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ASSESSMENT OF LOW-TEMPERATURE GEOTHERMAL RESOURCE OF HAMMAM FARAUN HOT SPRING, SINAI PENINSULA, EGYPT

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ABSTRACT

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. The most promising areas for geothermal exploration in the NW Red Sea-Gulf of Suez rift system are located where the eastern shore of the Gulf of Suez is characterized by superficial thermal manifestations including a cluster of hot springs with varied temperatures. Gravity and magnetotelluric reconnaissance surveys were carried out over the geothermal region of Hammam Faraun in order to infer the subsurface densities and electric resistivity that can be related to rock units. The objectives of these surveys were to determine and parameterize the subsurface source of Hammam Faraun hot spring and therefore, eliciting the origin of Hammam Faraun hot spring. Based on these data a conceptual model and numerical simulation were made in the geothermal area of Hammam Faraun. The geothermal numerical simulation succeeded to determine the characteristics of the heat sources beneath Hammam Faraun hot spring and showed that the origin of the hot spring is due to high heat flow and deep ground water circulation in the subsurface reservoir controlled by faults. This studies followed by an assessment of geothermal potential for electric generation on Hammam Faraun hot spring.

Keywords: geothermal exploration, gravity, magnetotelluric, numerical simulation, Hammam Faraun

INTRODUCTION

The most promising areas for geothermal development in the northwestern Red Sea-Gulf of Suez rift system are located where the eastern shore of the Gulf of Suez is characterized by superficial thermal manifestations, including a cluster of hot springs with various temperatures. Recently obtained data indicate that a temperature of 120°C or higher may be found in the reservoir located adjacent to the Gulf of Suez and Red Sea coastal zone (Morgan et al., 1983). The most important area for geothermal manifestation is located in the Hammam Faraun hot spring, which represents the hottest spring in Egypt (Morgan et al., 1983).

In this study, gravity and MT reconnaissance surveys were carried out over the geothermal region of Hammam Faraun to infer the subsurface densities and electric resistivity related to rock units. These surveys were conducted along two profiles (shown in Fig. 1).

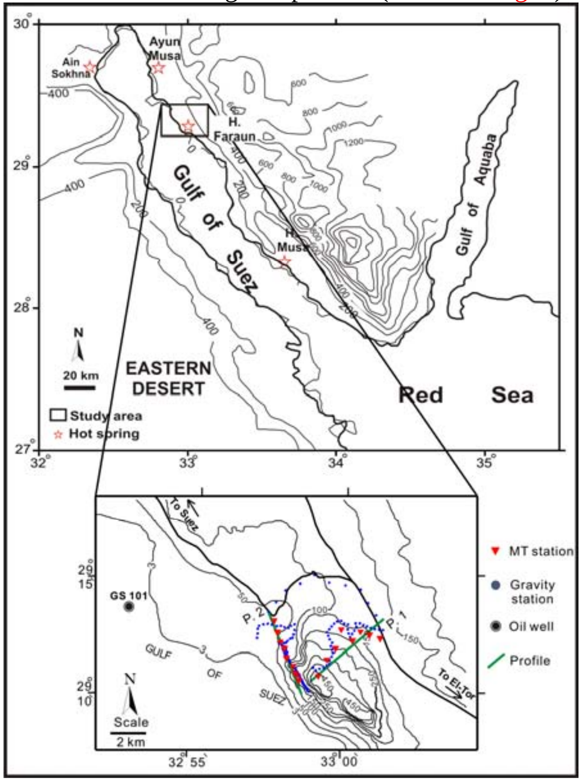

Figure 1: The location of the hot springs on the eastern and western margins of the Gulf. Locations of the measured gravity and MT sites are plotted on a topographic map of the study area.

Based on these data, a conceptual model and numerical simulation was created for the geothermal area of Hammam Faraun. These studies were followed by an assessment of the geothermal potential for the electric generation of the Hammam Faraun hot spring.

GEOLOGICAL & GEOCHEMICAL REGEMES

The Hammam Faraun tilted block is one of the main fault blocks in the central dip province of the Suez rift, and it is bound on the east and west by major normal fault zones. These major border fault zones are in excess of 25 km long, dip steeply to the west and have displacements up to 2-5 km (Moustafa and Abdeen, 1992; Sharp et al., 2000). The geological map of the Hammam Faraun fault block (Fig. 2) shows that this fault block has a half-graben geometry dipping moderately to the east, and it is up to 25 km wide and 40 km long.

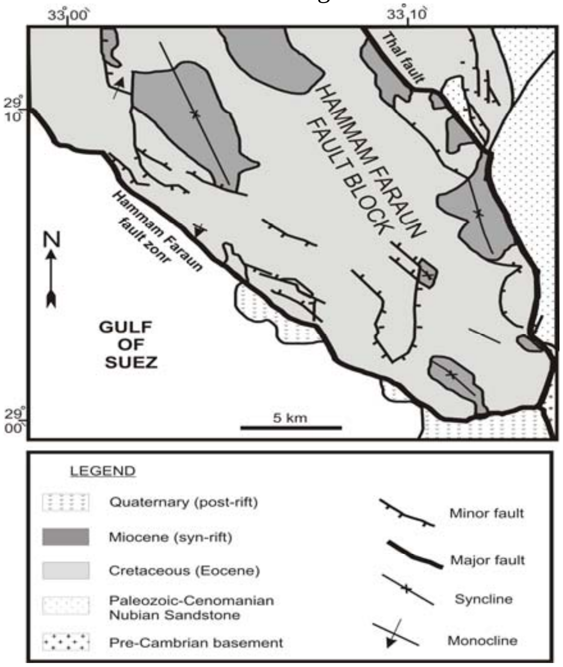

Figure 2: Geological map of Hammam Faraun area (after Moustafa and Abdeen, 1992; Sharp et al., 2000).

The shallow geological succession in the Hammam Faraun area is distinguished by sand, conglomerate, sandy limestone, lagoonal gypsum limestone, salty limestone and chalk with flinty limestone. This succession varies with age from post Pliocene, Pliocene, Miocene, Oligocene, Eocene and upper Cretaceous, respectively (Jackson et al., 2002). The Hammam Faraun hot spring (70°C) issues from faulted dolomitic Eocene limestone.

Chemical and isotopic analyses of the thermal water from the Hammam Faraun hot spring were conducted by Sturchio and Arehart (1996). The most abundant solutes in the Hammam Faraun water are Na and Cl, while Mg, Ca and SO_4 are also prominent. The pH values are near neutral, which indicates that the derivation of solutes is mainly from regional marine sedimentary rocks and windblown deposits (marine aerosol and evaporate dust). Additionally, the ratio of $^{3}He/^{4}He$ was recorded to be 0.256 times the atmospheric ratio (R_{atm}) in the gases emitted from the Hammam Faraun hot spring, whereas this ratio equals eight times R_{atm} in the mantle. Hence, this ratio indicates that there is an excess of He (3.2%) in the Hammam Faraun hot spring, which may be attributed to a deeper source of mantle (Sano et al., 1988). Sturchio and Arehart (1996) related mantle He to the alteration in the subsurface due to late Tertiary volcanic eruptions.

MAGNETOTELLURIC MEASUREMENT

MT data was measured from 16 stations along two profiles; one profile was parallel to the Gulf of Suez coast and the other profile was oriented northeast-southwest and as close as possible to the line perpendicular to the coast of the Gulf of Suez. The MT survey was performed using a Stratagem instrument with two frequencies: high (10 Hz to 100 kHz) and low (0.1 Hz to 1 kHz). In general, high frequency data are influenced by shallow or nearby features, whereas low frequency data are influenced by structures at greater depths. The distance between MT stations ranged from 500 m to 1000 m, depending on the suitable space for spreading the electrodes of the electric and magnetic fields.

The area of Hammam Faraun represents a part of the desert of the Sinai Peninsula that is characterized by low human activity and minimal human electric sources. This increases the accuracy of the acquired MT signals. Nevertheless, some of the noisier sites were excluded from the database. For preliminary data processing, MT data at different frequencies for the same MT site were merged. Then, these combined data were used to estimate the elements of the MT impedance tensor, which was finally used to determine the apparent resistivities and phases for both transverse electric (TE) and transverse magnetic (TM) modes.

One-dimensional inversion of MT data

1-D inversion of MT data was conducted using Bostick algorithm which represents one of the simplest ways to invert the MT data. This heuristic inversion scheme generates a near-continuous resistivity distribution versus depth (Bostick, 1977). For easy interpretation, sections were created using Bostick 1D model along each profile (Fig. 3). These sections elucidate the subsurface geological situation below the study area by correlating MT soundings with each other along each profile and hence illuminating the lateral change of resistivity along profiles. The agreement between the two sections is obvious and shows the high resistivity at moderately shallow depth below Hammam Faraun hot spring.

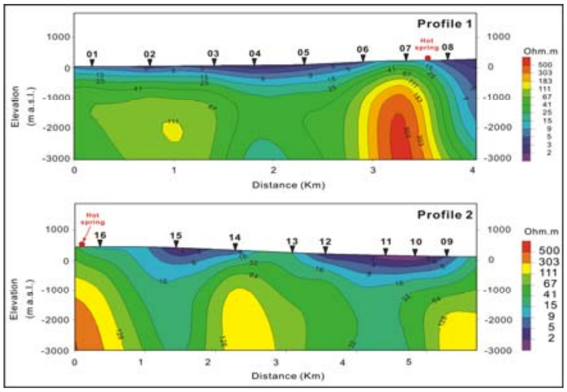

Figure 3: Cross sections of apparent resistivity versus depth using Bostick 1-D model for both profiles 1 and 2.

Two-dimensional of MT data

The MT data was also inverted with a 2-D smooth model inversion routine using the method of nonlinear conjugate gradients (see Rodi and Mackie, 2001). The forward model simulations were computed using finite difference equations, which were generated by network analogs to Maxwell's equations. Figure 4 shows the integration between 2-D inversion models along Profiles 1 and 2, which gave reasonable results for the subsurface structure of the study area.

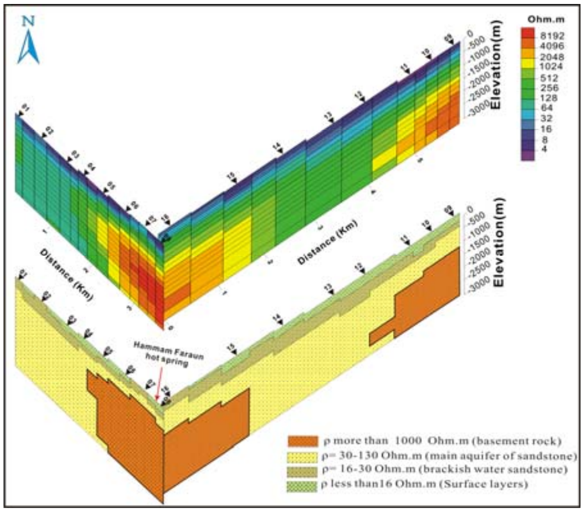

Figure 4: Correlation between 2-D models of profiles 1, 2 and their corresponding Interpreted conceptual sketch. The origin of Hammam Faraun hot spring is due to uplift of high resistive basement rock.

The inversion of the MT data showed the existence of a highly resistive body at a shallow depth below the Hammam Faraun hot spring, which demonstrated that, the origin of the Hammam Faraun hot spring is due to the uplifting of the hot plutonic basement rock. Furthermore, the 2-D models helped to delineate the subsurface reservoir that corresponds to the shallow conductive region (16-32 Ohm-m) above the high resistive region (> 1000 Ohm-m). The reservoir also extends deeper north and east of the hot spring.

CONCEPTUAL HYDROTHERMAL MODEL

A conceptual model of the hydrothermal system in the Hammam Faraun hot spring was proposed based on information extracted from the geological and geochemical backgrounds, as well as geophysical data. This information suggested that the source of the hot spring is due to the tectonic uplift of hotter rocks causing deep fluid circulation through faults on the surface of the basement rock (Fig. 5). Such faults allow the formation of discharging conduits for water ascending from depth after being heated and mixed with other water types.

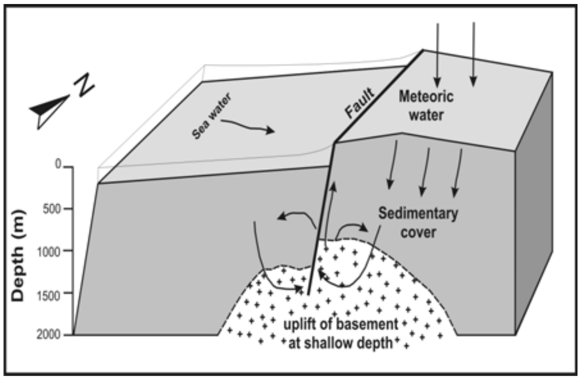

Figure 5: Schematic diagrams show the conceptual models of the hydrothermal system in the Hammam Faraun hot spring.

NUMERICAL SIMULATION

A 3-D finite difference model (HYDROTHERM, Version 2.2; Hayba and Ingebritsen, 1994) was used to simulate groundwater flow and heat transport in the porous medium below the hot springs. The model of Hammam Faraun covered 77 km^2 and was oriented in the N–S direction, extending 8.5 km in the east–west direction and 9.1 km in the north–south direction. The special discretization was rather coarse, with 31 grid blocks in the east–west direction (“i” index) and 43 blocks in the north–south direction (“j” index). Grid block dimensions varied between 100 m and 1000 m in the E–W and N–S directions, with the highest resolution applied near the Hammam Faraun hot spring. The model extended vertically from the ground surface (ranging from +0 m to +500 m above sea level “ASL”) to -2000 m ASL. A total of 16 layers (“k” index) were used. The thickness of the layers was assigned to be 100 m ASL and 200 m below sea level (Fig. 6). The uppermost grid blocks lying above the topography were considered to be “void.”

The subsurface strata were assumed to be four layers with different physical properties: alluvial deposits, limestone, sandstone and basement rock (mainly granite).

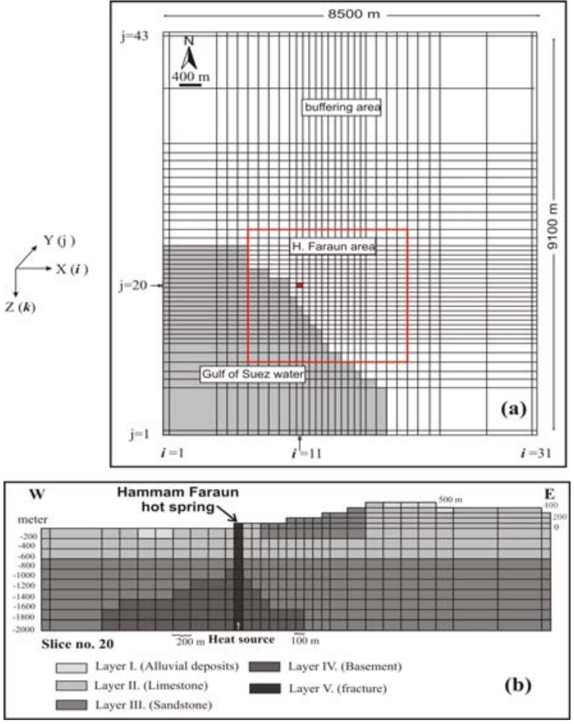

Figure 6: (a) Plain view of the finite difference blocks for the comprehensive hydrothermal model of the Hammam Faraun area. (b) The E–W section for slice j = 20.

In this study, isotropic permeabilities were assumed and rock properties other than permeability (i.e., porosity, thermal conductivity, specific heat and density) were used as the input data to the model. These properties are shown in Table 1 and were considered to be the main parameters for that area. Their values were determined by previous studies, such as El-Nouby and Ahmed (2007), Meneisy (1990) and Morgan et al. (1983, 1985).

	Density gm/cm^3	Porosity %	Permeability mdarcy	Thermal conductivity W/mk	Heat capacity J/kg.K
Layer 1	2.4	10	10^{-4}	2.4	920
Layer 2	2.5	5	10^{-3}	1.3	880
Layer 3	2.4	15	10^{-2}	2.7	920
Layer 4	2.67	1.5	10^{-5}	1.7	790
Fracture	1.5	30	10	0.5	1000
Heat source	Temperature (^{o}C)			Mass flow (kg/s)	
	180			60	

Table 1: Physical rock properties of each layer for the hydrothermal model.

To calculate the background temperature and pressure distribution of the study area, a steady-state (without intruding a heat source and fracture parameters) simulation was executed by fixing both pressure and temperature at the upper boundaries of the lithological units at 1.013 bars and 26.7^{o}C, respectively. The bottom was set as impermeable, with a constant heat flux of 120 mW/m^2 as a boundary condition constraint. Lateral boundaries were thermally insulated and impermeable. Thus, the output temperature and pressure distribution from the steady-state simulation were used as the initial conditions for the construction of the fracture-state model by adding a fracture zone and a heat source at the bottom of the numerical model. The fracture zone was assumed to be a simple porous medium with different hydraulic properties.

The most important factor in the success of geological modeling is estimating heat sources below hot springs. Chemical geothermometers are the most well-known method for inferring subsurface temperature, but the Hammam Faraun thermal water does not attain a water-rock chemical equilibrium, which indicates a partial equilibrium with the host rock and a possible mixing of different water types (Barragán et al., 2001). Consequently, it was difficult to use chemical geothermometers with a degree of confidence under these conditions. However, the emergence temperature at the Hammam Faraun hot spring is known to be 70^{o} C. Therefore, the model was completed by repeating simulations and inserting different values of temperature and mass flow of the heat source until the surface temperature reached this value (Fig. 7).

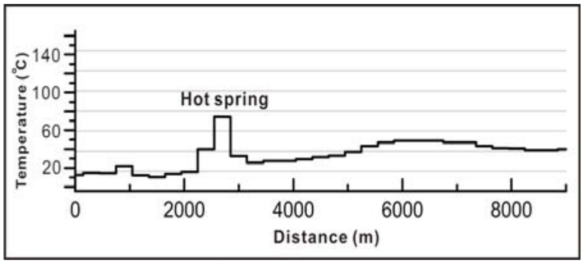

Figure 7: Near-surface temperature changes (slice j = 20). The calculated temperature equals 73^{o} C at the emergence of the hot spring.

The subsurface circulation of geothermal fluids through a granitic-fractured reservoir leads to chemical reactions, mineral dissolution and precipitation, affecting the fracture porosity and permeability and making the estimation of these values difficult. Hence, by applying different values for fracture permeability in the simulation model, we found that the fracture permeability must not be less than 10 mdarcy in order to reach the steady state. Figure 8 shows the distribution of temperatures with the depth of the Hammam Faraun region, based on the calculated temperatures from the numerical simulation. The temperature increases rapidly below the Hammam Faraun hot spring, reaching 170°C at depths less than 2 km.

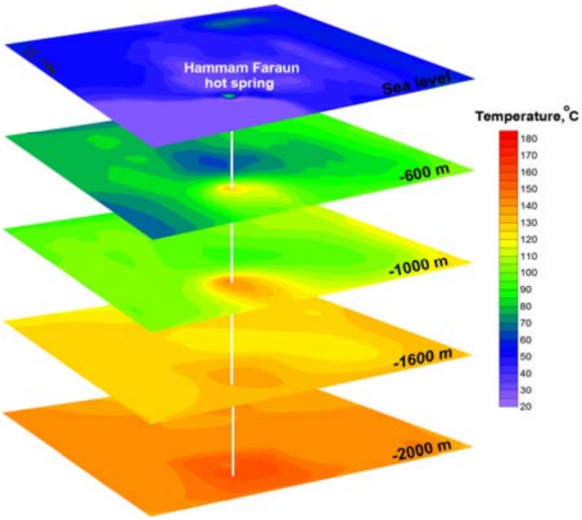

Figure 8: Temperature distribution across depths of the Hammam Faraun region calculated from the numerical simulation.

The numerical simulation succeeded in determining the characteristics of the heat sources beneath the Hammam Faraun hot spring and showed that the origin of the hot spring is due to high heat flow and deep ground water circulation controlled by faults in the subsurface reservoir. The water velocity increased below the hot spring and flowed upward through fractures and faults (Fig. 9). The calculated time for the steady-state simulation was up to 100,000 years and up to 30,000 years for the next simulation (by intruding a heat source at the bottom of the numerical model). Thus, the temperature and pressure distributions in the model did not change significantly with time. At each block of the model, they were assumed to represent natural-state (pre-exploitation) conditions in the hot springs.

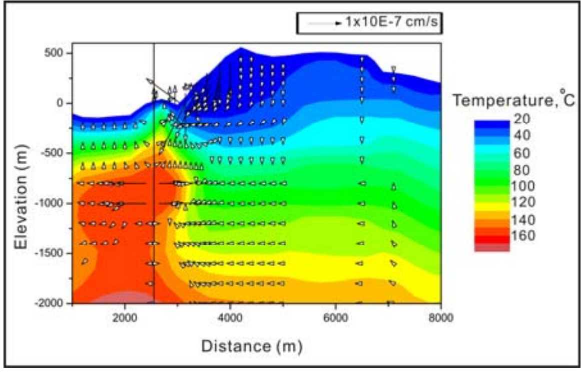

Figure 9: East-West temperature distribution and water velocity pattern of the Hammam Faraun hot spring at a natural state, (slice j = 20).

GEOTHERMAL POTENTIAL ASSESSMENT

The volumetric method is convenient to apply to the first stage of an estimation of the stored heat and recoverable thermal energy. Using the temperature versus depth information obtained from the temperature gradient map of the Gulf of Suez, the amount of stored thermal energy for a given location could easily be determined. This stored heat value is multiplied by a coefficient called the recovery factor to estimate the useful heat that can be extracted for the above rock volume.

The value of the estimated geothermal potential for the Hammam Faraun hot spring area was 19.8 MW for an assumed reservoir thickness of 500 m. With the same thickness, the initial temperature was 130oC and the performance of the reservoir was assessed for 30 years of production. Additionally, the geothermal reservoir was assumed to contain hot solid rock and single-phase liquid water.

This geothermal resource is typically used for direct-use applications, such as district heating, greenhouses, fisheries, mineral recovery, and industrial process heating. However, a low-enthalpy resource can be harnessed to generate electricity using conventional binary cycle electricity-generating technology. In binary power plants, a heat exchanger is used to transfer energy from the geothermally heated fluid to a secondary fluid that has a lower boiling point and higher vapor pressure than steam at the same temperature. The working fluid is vaporized as it passes through the heat exchanger, and then expanded through a turbine to generate electricity. It is then cooled and condensed to begin the cycle again. The resulting power electricity would be enough for the desalination of water for human and agricultural consumption. This could be used for sustainable development in the Sinai Peninsula.

CONCLUSION

The processing and analyses of the MT data acquired from the Hammam Faraun region permitted us to characterize the subsurface electric structure of the area. The 1-D and 2-D inversion results of the MT data revealed the existence of a high resistivity body at shallow depths (> 1000 m) below the Hammam Faraun hot spring. Therefore, our results could be used to determine the origin of this hot spring, where the highly resistive region reflects the basement structure. Conceptual modeling and numerical simulations of the Hammam Faraun hot spring showed that the origin of the hot spring is derived from high heat flow and deep circulation of the underground water controlled by faults that may be associated with the opening of the Red Sea and Gulf of Suez rifts. The uplifted basement is the site of the high heat flow. The value of the estimated potential for electric generation was 19.8 MW. This value would be enough for the desalination of water for human and agricultural consumption and can thereby be used for sustainable development in Sinai Peninsula.

ACKNOWLEDGMENT

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