil window can be estimated by *Dof–Doc*, where *Dof* is the depth to oil floor at which oil is no longer generated and gas begins to dominate, and *Doc* is depth for the oil ceiling, defined as that depth below which oil generation begins to increase substantially. These two depths (*Dof* and *Doc*) are given by Piggot (1985) as $Dof = 100(150 - Ts)/(dT/dZ)$ and $Doc = 100[(T - Ts)/(dT/dZ)]$, where Ts is the average surface temperature, and dT/dZ is the geothermal gradient in °C/100 m and T is the oil threshold temperature that can be empirically described in a non-Arrhenius relationship as a function of sediment age: $T = 164.4–19.39 \ln t$, where T is threshold temperature in °C and t is time in 10^6 years. Assuming the mean annual surface temperature of 26.7 °C and the age of the sediment at Gulf of Suez region to be Miocene (23 Ma), the depths to the oil windows for the Eastern margin of the Gulf of Suez were calculated and listed in Table 2. High temperature gradients cause to expedite the formation of oil at relatively shallow depths and narrow oil windows. While, low temperature gradient makes the oil window to be quite broad at located at high depths. (Fig. 6).

5. Conclusion

Temperature gradients of the eastern coast of the Gulf of Suez, estimated from the temperature logs of deep onshore and offshore oil wells, show highest temperature gradient westward and on the margin of the Gulf of Suez. Simultaneously, high heat flows are recorded westward with the maximum record of 115 mW m^{-2}. Thus, the temperature gradient and heat flow increase westward and from the Gulf of Suez margin inward toward the axial rift. In addition to the main three geothermal resources, Ayun Musa, Sudr and Hammam Faraun, there are also five promising sites which are as follows: Ras Missalla (27 °C/m, 68 mW/m^2), Abu El Darag

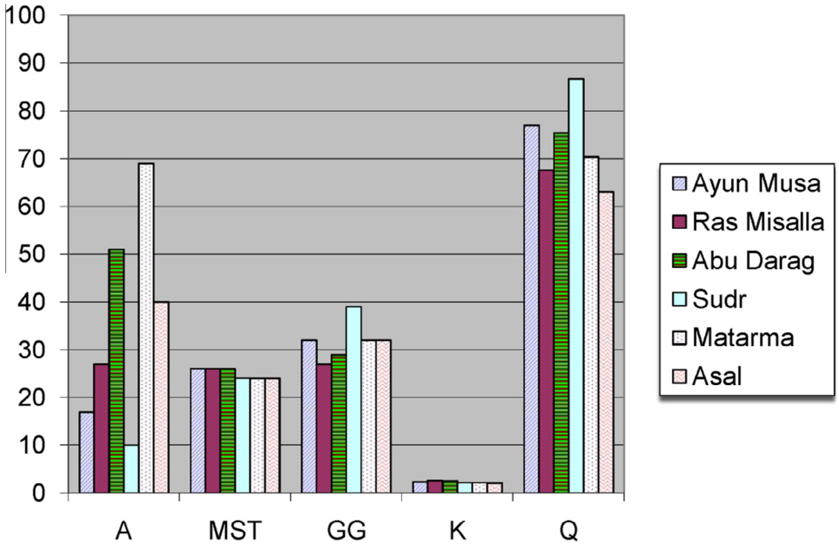

Fig. 7 Geothermal parameters of main geothermal resources at the eastern margin of the Gulf of Suez. Where; [*A*] amplitude temperature (°C), [*MST*] main surface temperature (°C), [*GG*] temperature gradients (°C/m), [*K*] thermal conductivity (W·m^{-1}·K^{-1}), and [*Q*] heat flow (mW/m^2).

(29 °C/m, 75 mW/m^2), Sudr (38 °C/m, 86 mW/m^2), Lagia (27 °C/m, 70 mW/m^2) and Matarma (32 °C/m, 70 mW/m^2) (Fig. 7). It is recommended to perform geophysical studies (magnetic, gravity, electric and well logging) to establish the geothermal energy resource modeling at these areas. The depth to oil floor and depth for the oil ceiling as well as oil window for each well were estimated by combining temperature gradients with the temperature of oil threshold. At high temperature gradients the oil can be formed at relatively shallow depths but narrow oil windows. While, low temperature gradient makes the oil window to be quite broad and locate at high depths.

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