NRIAG Journal of Astronomy and Geophysics (2014) 3, 184–191

National Research Institute of Astronomy and Geophysics

NRIAG Journal of Astronomy and Geophysics

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REVIEW ARTICLE

Water exploration using Magnetotelluric and gravity data analysis; Wadi Nisah, Riyadh, Saudi Arabia

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Received 14 November 2013; revised 26 August 2014; accepted 8 September 2014
Available online 11 November 2014

KEYWORDS

Wadi Nisah;
Magnetotelluric;
Gravity;
Water exploration;
Saudi Arabia

Abstract Saudi Arabia is a desert country with no permanent rivers or lakes and very little rainfall. Ground water aquifers are the major source of water in Saudi Arabia. In the Riyadh region, several Wadies including Wadi Nisah store about 14×10^6 m^3 of water, which is extracted for local irrigation purposes. In such areas, the water wells are as shallow as 200–300 m in depth. The importance of Wadi Nisah is because the subsurface water aquifers that are present there could support the region for many years as a water resource. Accordingly, in this study, we performed a Magnetotelluric survey using a portable broadband sounding system (MT24/LF) to evaluate the ground water aquifer at great depths. We collected 10 broadband Magnetotelluric sounding stations (1 station/day) with an interval of about 2–3 km reaching a profile length of about 25–30 km along Wadi Nisah. Additionally, we used available gravity data to image the subsurface structure containing the aquifer.

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Peer review under responsibility of National Research Institute of Astronomy and Geophysics.

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http://dx.doi.org/10.1016/j.nrjag.2014.09.002

MT results indicated a low resistivity layer, associated with alluvium deposits, which was defined at a depth of about 1–2 km and extended horizontally about 15 km. Gravity data analysis was used to model this resistivity layer indicating a basement surface at 3–4 km depth.

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1. Introduction

Wadi Nisah (Valley of Nisah) is one of the largest/most important Wadies in the city of Riyadh, Saudi Arabia due to its promising subsurface water aquifer. It feeds number of sub-Wadies to the east and north (Ibrahim, 2012; Abo El-kheer, 1985). Thus, Wadi Nisah is a suitable place for agricultural development due to the large rainwater recharge. However, the structure and character of the Wadi is not well known.

Our study area is located in Wadi Nisah, south–west of Riyadh city as shown in Fig. 1. On the borders of Wadi Nisah, on the east, is the Al Kharj Basin and, on the west, is Gebel Tuwaiqu. Wadi Nisah has an area of about 169 km^2 and a length of more than 70 km. Most of all previous researches for Wadi Nisah were looking for shallow water (250–500 m depth). In this study, it is considered the first work which looks for water at depths more than 1 km.

We carried out a Magnetotelluric (MT) survey at Wadi Nisah to evaluate deeper sources of groundwater using a portable electromagnetic broadband receiver, the MT24/LF. Ten MT stations were acquired along Wadi Nisah using an interval of 2–3 km between stations. Duration of the measurements was 20–24 h in order to achieve a greater depth of exploration. MT data was processed using Egbert and Booker (1986) Cascade Decimation and Robust processing tools.

The available gravity data from Arabian Geophysical and Survey Company (ARGAS, 1976) was used as east–west profile coincident with the MT profile location in order to model/estimate the depth to the basement and integrate the results.

GTZ (2011) conducted a geophysical survey as a joint project with King Abdulaziz City for Science and Technology (KACST) for water exploration at Wadi Nisah area. The objective of this study is explicitly to investigate aquifer depth in Wadi Nisah using high-resolution seismic reflection method. Seismic data interpretation revealed that an aquifer layer does exist and varies generally between 100 m and 240 m in an area east of the study area.

Results of MT survey indicated that, a low resistivity zone was detected at depth of about 1–2 km and extended laterally for about 15 km. This layer has a resistivity value of $> 16\ \Omega$ m which could be a water saturated layer. Shallower layer is located at depth of 1–1.5 km with resistivity value of $< 3\ \Omega$ m indicating an aquifer.

1.1. Geologic setting

Wadi Nisah is underlain by Phanerozoic sedimentary rocks of the western edge of the Arabian platform, which rests on Proterozoic basement at depths estimated between 5 and 8 km (Phoenix Corporation, 1985). The Phanerozoic succession is unconformably overlain in much of the area by Late Tertiary to Quaternary Eolian, fluviatile, and (lacustrine) depression deposits. The Phanerozoic outcrop succession is in a gently dipping homocline, and has been assigned to lithological formations ranging in age from Mesozoic to Cenozoic. Wadi Nisah is considered as a graben system (Fig. 2) that follows large faults crossing the Tuwaiq mountain chain in the east–west direction. It opens into the basin of Al Kharj. It is considered as a part of the central Arabian graben and trough system (Powers et al., 1966). The east west trending Nisah graben is about 90 km long and 2–8 km wide (Powers et al., 1966; Vaslet et al., 1991). The graben formation may have occurred in Plio-Quaternary time (Weijermars, 1998). Previous geological investigations by Wolfart (1961) and Sogrea (1968) have revealed that complex geological formations which outcrop within the Wadi Nisah drainage basin are mainly limestone and of marine origin. These formations were belonging to the geologic periods of Jurassic and early Cretaceous.

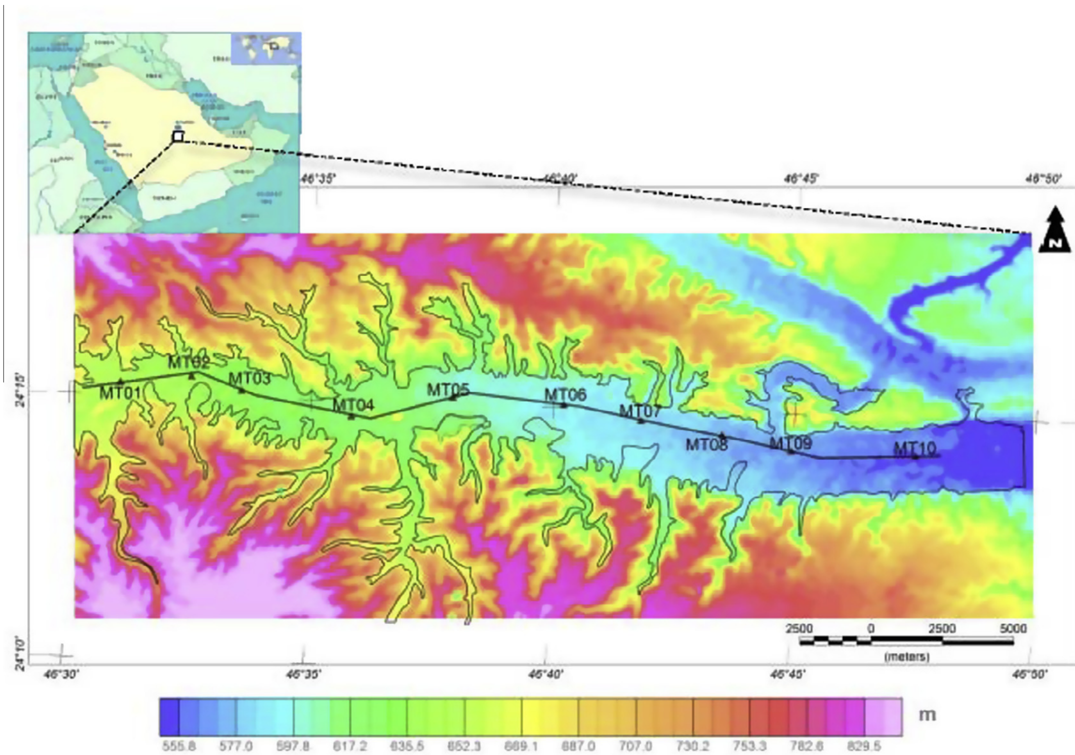

Figure 1 Location of Wadi Nisah area, Riyadh province, Saudi Arabia. MT stations (from MT01 to MT10) are plotted along Wadi Nisah as well as East–west gravity profile (solid black line). Background image is the DEM data for the study area.

1.2. The Magnetotelluric method (MT)

The Magnetotelluric (MT) method is a passive surface geophysical technique that uses the Earth's natural electromagnetic fields to investigate the electrical resistivity structure of the subsurface from shallow depths, tens of meters, to deep depths, tens of kilometers (Vozoff, 1991). Natural variations of Earth's magnetic and electric fields are measured and recorded simultaneously at each MT station. Worldwide lightning activity at frequencies of about 1–20,000 Hz and geomagnetic micro-pulsations at frequencies of about 0.0001–1 Hz provide majority of the signal sensed by MT method (Garcia and Jones, 2002; McPherron, 2005).

The observed MT data are often transformed to the frequency domain, and the electric field, E, and the magnetic field, H, are linearly related with each other,

$$\begin{bmatrix} Ex \\ Ey \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix} \quad (1)$$

Z is the Magnetotelluric impedance tensor, and it is generally complex due to phase differences between the electric and magnetic fields. The components of this impedance tensor are used for calculating the apparent resistivity functions along two orthogonal axes, calculated according to the following relations:

$$\rho_{xy} = \frac{1}{\omega\mu_0}[Z_{xy}]^2, \quad (2)$$

$$\rho_{yx} = \frac{1}{\omega\mu_0}[Z_{yx}]^2, \quad (3)$$

The phases of the impedance tensor are defined as the phase angle between E and H, and are given by:

$$\varphi_{xy=tan^{-1}}[Z_{xy}(\omega)], \quad (4)$$

$$\varphi_{yx=tan^{-1}}[Z_{yx}(\omega)], \quad (5)$$

where ω is the angular frequency and μ is the magnetic permeability of the vacuum. For the one-dimensional case where the geological structure varies with depth only (horizontally layered medium), $Z_{xx} = Z_{yy} = 0$ and $Z_{xy} = -Z_{yx}$. The orthogonal horizontal electric field components (Ex and Ey), magnetic field components (H_x and H_y), and the vertical magnetic field component (H_z) were recorded during the MT survey. The MT response curves (phase and apparent resistivities) are calculated from the measured fields at various frequencies for each site recorded. As lower frequencies penetrate deeper through resistive materials, an estimate of conductivity variation with depth can be made from the response curves beneath each site. The MT skin depth (depth of penetration, investigation depth) from the measured above components can be estimated by:

$$d = 503(\rho\ T)^{1/2} \quad (6)$$

where d is the depth in meter, ρ is the resistivity value (Ω m) and T is the time in seconds (Cagniard, 1953).

In the Wadi Nisah area, since we are looking for mapping the subsurface water aquifer, MT sounding stations were located along Wadi Nisah (typically TE mode) for mapping/reconnaissance mode. Each sounding was individually processed and inverted (1D) in order to estimate the promised water aquifer. Finally, cross section was produced from all

Table 1 Details of MT stations along Wadi Nisah.

Station	Longitude	Latitude	Elevation (m)
MT01	46.5174	24.25359	639.95
MT02	46.5417	24.25604	637.99
MT03	46.5592	24.25206	632.94
MT04	46.5972	24.24500	620.98
MT05	46.6319	24.25195	607.03
MT06	46.6703	24.25062	589.60
MT07	46.6970	24.24640	582.16
MT08	46.7250	24.24262	574.22
MT09	46.7491	24.23827	570.08
MT10	46.7919	24.23764	551.02

stations in one profile. MT method is well suited for studying complicated geological environments because the electric and magnetic field transfer functions are sensitive to vertical and horizontal variations in resistivity. The method is capable of establishing whether the electromagnetic fields are responding to subsurface rock bodies of effectively one, two, or three dimensions. In the present research, we will focus only on 1D processing and interpretation where the acquisition was parallel to the geologic strike. More details about MT method and references for a more advanced understanding are in Kaufman and Keller (1981), Dobrin and Savit (1988), Vozoff (1991), and Chave and Jones (2012).

2. The Wadi Nisah Magnetotelluric survey

MT survey in Wadi Nisah was conducted in two stages. The first survey was in May, 2012 and the second one in January, 2013. We recorded 18 broadband MT soundings using the MT24/LF, a 24-bit MT receiver. Some of these stations were very noisy due to nearby water extraction wells, strong winds (e.g. for the vertical magnetic component), and some disturbances by animals grazing in Wadi. Between the two surveys, we selected the best ten MT stations along Wadi for further analysis (Table 1). During the surveys, low frequency (LF) and high frequency (HF) signals were acquired. This resulted in a profile length of about 25–30 km with a station spacing interval of about 2–3 km (Fig. 1).

The electric field components were measured as a voltage between pairs of Copper–Copper Sulfate (Cu–$CuSO_4$) electrodes placed 50–70 m apart and the magnetic field was recorded using EMI induction coil magnetometers with μ-metal cores (BF-4) which has low noise preamplifier.

MT data were recorded in the frequency range 0.001–50 Hz using the MT24/LF broadband system. Time series data were displayed and filtered using ACQ24, processing software from EMI (1999). The combination of a high accuracy 24-bit digitizer and GPS positioning allows the MT24/LF system to be effective in areas as Wadi Nisah. Low and high frequency time series data were edited using ACQ24 tools, and cross-power files were created using Egbert and Booker (1986) robust analysis technique. The later technique sequences as (1) outliers cleaning with median and median absolute filter, (2) Cascade decimation, (3) data selection based on minimum and maximum acceptable B-field energies and (4) band and section averaging of spectra using regression M-estimate.

Note that while apparent resistivities can be distorted by near-surface resistivity inhomogeneities causing what is known as "static shifts" in the data (Sternberg et al., 1988; Pellerin and Hohmann, 1990), we were not able to apply static shift correction to the data where just one MT24/LF unit was available and no other tools (e.g. TEM or AMT).

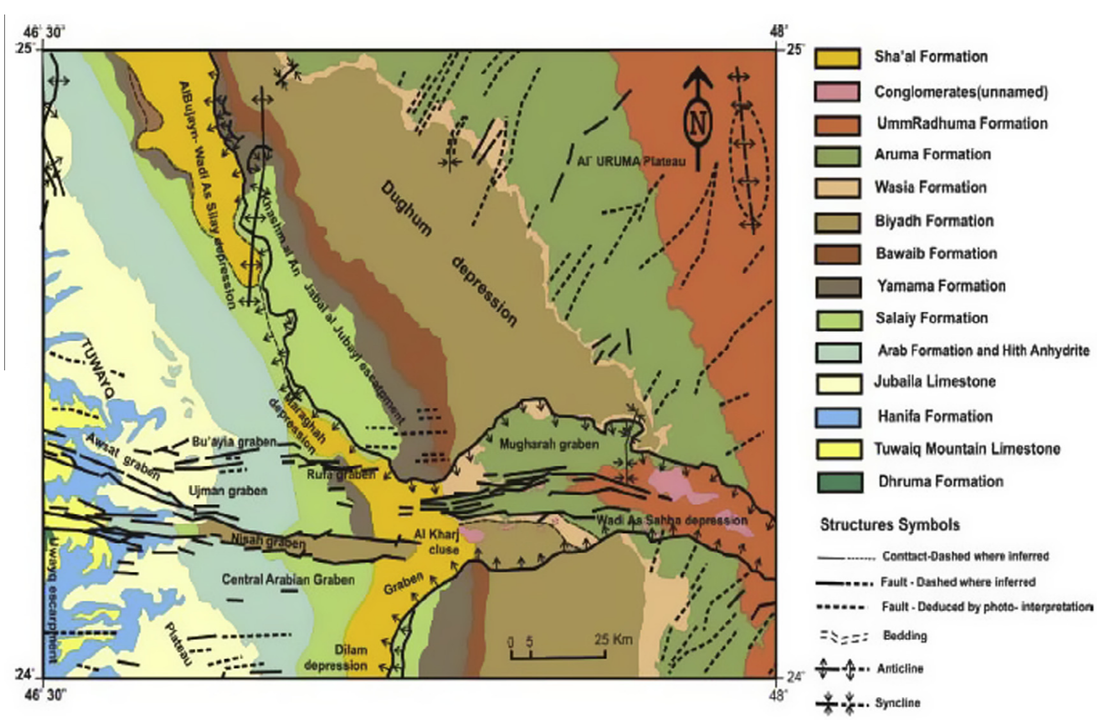

Figure 2 Geological map of Riyadh region showing the main east west graben structure of Wadi Nisah (black rectangle) and major structural blocks in the study area (adapted after Vaslet et al., 1991).

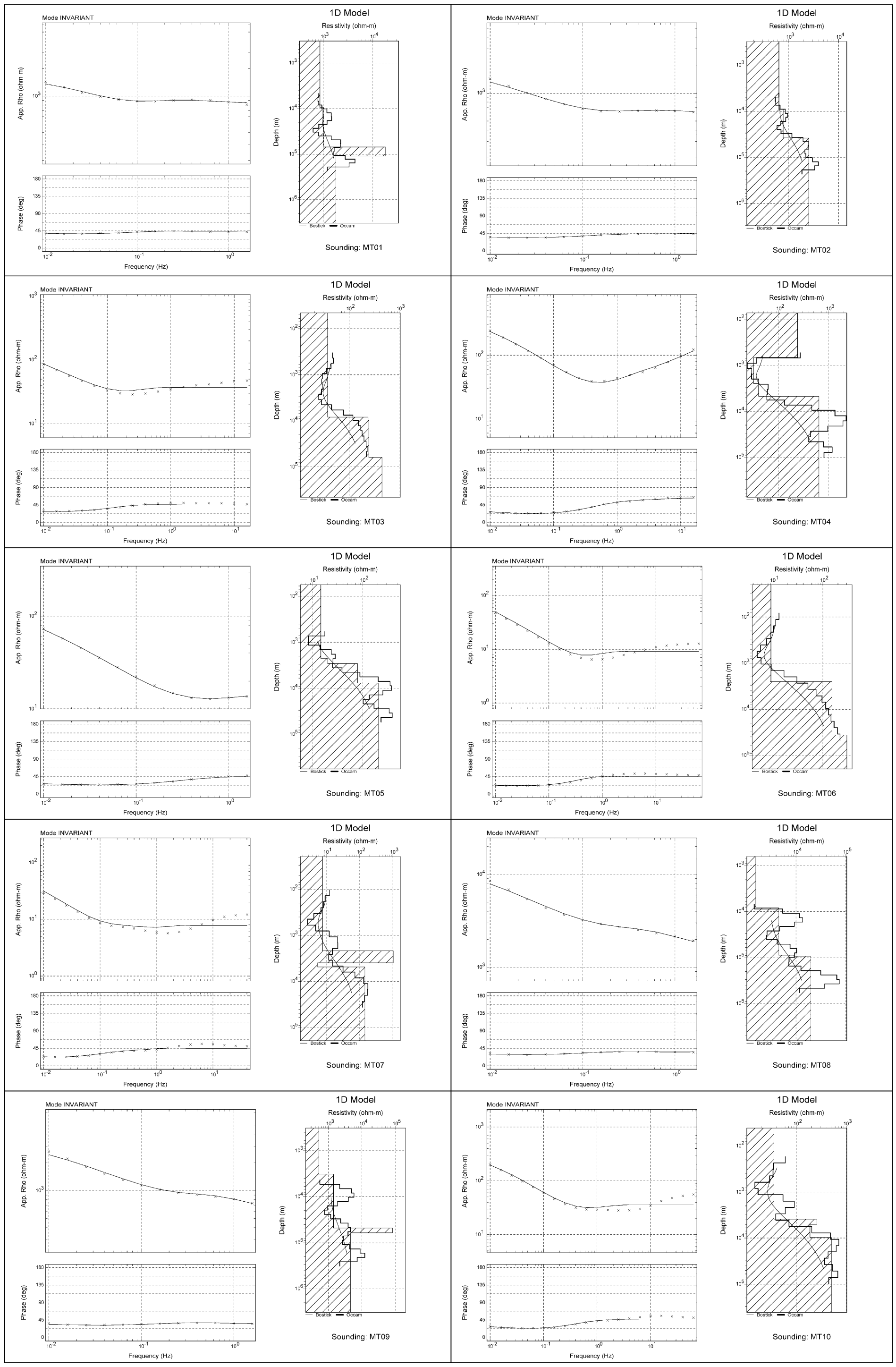

Figure 3 1-dimentional inversion of the MT soundings using invariant mode.

3. MT data corrections

The recorded time-series data were transformed to frequency domain and processed to determine apparent resistivity and phase tensor at each site. MT time series data were inspected visually by displaying the five MT components (E_x, E_y, H_x, H_y, and H_z) for each station in order to remove the noisy segments (e.g. spikes, power line effect,...etc). The best time series segments were selected and combined into the final plots. The results of the MT survey show a single complete data profile consisting of 10 MT soundings. Typically, when static shifts are evident in MT data, DC or TEM data are acquired to provide independent measures of the electrical section. Jones and Dumas (1993) have used a correction procedure based on the assumption that the low frequency MT responses show only smooth spatial variations. Under the assumption of a laterally uniform deep structure, they have shifted the TE apparent resistivities to the averaged low frequency value at all stations.

3.1. 1-D inversion of MT data

One dimensional inversion of MT data was carried out using the invariant curves of resistivity and phase where the invariant resistivity is calculated as the geometric mean of ρ_{xy} and ρ_{yx} while the invariant phase is calculated as the arithmetic mean of the two. The results of the 1-D inversion are displayed in Fig. 3. The inversion was conducted using two types of algorithms; Bostick and Occam (Bostick, 1977). Bostick transformation represents one of the simplest ways to invert the MT data. This inversion scheme generates a near-continuous resistivity distribution versus depth. On the other hand, Occam inversion automatically produces modes with maximally smooth resistivity structure. Occam algorithm leads to a simple model containing the essential properties of all possible models fitting the MT data (Constable et al., 1987). D+ smoothing technique was used to smooth the resistivity and phase curves; this technique relates the apparent resistivity and phase to the same component through D+ function (Beamish and Travassos, 1992). The inversion results indicated that there is a low resistive layer at depth 1–2 km which could represent the water aquifer in the area (e.g. MT06). For example, MT03, MT04, MT05, MT06, and MT10 showed resistivity values as 30–50 Ω m reaching depth of 1–2 km. These results were used to build up resistivity cross section along the main profile using both Occam and Bostick methods (Figs. 4 and 5) representing the variations in resistivity with depth.

3.2. Data interpretation

MT soundings were initially modeled using (1) Occam layer model (Fig. 4) and (2) Bostick layer model (Fig. 5) in order to estimate the vertical resistivity distribution within depth. Each 1-D resistivity model either Occam or Bostick is constructed by adjusting the resistivity values beneath the profile of MT stations.

Occam layer model (Fig. 4) which shows a low resistivity zone was located at the study area. This zone is thinner at western portion of the profile and thicker when going to the eastern portion. Bostick layer model (Fig. 5) shows that between MT04 and MT09, a very low and shallow resistivity layer exists. It can be recognized that, Bostick and Occam layer models have some differences suggesting that Occam is more sensitive to small variations in resistivity with frequency and Bostick being less sensitive.

4. Results and discussions

Gravity data from ARGAS (1976) were used for 2D modeling in order to estimate the depth to the low resistivity layer. Forward modeling involves creating a hypothetical geologic model and calculating the geophysical response to that earth model. Because the gravity calculations are non-linear, gravity model is not unique; i.e. several earth models can produce the same gravity response. Because of this non-uniqueness, and because the process is non-linear, the results or solutions depend on the starting model. The better the starting model, the better the results. For that reason, we traced the depth to the low

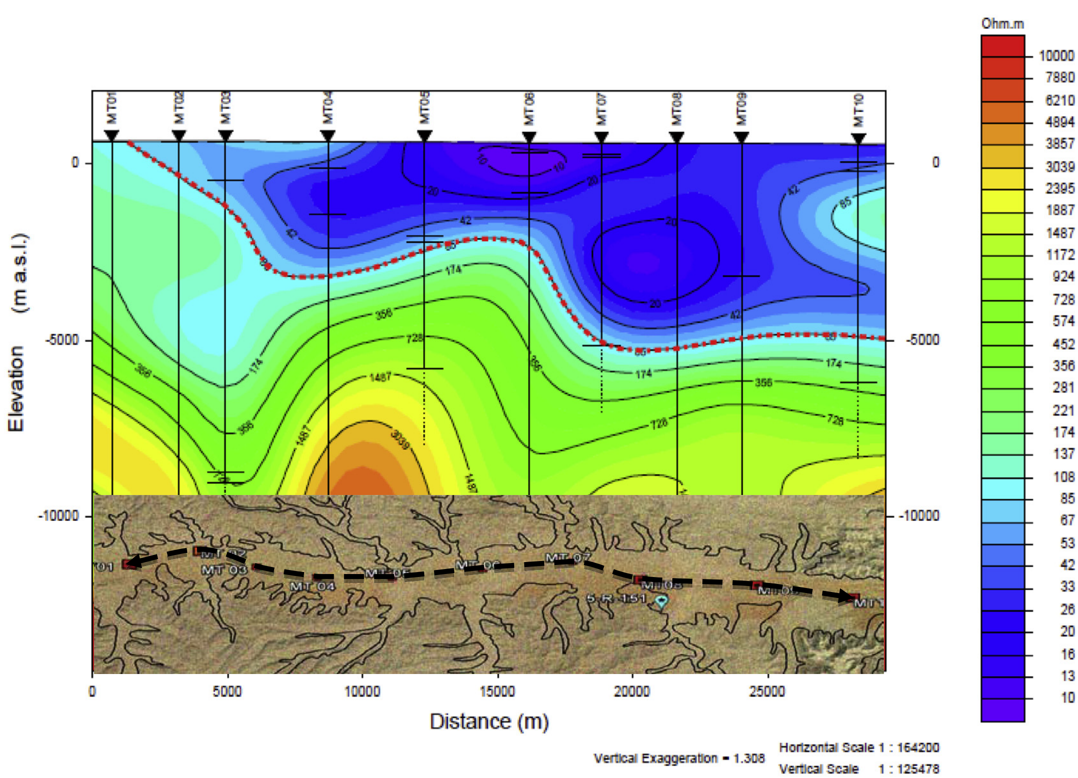

Figure 4 Resistivity cross-section along the profile using Occam layer method. Dashed red line indicates the location of the low resistivity zone. Overlaid image shows the profile and stations along Wadi. Water level is 80 m at the water well 5-R-151 near the study area.

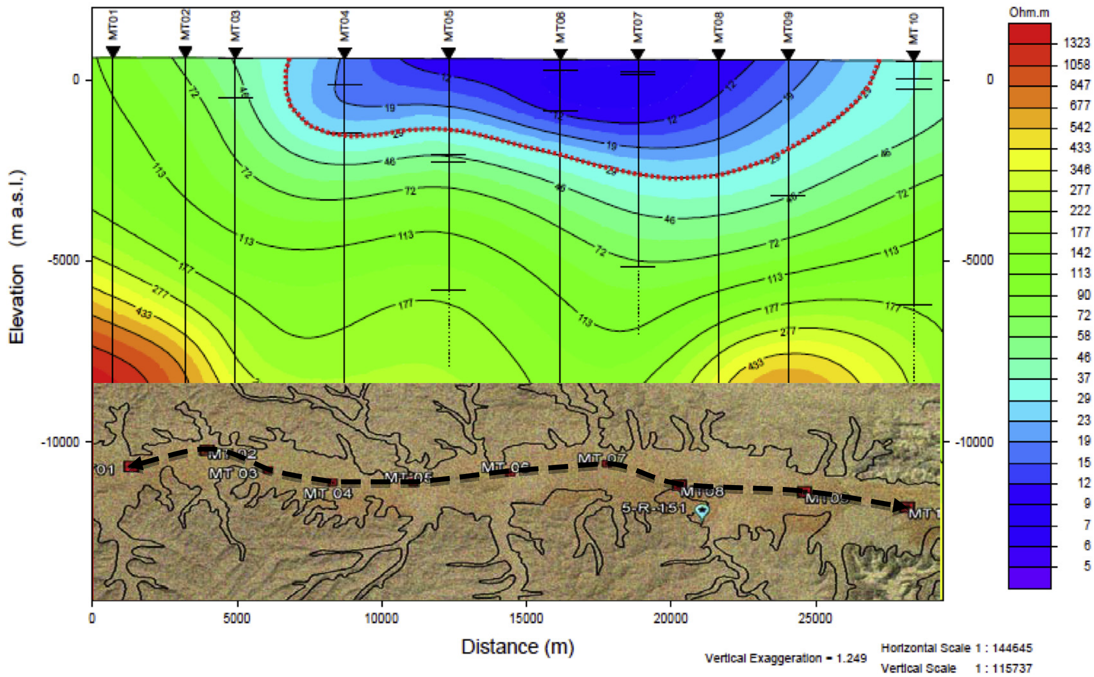

Figure 5 Resistivity cross-section along the profile using Bostick layer method. Dashed red line indicates the location of the low resistivity zone. Overlaid image shows the profile and stations along Wadi.

resistivity layer from MT results and inputted into the gravity model as a horizon/layer using density contrast of 2.0 g/cc^3 for sedimentary succession. It is common that, modeling algorithms assumed that the density above the basement interface is uniform. Therefore, a constant density is adopted in modeling scheme. Slight changes in the basement surface gives

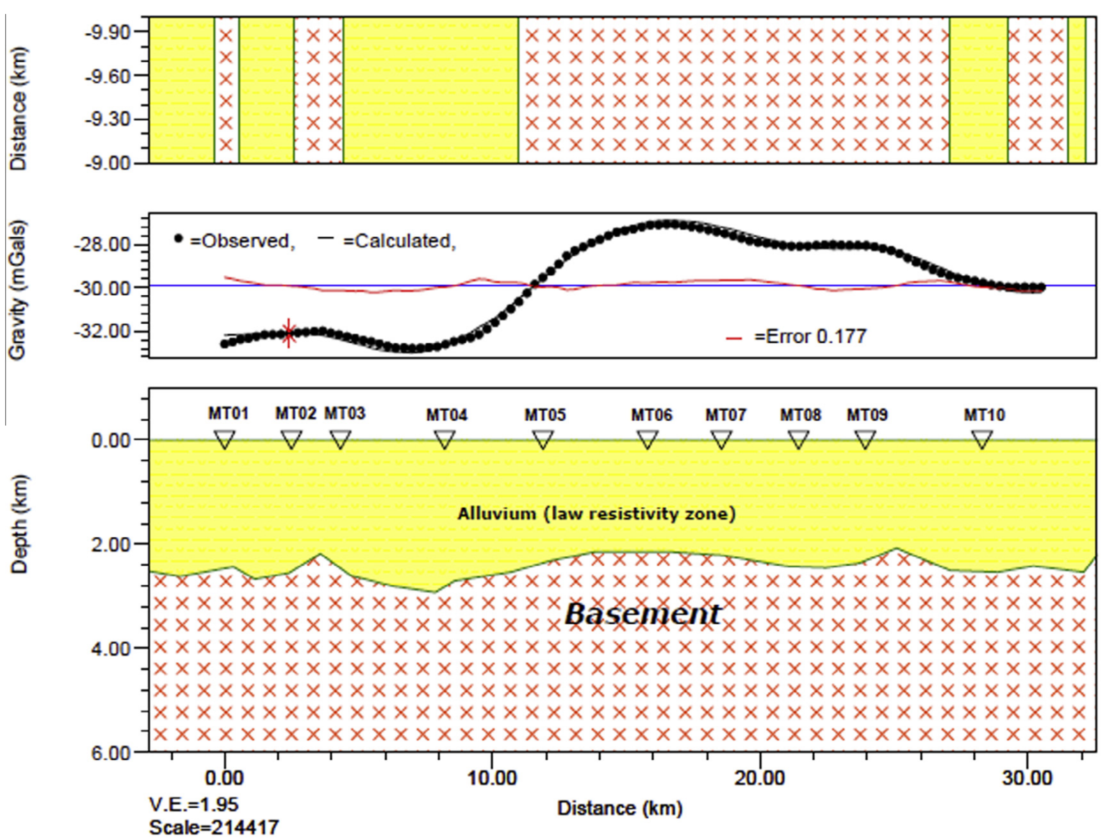

Figure 6 Gravity profile modeling shows the relief of the basement surface and the thickness of the alluvium deposit layer.

the best fit of the calculated and observed gravity curve. The best-fit model (Fig. 6) indicated that, basement layer can be detected at a depth of 2.5 km along the EW profile.

The MT data indicating that, Wadi Nisah has a low resistivity layer extending laterally as 15 km and has a depth of about 2 km, averaging area of about 30 km^2 which could consider as a promised aquifer. This layer has a resistivity value $< 10\ \Omega$ m that can be interpreted as water aquifer where some resistivity values were about 3 Ω m. Some locations of this layer have a resistivity value of $>$20–30 Ω m indicating that these locations are water saturated with Wadi deposits.

From the previous results, we can state that, MT and gravity data were used successfully to image the underground water aquifer in Wadi Nisah. We recommend more MT profiles perpendicular to the Wadi strike in order to map the subsurface aquifer.

Acknowledgments

The authors would like to deeply thank King Abdulaziz City for Science and Technology (KACST), Saudi Arabia, for funding the Magnetotelluric surveys. We also would like to thank KACST's researchers who helped and supported during the fieldwork. Finally, our sincere thanks goes to the anonymous reviewers for their fruitful comments.

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