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# Investigation of Geothermal Resources in Egypt Using Geophysical Data

Mohamed Abdel Zaher and Samah Elbarbary

National Research Institute of Astronomy and Geophysics (NRIAG), 11421 Helwan, Cairo, Egypt

moh_zaher@nriag.sci.eg

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## ABSTRACT

In a national appeal, the Egyptian Supreme Energy Council announced the state's plan, which aims to get the contribution of new and renewable energy to about 20% in electricity production of the total demand by year 2020. This points to initiate, locate and prepare energy resource feasibility studies. Among the promising renewable energy resources are geothermal sources. The geological structure and tectonic setting of Egypt suggests that it might contain an immense distribution of geothermal resources, particularly along its eastern edge. The most encouraging areas for geothermal development are located close to the Red Sea and the Gulf of Suez, which are associated with the East African Rift System. This paper reviews the state-of-the-art geothermal resources in Egypt, with an emphasis on the current investigation utilizing aeromagnetic data.

Aeromagnetic data of Egypt was used to estimate the Curie point depth (CPD), heat flow and geothermal gradient. This was compared with seismic activity. The CPDs range from 8.6 to 35.7 km, the derived geothermal gradients vary from 16.3 to 67.4°C/km, and the heat flow values range from 47.1 to 195.5 mW/m$^2$. Most of the earthquakes that originated in areas with CPDs of less than 25 km are considered promising regions for geothermal exploration, especially in the Gulf of Suez. The results of the current study may guide governmental and private sectors interested in the geothermal energy industry to select the most appropriate geothermal power plant sites in Egypt.

## 1. INTRODUCTION

Several studies have been conducted on the geothermal resources of Egypt (Morgan el al., 1983; Lashin, 2007, 2015; Abdel Zaher et al., 2011, 2014; Mohamed et al 2015). Generally, Egypt lies in the northeastern corner of Africa. It is bounded to the north by a zone of compression in the northeastern Mediterranean and Anatolia, and is characterized by low heat flow, which suggests that northern Egypt is an unlikely area for geothermal resources exploration. In contrast, heat flow determinations from the northern Red Sea region yield high values (125-250 mW/m$^2$) associated with the axial depression of the Red Sea rift (Martinez and Cochran, 1989). The Red Sea and the Gulf of Suez are responsible for the geothermal activity around the Gulf of Suez (Boulos, 1990). The heat flow values in the southern part of the Gulf of Suez range from 45 to 115 mW/m$^2$, which suggests that there is an anomalous hydrothermal heat source located at relatively shallow depths that is likely due to the uplift of the basement in the area. The geothermal gradient beneath the eastern coast of the Gulf of Suez varies between 20 and 44 °C/km, with a heat flow ranging from 45 to 120 mW/m$^2$ that increases toward the rift axis of the Gulf of Suez (Abdel Zaher et al., 2014). The average geothermal gradient in the Nile Delta ranges between 18.1 and 26.5 °C/km, indicating that the Nile Delta is a geothermally anomalous area due to lithological variations (Riad et al., 1989). The geothermal gradient in the northern Western Desert is generally 30 °C/km, although a few locally high geothermal gradients (40°C/km) are observed and are explained by potential local geothermal fields (Mohamed et al., 2015).

In this paper, aeromagnetic data are used to estimate the Curie point depth (CPD), temperature gradient, and heat flow using power spectrum analysis. The results are examined in conjunction with seismic activity to assess the geothermal resources of Egypt for future geothermal development and applications. This study may help to assess the geothermal resources throughout Egypt for future geothermal development projects and to detect the most promising areas for geothermal exploration, which could be exploited for the generation of sustainable indigenous energy in Egypt.

## 2. GEOTHERMAL MANIFESTATION IN EGYPT

The available data on the hot springs throughout Egypt are summarized in in Fig. 1. Nearly all of the hot springs in Egypt are detected around the coastal region of the Gulf of Suez, around the Cairo-Suez Road and in the Western Desert of Egypt. The most promising geothermal resources in Egypt are situated along the shores of the Gulf of Suez and are characterized by superficial thermal manifestations, including a cluster of hot springs with different temperatures. These hot springs include Ayun Musa (37°C), Ain Hammam Faraun (71°C), Hammam Musa (48°C), and Ain Sukhna (33°C). These springs were formed as a result of tectonic (or volcanic) heating associated with the opening of the Red Sea/Gulf of Suez rift (Boulos, 1990). The heat for these springs is probably derived from high heat flow and deep circulation controlled by faults associated with the opening of the Red Sea and Gulf of Suez rifts (Abdel Zaher et al., 2011).

The hot springs in the Western Desert include Ain El-Gabal (40°C) and Ain El-Kasr (39°C) in the Dakhla Oasis, Ain El-Balad (28°C) and Ain Dalla (35°C) in the Farafra Oasis, and Ain El-Bishmou (31.6°C) and Ain El-Ris (28.3°C) in the Bahariya Oasis (Idris, 2001). Very good examples of thermal waters from deep wells can be found in the Kharga, Farafra and Bahariya Oases in the Western Desert. Some hot springs in the Dakhla and Bahariya Oases are used for direct heating. The Helwan sulfur spring, which is located just south of Cairo, has reported temperatures of 36.1°C [28] and 28.9°C [20], which probably represents deeply circulating groundwater that has ascended to the surface along a fault zone [4]. According to observations of extinct geysers on both sides of the Cairo-Suez Road and in the Gebal El-Uweinat area, the southwestern corner of Egypt has shown thermal activity in the recent geological past (Boulos, 1990).

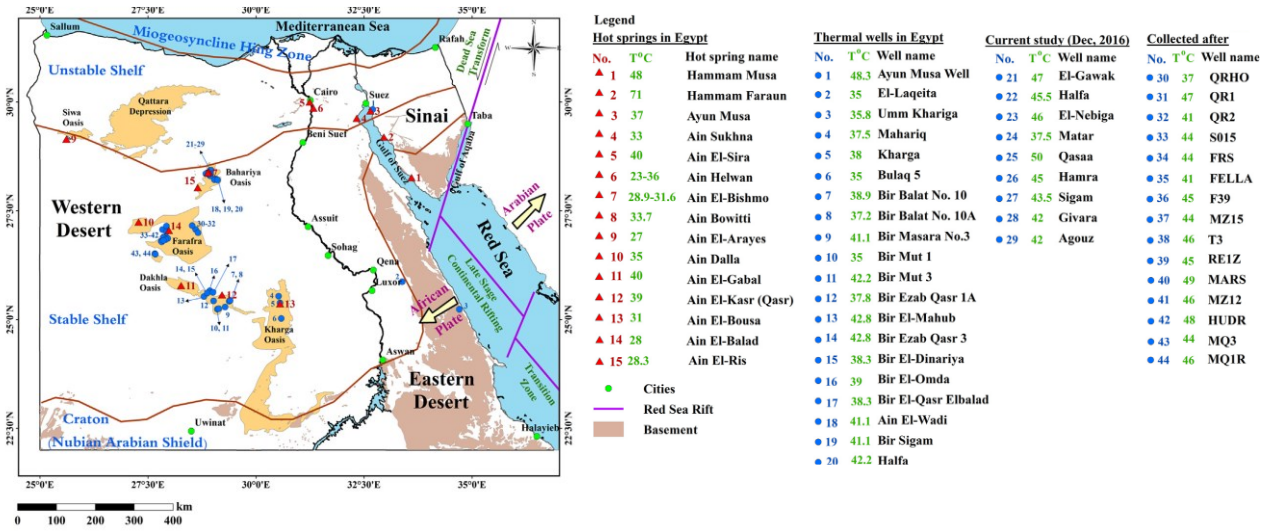



**Figure 1: Location map showing the main geothermal manifestations in Egypt, including the distributions of the hot springs and thermal wells. This figure includes the structural aspects of the Nubian-Arabian Shield margin and the tectonic framework of the Red Sea region.**

## 3. GEOPHYSICAL STUDIES

### 3.1 Aeromagnetic Studies

The objective of this aeromagnetic study is to examine the thermal structure of the crust in Egypt by estimating the CPD. The CPD is the depth in the Earth's crust at which ferromagnetic minerals are converted into paramagnetic minerals due to an increase in the temperature; generally, no noticeable magnetic field is detected below this depth (Hsieh et al., 2014). The centroid method was used to estimate the CPDs based on spectral analysis of the observed aeromagnetic data, where the basal depth of a magnetic source is considered to be the CPD. Briefly, the depths to the centroid (Z0) and to the top (Zt) of a magnetic layer can be computed from the slope of the radially averaged power spectrum of the magnetic anomaly, and the basal depth (Zb) can then be calculated according to Zb = 2Z0-Zt. Generally, a larger window size is required to calculate the radial power spectrum and distinguish the CPD. Very large windows are used to estimate the radially averaged power spectrum by dividing the aeromagnetic map into overlapping square sub-regions (95 windows) with dimensions of 293 x 278 km. The locations of the centers of these windows are illustrated in Fig. 2.

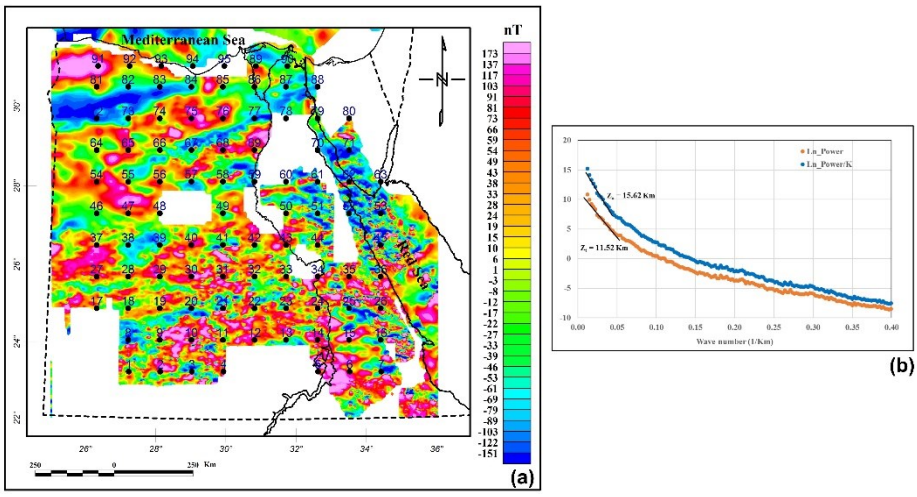



**Figure 2: (a) Aeromagnetic map of Egypt extracted from the African Magnetic Mapping Project (AMMP) sponsored by Getech (Getech, 1992). Black dots refer to the locations of the centers of sub-regions used to calculate the CPDs. (b) Example of the radially averaged power spectrum of the aeromagnetic anomaly data from sub-region no. 46.**

The CPDs range from 8.6 to 35.7 km with an average value of 20 km. The shallowest CPDs are associated with crustal thinning and outcropping basement rocks. They are found in the northeastern portion of Egypt, including the Nile Delta, the Gulf of Suez and the Red Sea. The CPDs increase towards the west and the southern margin of Egypt. The shallowest CPDs, which are associated with high heat flow, are proposed as promising areas for geothermal exploration (Fig. 3). The geothermal gradient (dT/dz) between the Earth's surface and the CPD (Zb) can be computed by the relation dT/dz = 580°C/Zb. Then, the heat flow q can be defined using the equation q = λdT/dz, where λ is the coefficient of thermal conductivity assuming no radioactive sources. The thermal conductivities of the different rocks in Egypt are assumed to be 2.9 W/mK, which is calculated by taking the average thermal conductivity for the rock samples in different parts of Egypt (Morgan et al., 1983). The geothermal gradient values in Egypt range from 16.3 to 67.4°C/km with an average value of approximately 31°C/km (Fig. 4).

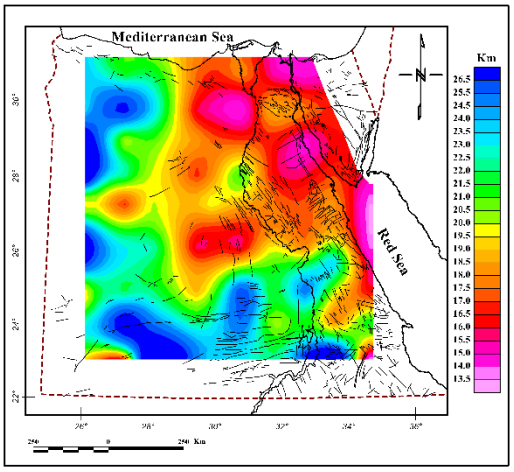



**Figure 3: CPD (Zb) map of Egypt calculated using the relation $Z_b = 2Z_0 - Z_t$. The structure lines, derived from the geological map on scale 1:2000000 © Geological Survey of Egypt 1981, are overprinted on the map.**

The heat flow values range between 47.1 and 195.5 mW/m$^2$ with an average value of approximately 89.8 mW/m$^2$. The heat flow values show a general increasing trend towards the Gulf of Suez and Red Sea and a decreasing trend towards the western and southern parts of Egypt. Based on geothermal gradient/heat flow measurements, the geothermal resources of Egypt can be classified into the following three areas; areas of low geothermal potential, which are located mainly in the Western Desert of Egypt and in the Nile Delta, areas of medium geothermal potential, which are located along the margins of the Gulf of Suez and the Red Sea, and areas of high geothermal potential, which are located within offshore deep marine rift areas of the Gulf of Suez and Red Sea.

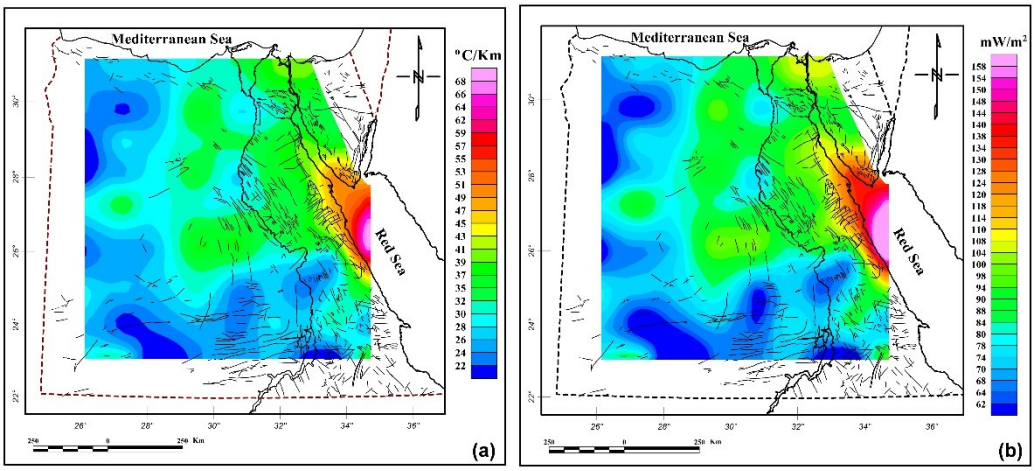



**Figure 4: (a) Temperature gradient map of Egypt derived from the CPDs and a Curie temperature of 580° C. (b) Heat flow map of Egypt using an average thermal conductivity of 2.9 W/m°C. The solid lines refer to surface faults and fractures obtained from the geological map on scale 1:2000000 © Geological Survey of Egypt 1981.**

### 3.2 Seismicity Data

The Egyptian National Seismic Network (ENSN) within the National Research Institute of Astronomy and Geophysics (NRIAG) contains continuous records of seismicity data across Egypt. Figure 5 shows the seismicity map of Egypt based on the variation in seismic magnitudes. The earthquakes throughout Egypt have small to moderate magnitudes that are explained by relative movements between the African, Arabian and Eurasian plates (Abou Elenean et al., 2009). The highest seismicity rates were recorded along the eastern border of Egypt along the Gulf of Aqaba; this seismicity might be related to active sinistral motion along the Dead Sea Fault system and the Gulf of Aqaba. High levels of seismicity along the Red Sea, Gulf of Suez, and Gulf of Aqaba confirm the presence of active tectonics in northeastern Egypt. A geostatistical analysis of the seismicity throughout Egypt within the period of 1995-2014 indicated that the mean earthquake depth is 12.79 km, while the mean Curie depth is approximately 20 km. This seismic activity could be the main reason for possible thermal accumulation, which could consequently be responsible for the observed Curie depths; otherwise, the observed CPDs could be due to abrupt changes caused by faults. Integration of seismicity and thermal structure of Egypt indicates that the areas with high heat flow correspond to areas of high seismicity. Most of the seismic energy in Egypt is concentrated in the depth range of 10-25 km. Figure 5 shows the relation between the CPDs, the heat flow and the seismicity. Shallower CPDs thus correspond to higher heat flow values and higher earthquake magnitudes. The high heat flow in the Red Sea and the southern Gulf of Suez may be related to seismic activity. Additionally, the high seismicity in the Red Sea and the southern part of the Gulf of Suez may be attributed to the presence of the Sinai Triple Junction and the Red Sea rift. The formation of shallow-seated geothermal systems in the Gulf of Suez and Red Sea is controlled by fault systems that act as pathways for geothermal fluids.

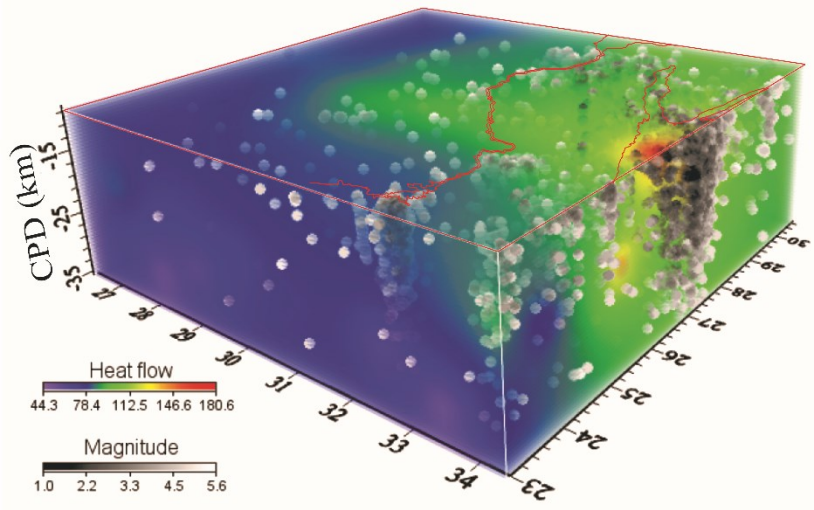



**Figure 5: A three-dimensional display of the Curie point depths, heat flow and seismicity of Egypt. The heat flow data were gridded onto a uniform XYZ array, where X is the longitude, Y is the latitude and Z is the CPD. The seismicity is plotted as data points within a volume of space, where the colors represent the magnitude.**

## 4. CONCLUSION

Aeromagnetic data were used to evaluate the geothermal potential of Egypt. The power spectral method was applied to the aeromagnetic data of Egypt to estimate the depth extent of the magnetic sources (i.e., the Curie point isotherm). The shallowest CPDs are associated with crustal thinning and outcropping basement rocks in the northeastern portion of Egypt, including the Gulf of Suez and the Red Sea. The regions with the shallowest CPDs, which are associated with high heat flow, are proposed as promising areas for geothermal exploration. Additionally, most of the earthquakes originated in areas with CPDs of less than 25 km; therefore, these areas are considered promising regions for geothermal exploration, especially in the Gulf of Suez.

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