

## Joint Inversion of VES and TEM Data for Investigation of Geothermal Resources and Sea Water Intrusion at Hammam Mousa Hot Spring, Sinai, Egypt

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### ABSTRACT

In this work, DC resistivity and transient electromagnetic surveys were conducted at Hammam Mousa area, Sinai, Egypt to explore the geothermal resources, groundwater aquifer and the effect of sea water invasion on this aquifer. The field survey comprises 19 DC resistivity soundings (VESes) with AB/2 up to 1000 m and 27 transient electromagnetic (TEM) stations using a square loop of 25 m side length. Both data sets were firstly inverted in 1-D scheme using a nonlinear least-squares method and gave a layered-earth resistivity model. Moreover, the joint interpretation of both VES and TEM data, using the available geological information as a constraining factor, successfully enhanced the inversion results. The geoelectrical cross sections obtained from the inversion process show the effect of the Suez Gulf water intrusion in the western part of the study area, the resistivity values go below 10 Ohm.m. Meanwhile, hot water reduces the resistivity values drastically near the hot spring leading to measurements of less than 3 Ohm.m.

### 1. INTRODUCTION

Geophysics, mainly geoelectrical methods are frequently employed in exploration for geothermal resources. Geoelectrical methods, in particular, have been employed in the study of most geothermal fields. Reviews as well as some characteristic examples are discussed by Thanassoulas (1991).

Sinai Peninsula is considered as a bridge and barrier between the Asian and African Continents. Recently, new projects to settle the Bedouin have begun, and the development is transforming several coastal areas. Tectonically, the Sinai area is considered as an unstable shelf due to frequent earthquake activity and its geologic setting, which is controlled by tectonic activity at the Red Sea, Gulf of Suez, and Gulf of Aqaba (Said, 1962). This tectonic activity has been accompanied by thermal activity represented by a cluster of thermal surface manifestations along the eastern shore of the Gulf of Suez. Among these thermal manifestations, Hammam Mousa (Moses's Bath) is representing one of the best known hot springs along the Gulf of Suez, located at El-Tor City, the capital of South Sinai (Figure 1).

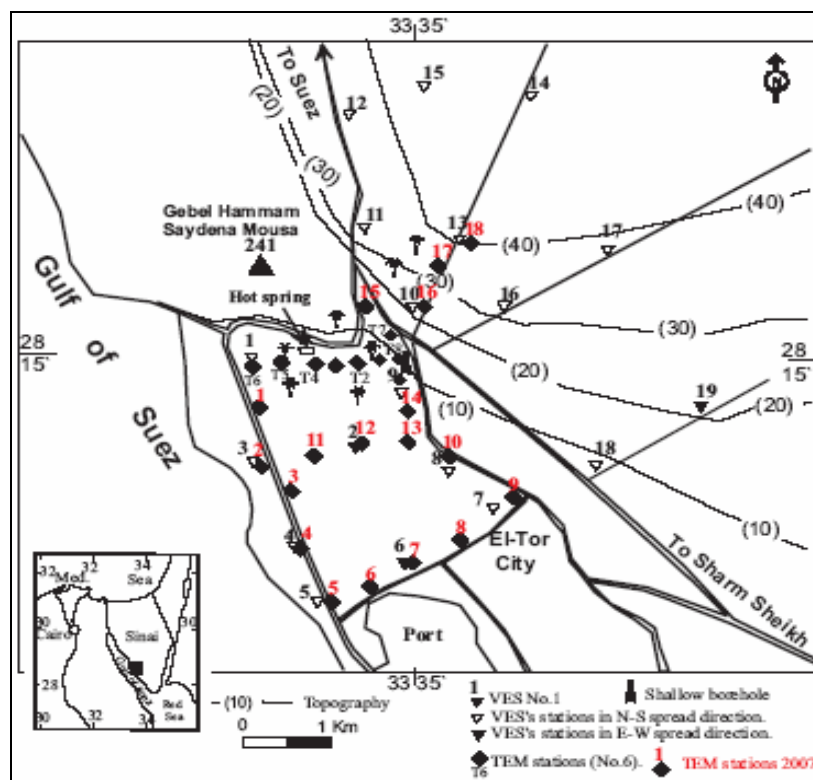
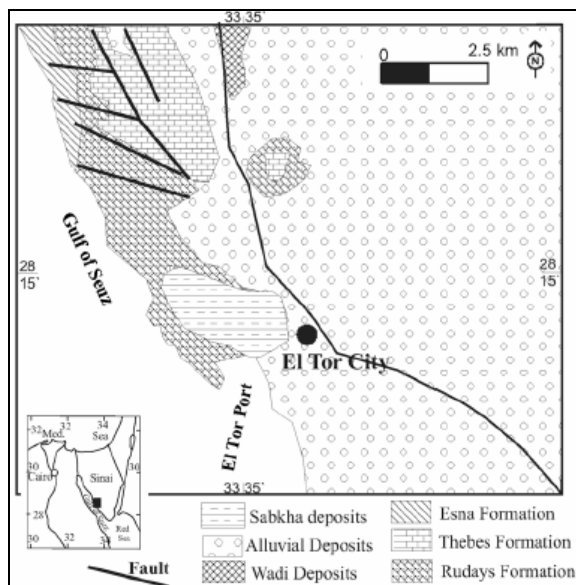


Figure 1: Location map of the study area and its surroundings showing locations of VES-TEM stations (Topographic contours are measured in meters).

Consequently, the main goal of this study is to investigate the geothermal prospect and groundwater aquifer at the Hammam Mousa hot spring, as well as, the effect of sea water invasion on this aquifer using a joint geoelectrical resistivity and TEM survey.

## 2. GEOLOGIC CONTEXT

The Hammam Mousa area is located on the eastern shoreline of the Gulf of Suez (Figure 1). The surface area near the hot spring is composed of sabkha deposits. Far to the east, alluvial deposits dominate and occupy the surface of the El-Qaa plain (Figure 2). The subsurface geologic section is represented by Cretaceous (Campanian to Cenomanian) up to Miocene rocks (Said, 1962).



**Figure 2: Geologic map of the study area and its surroundings (modified after Geological Survey of Egypt 1994).**

During the Early Cretaceous, the study area was a shallow sea, where Nubian sandy facies are represented. These sediments are overlain by Cenomanian beds, which are brownish and varicolored marls, with a clastic content of sand and shale (Kostandi, 1959; Said, 1961). Above the Cenomanian beds, the lower Turonian beds; represented by Rudaeis Formation of soft marl and shale rest (Beadnell, 1927), the Lower Eocene beds of limestone with flint and marls of Thebes Formation rest unconformably above the Rudaeis Formation. This is followed by the laminated green and grey shale of Esna Formation of the Upper Paleocene (Said, 1962). At the top, the Quaternary clastic sediments of gravel, sand, clay and silt are represented by El-Tor Group. During the early Tertiary (Oligocene to Miocene), at the opening of the Red Sea Rift, some volcanic activities took place. In the western and central Sinai, there are many basaltic bodies mostly represented in the form of doleritic dikes, sills, plugs, and flows (Meneisy, 1990). Also, the great synclinal area of the El-Qaa Plain that lies to the east of the study area belongs to this episode of deformation. The major structural features are well defined NNW trending fault blocks, which tilt strongly eastward on their west side (Said, 1962).

## 3. GEOTHERMAL CONTEXT

At a distance of 100 km from Sharm El-Sheikh, Moses's Bath (Hammam Mousa) is just 3 km from the centre of El Tor City. Basically, it has five springs categorized into two

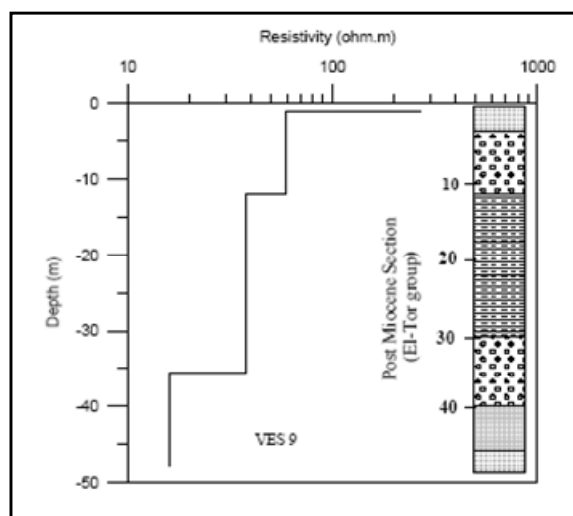
groups. The first group issues into a bathhouse with a temperature of 33°C, and the second, nearby, flows into a trench with a temperature of 31°C. For a long time, the springs' water has been considered highly effective in treating skin diseases and healing wounds especially resulting from diabetes. Additionally, it helps in reducing tension and increasing relaxation; so it has been used for tourist purposes for many years.

Compositionally, Hammam Mousa thermal waters seem to be Tiberias–Faraun waters (Mazor et al 1973) that dissolved additional salts from the Neogene rocks, being enriched in  $\text{SO}_4$  and  $\text{HCO}_3$  along with Mg and Ca. The relative amount of the dissolved ions in the water of the two spring groups are almost identical, the bathhouse springs being a little saltier. Detailed geochemical analysis is cited at Sturchio et al. 1996 and Boulos, 1990, and not repeated here since it is not the main goal of this work. The heat source 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. The spring's water is presumably a mixture of brine and water contained in the Nubian sandstone aquifer that infiltrated outcrops on the highland of Sinai and emerged along the fault lines bordering the Sinai Peninsula. However, the springs issue from Neogene rocks (Magaritz and Issar 1973).

## 4. GEOPHYSICAL EXPLORATION

The geophysical survey described in this work was carried out by DC resistivity and transient electromagnetic (TEM) soundings. The DC resistivity data was collected using a Schlumberger array. Nineteen VES stations were measured, (Figure 1) using electrode spacing starting from  $AB/2 = 2$  up to 1000 m, in successive steps. The electromagnetic survey comprises twenty seven TEM stations measured in two stages during 2006 and 2007 using a Sirotem MK3 conductivity meter, with the single loop configuration, where 25 and 50 m loop side lengths were used.

The DC soundings curves exhibit relatively high apparent values at the shallow parts compared to the deeper parts. Relatively low resistivity values characterize the central and southwestern parts of the study area. The resistivity field curves of all the stations have been inverted one dimensionally (Zohdy, 1989). Figure 3 shows an example of 1-D models and its correlation with the lithology of a nearby shallow log.



**Figure 3: Correlation of Inverted 1-D model of VES 9 with the borehole information.**

The TEM data have been inverted in a 1-D scheme by the Temixl 4 (2002) software, where the VES data models were used as initial models for the TEM data inversion. Figure 4 shows a selected example for the TEM data inversion at station No. 6. As shown the fit between observed and calculated data is generally good. In this example, a thick conductive zone is clearly defined and its boundaries are concordant with the alterations of resistivity-depth transformation which could be very useful for getting a starting model if there is no a priori information. The distinction between the clay layer and the water bearing formation could be delineated. This is attributed to the high sensitivity of the TEM method for detecting conductive zones.

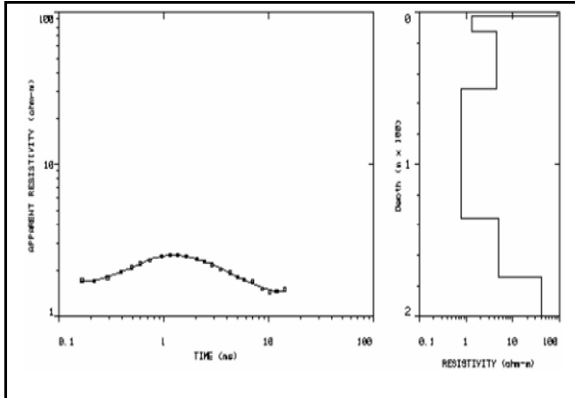


Figure 4: Interpretation of TEM station No. 6.

#### 4.1. Joint Inversion

Joint inversion or multi-objective optimization means the simultaneous minimization (or maximization) of several objective functions. These types of problems occur in many areas such as economics, engineering and physics. In geophysics joint inversion usually means finding a model that explains several data sets at once. Numerous studies have shown that, the joint inversion of galvanic and inductive data, where a single model satisfies both data sets, will generally enhance the resolution of the subsurface resistivity distribution (Jupp and Vozoff, 1975; Sandberg, 1993 and Raiche et al., 1985). Thus, joining of these data sets must be expected to reduce problems with layer suppression, reduce the low resistivity equivalence, and drastically reduce the high resistivity equivalence otherwise encountered with a single method.

The electrical resistivity and TEM methods are well known in exploration geophysics (Telford et al., 1995 and Nabighian and Macnae, 1991). The methods are complementary in many ways making them ideal partners for combined inversion process. Although both methods measure electrical conductivity or resistivity of the subsurface, they sample different volumes and have different sensitivities. TEM, an inductive technique, has an area of investigation that is a function of the descending and expanding image of the transmitted current. The resistivity method is a galvanic technique that samples a more linear portion of the ground as defined by the area of current flow.

In an attempt to attain an unambiguous discussion of the results in the present work, a joint interpretation has been applied to the measured data. This cooperative process generally implies that the two related data sets are used in the same objective function and one model is produced through the optimization process. This is based on the concept that, each data set has a priority to constrain the

inversion process at a specific part of the model. This procedure has improved the results of the inversion process and overcomes the problems of the equivalence and layer suppression, and hence allowed us to arrive to more reasonable and accurate models.

#### 5. CONCLUSIONS AND RECOMMENDATION

The present work aimed to delineate and elucidate the geothermal reservoir at Hammam Mousa hot spring. To achieve this purpose a joint 1-D interpretation for Dc VES and TEM soundings had been conducted. It is clear that there is a huge thick, high conductive layer at a depth ranging from 40 m to 125 m. That can be attributed to the effect of geothermal water circulation or seawater intrusion in this part.

According to the interpretation of this data set (Figure 5), a promising area for geothermal drilling is recommended, around the hot spring and its neighborhood, where there is a considerable aquifer thickness. Although the 1-D interpretation has proved feasible and reliable in many practical cases, significant inaccuracies may occur when true geological structure is essentially multidimensional. In this case, multidimensional inversion schemes would be more useful. The true resistivity distribution in the study area at depths from 70 to 100 m (Figure 6) shows that very low resistivity values (5-3 ohm.m) are associated with the hot spring and probably the geothermal prospect. To the south west of the map, there are very low resistivity values that can be associated with the sea water intrusion from the Gulf of Suez.

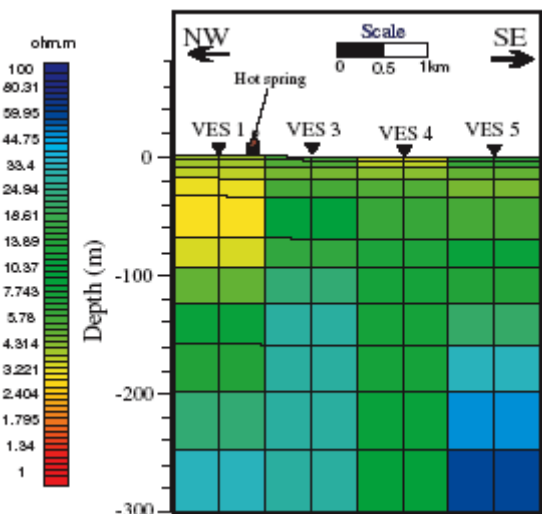


Figure 5: The geoelectrical cross section along profile 1.

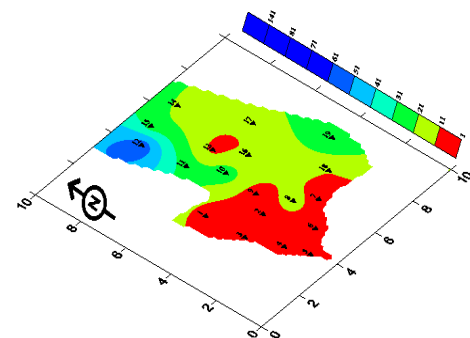


Figure 6: The true resistivity distribution at depth ranges from 70 – 100 m at the study area.

We hope future work will enable us to collect data (3-D survey) for a 3-D modeling scheme. In addition, a detailed geophysical survey is recommended using different geophysical tools with deeper investigation depth such as magnetotelluric. These methods can be used effectively for monitoring and mapping of the seawater invasion to this promising coastal area.

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