Evaluation of Groundwater Potentiality and Subsurface Structural Setting by Using Geophysical Data in Wadi Hubuna, Southwest Najran, Saudi Arabia

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Abstract

A geophysical study was conducted to explore the shallow groundwater aquifer and to identify the subsurface structure on the basis of resistivity and geomagnetic surveys. The study area is situated in the southwestern portion of Saudi Arabia, southwest of the Najran region. The total intensity magnetic map is reduced to the northern magnetic pole. The estimated mean depths of the regional and residual magnetic sources are 3 km and 1.4 km respectively. Eighty vertical electrical soundings were measured using the Schlumberger configuration with AB/2 spacing of up to 700 m. Four geoelectrical layers were identified, and could be described from ground surface to deeper layers as the following: The first layer encompasses wadi deposits with true resistivity values ranging from 452 $\Omega$ m to 1353 $\Omega$ m and thicknesses of 2-4 m. The second layer is comprised of dry fine to medium grain-sized deposits with true resistivity values ranging from 104 $\Omega$ m to 451 $\Omega$ m, and thickness varying between 2 and 16 m. The third layer consists of water-bearing friable deposits beside the topmost part of the underlying weathered (fractured) basement. The true resistivity of this layer ranges from 22 $\Omega$ m to 188 $\Omega$ m, whereas the thickness of this layer is highly variable and ranges from 5 to 35 m. Generally, the resistivity values and the thickness of these three layers exhibit an increasing trend toward the main wadi stream. A fourth layer was also detected and is represented by a thin clay layer directly overlying the hard rocks of the basement complex. The dominant tectonic trends controlling the shallower parts are N-S and NNW-SSE. Meanwhile, the structural trend controlling the deeper parts is NE-SW, E-W, and NNE-SSW. The ideal areas for drilling wells, according to the interpreted cross-sections, are along the main stream of Wadi Hubuna and other small wadis, as well as the lower portions of the wadi in the extreme east direction.

Keywords: Aeromagnetic; RTP; Euler deconvolution; Geoelectric; Groundwater

1. Introduction

The study area includes the western portion of the Najran region, a small portion of the Asir region in the southeast and extends eastward into the Rub El Khali desert. The study area ranges in altitude from approximately 1200 meters above sea level at the main wadi channel to more than 3000 meters in the Asir region. The catchment area encompasses roughly 6837 km\textsuperscript{2} (Fig. 1). The upper hard-rock section, which comprises approximately 85\% of the watershed of wadi Hubuna, consists primarily of DOI: 10.46717/igj.56.2D.17ms-2023-10-23
volcanic and metamorphic rocks with some alluvial deposits. The lower alluvial zone appears to have minimal relief and is predominantly composed of alluvium. The annual average rainfall in Wadi Hubuna is around 90 mm per year.

Wadi Hubuna was selected to explore and evaluate the groundwater resources in the region, where the groundwater quality was taken into consideration. The aquifer in the studied region differs from those of the upper to lower parts of the wadi. In each case, major unconfined aquifers represent the essential groundwater resources in the area. The groundwater represents the primary irrigation water source for ensuring regular crop production at Wadi Hubuna. Considerable amounts of groundwater are currently withdrawn from the underground storage. All these aforementioned issues have attracted the researcher's attention to accomplish detailed hydro-geophysical investigations using the latest reliable conventional and statistical techniques to collect more information as possible about groundwater availability. Geophysical techniques have been commonly utilized in various studies and investigations, including subsurface mapping, hydrology, and geothermal resource delineation (Dumont et al., 2016; Lal et al., 2018; Nieto et al., 2019). The objective of this study is to evaluate the subsurface structure and assess the groundwater potential of these finite resources to provide a relevant solution for the best utilization approaches in domestic and irrigation usage.

Precipitation attains higher rates during September to March, where it is commonly reduced during October-February. It attains the highest values of around 300 mm southwest of the study area, whereas the lowest values (~50 mm) occurred in the northeastern part of the area (Taha et al., 2021). The topography is steep in the western upper reaches of the catchment area, with narrow wadi channels that turn into broad thick alluvial deposits in the east and north. Wadi channel slope decreases from 3 % in the western portion of the catchment to 0.1 % at the eastern catchment boundary, with an average of 0.6 %. Surface drainage systems were identified from digital elevation models.

![Fig. 1. Location map of the study area](image)

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2. Geologic Setting

The geologic setting and distribution of different rock units in the study area (Fig. 2) will be presented below from younger to older.

Quaternary Deposits: Unconsolidated sediments ranging in size from silt to stones are widespread within the wadi. These alluvial deposits are located between mountain ranges or between hard rock outcrops. Sand, gravel, and pebbles constitute many of the wadi deposits, which are among the most productive aquifers. Quaternary deposits occupy the wadi courses and floodplains, covering 20% (1394 km²) of the total area in the Hubuna catchment. These sediments generally overlie the basement rocks and include alluvial, eolian, colluvial, and terrace deposits, according to Saudi Geological Survey (SGS) surficial geology mapping (Fairer, 1985; Greenwood, 1985; Sable, 1985).

Fig. 2. Geological map of the investigated area (after Greenwood, 1981)

Tertiary Basalt: Tertiary basic volcanic (Oligocene-Miocene) occur in a trend parallel to the Red Sea, extending from the NW (Jordan and Syria) to the SE (Yemen). These volcanics are rift-related and predominantly consist of basalts and olivine basalts. In western Saudi Arabia, the total amount of eruptive material ranges from 103 to 105 km³. The eruptive history of these volcanics straddles from Oligocene to the present (Coleman et al., 1983). Harrat As-Sarat is the second smallest and southermost of western Saudi Arabia’s basalt fields and represents a part of the enormous Red Sea rift-related continental alkali basalt province (du Bray et al., 1991; Overstreet et al., 1977).

Wajid Group: The Cambro-Permian sedimentary sequence in southwest Saudi Arabia belongs to the Wajid Group. This group is well represented in a region extending southward from Wadi Al-Dawasir to Najran City (Benaafi et al., 2017). It outcrops in the northeastern, central, and northwestern portions of the studied Wadi Hubuna catchment. The northeastern exposures are amongst widespread strata blanket gently dipping east beneath the Quaternary deposits of the A1-Rub A1 Khali basin (Sable, 1982).

Basement: Basement outcrops comprise a range of rock types such as Proterozoic meta-sedimentary and volcanic rocks of the Halaban Group, which include meta-andesite, meta-basalt, and meta-dacite in western portions of the catchment transitioning to granite and diorite. Based on well
drilling and borehole logging in other nearby catchments, the upper part of the basement underlying the alluvium is typically weathered and has many deep fractures of up to 20 m depth (Fairer, 1985; Greenwood, 1985; Sable, 1985).

3. Materials and Methods

Integrated geophysical methods of airborne magnetic and vertical electrical sounding surveys were conducted in the area of research.

3.1. Airborne Magnetic Measurements

The area was surveyed by airborne magnetic techniques in multiple phases (1962-1983) using various survey specifications. Hunting geology and geophysical Ltd supervised by USGS flew above the southern portion of the research area in 1962 using the fluxgate Gulf Mark III magnetometer with an analogue recording. The terrain altitude was 300 m, the traverse direction was N55 E, and the line spacing was 1250 m. The northern part of the study area was flown over in 1966-1967 by a consortium of four corporations (Aero Services Corp., Hunting Geology and Geophysics Ltd, Lockwood Survey Corporation Ltd and ARGAS) using the fluxgate Gulf Mark III magnetometer with analogue recording. The terrain altitude was 300m, the traverse direction was N30E, and the traverse line spacing was 800m. The coastal plain of the study area was flown over in 1983 by Geo Survey International Ltd under the supervision of USGS with a terrain clearance was 300 m, and traverse direction was N30E and a traverse line spacing was 2000 m using the Geometrics G813 Proton precession magnetometer with digital recording. The Saudi Geological Survey (SGS) gathered data for the southern portion of the research area in 1985 in a single grid using data leveling and grid knitting. Here, we used the Oasis Montaj (GEOSOFT Inc. 2015) for gridding, contouring, and then applying some filters.

3.2. Geoelectrical Data

Geoelectric resistivity measurements of the present investigation have been conducted utilizing the Schlumberger array to determine the resistivity and thicknesses of various subsurface layers and exploring the groundwater. Hence, fifty three Schlumberger VES's were maintained at a maximum spacing of AB/2 equals 700 m and distributed along 7 geoelectrical profiles in which their central positions are shown as green triangles in the map of (Fig. 3).

4. Results and Discussion

4.1. Aeromagnetic Data Interpretation

4.1.1 Total intensity of aeromagnetic data

The total intensity of magnetic anomaly map is a reflection of the lateral variations in magnetic characteristic of the underlying rocks. Thus, the magnetic expression of the various structural features depends on the existence and magnitude of their magnetic contrasts. The qualitative interpretation of a magnetic data begins with a visual examination of the shapes and trends of the significant anomalies. The features which control the description of magnetic anomalies are: the relative location and amplitude of the positive and negative parts of the anomaly; the elongation and areal extension of the anomalies; and the sharpness of the anomaly, as seen by the spacing between the contours. In many cases, meaningful geologic information can be detected directly by looking at the map (Sharma, 1986). The total intensity of the magnetic anomalies map (Fig. 4) could be categorized based on the magnetic anomaly value.
Fig. 3. Locations of geoelectric profiles and wells.

Fig. 4. Total intensity magnetic contour map of Wadi Hubuna.

High values of magnetic anomalies occur in the east, southeast, and southwest parts of the study area, and range between -76 nT and 29 nT. It is supposed that high-magnetized bodies reveal these magnetic anomalies. The northeast, southeast, and northwest parts of the study region have low values of magnetic anomalies. Most of these lowered magnetic anomalies are oval and elongated in shape and
have values ranging between -232 nT and -125nT. High-frequency low magnetic anomalies suggest thick sediments or magnetized. Moderate magnetic anomalies between -76 and -125 nT are randomly dispersed elsewhere (Fig. 4). Magnetic anomalies exhibit different shapes. Some core areas have frequent abnormalities. The magnetic gradient varies greatly within the study area. Eastern, southern, and southwestern gradients are severe, but northern, center, and northwestern gradients are gentle (Fig. 4). The sharp gradient may designate shallow depths to the causative entities or high magnetic susceptibilities. E-W, NW-SE, and NE-SW trends are the main directions of the recognized anomalies.

4.1.2. Reduced to the North Magnetic Pole (RTP)

The total magnetic map was reduced to the northern magnetic pole by using 2-D wave number filtration, utilizing the known inclination and declination of the field area. In this case, the maximum of the anomalies will be directly over the center of the causative body (Baranov, 1957; Baranov et al 1964; Bhattacharyya, 1965; Bhattacharyya, 1967). Because of the inclination of the earth’s magnetic field, most magnetic anomalies show both positive and negative responses. These minima and maxima are generally offset from the center of the causative body along the magnetic meridian. Only in the case where the inclination is 90° the magnetic anomaly lies directly over the center of the source body. The method of reduction to the magnetic pole (RTP) is utilized to remove this effect so that the data appears as if it were observed at the pole, where the magnetic field is vertical. The magnetic maxima generally appear immediately over the magnetized bodies, especially when remnant magnetization is absent (Keary, 1994). In the opposite case, when the inclination is 0°, the minimum is located directly over the magnetic body.

By using (Oasis Montaj programme, 2010), the magnetic intensity map is reduced to the pole using inclination (24.1°), declination (2.3°), and magnetic field strength (44387). The RTP magnetic map (Fig. 5) shows anomalies of different frequencies and amplitudes, indicating distinct origins. The RTP magnetic map and total intensity magnetic map (Figs. 4 and 5) show how the magnetic field’s reduced inclination has pushed the inherited magnetic anomalies to the north. The RTP map shows research region anomalies ranging from 183 nT in the east and west to -294 nT. These anomalies can be divided into positive and negative magnetic anomaly. The positive magnetic anomaly is located in the southern, western, and eastern parts of Wadi, while the magnetic value ranges between 0 and 180 nT. This positive anomaly may be related to the shallow depths of basement rocks in the study area. The negative magnetic anomalies are located in the central and northern parts of the wadi. These negative anomalies range between 0 and -294 nT and may reflect thick sedimentary cover, which is considered a basin for ground water accumulation in this part of the study area. The N-S trend considers the major structural trends affecting the study area.

4.1.3. Two-dimensional radial average power spectrum

The 2-D radial average power spectrum analysis gives a simple view of the general depth distribution. The region can be separated into two sections: deep and shallow. The depth of each zone can be calculated from the slope of each part of the curve.

\[ h = - \frac{S}{4 \pi} \]  

(1)

Where: \( h \) = estimated depth, \( S \) = slope of the log (energy) spectrum

These estimates can be employed as an rough guide to the depth of the population of the magnetic source. The power spectrum is classified into three parts:

The deeper source zones with a wavenumber ranging from 0.27 to 0.38 1/k-unit, and a depth equal to 3000 m as calculated from Equation (1).
Shallower sources with a depth equal to 1400m as calculated from the previous equation and a wavenumber ranging between 0.2 and 1.16 1/k-unit. The noise part has a very shallow depth, and this marks the high wavenumber small signal from near sources.

**Fig. 5.** Reduced to the North Pole magnetic anomaly map (RTP).

From the above-mentioned results, we can classify the depth of magnetic anomalies in the area under study into two divisions: the depth of the shallow sources reaches 1400 m, and the deep sources reach 3000 m (Fig. 6).

**Fig. 6.** Radially averaged power spectrum and depth estimate of magnetic data.
4.1.4. Low-pass (regional) magnetic map

After removing residual anomalies from RTP magnetic anomalies, the low-pass (regional) map (Fig. 7) shows the deep-seated magnetic response at an average depth of 3 km. The magnetic 2D radially averaged power spectrum was used to calculate the low pass filtering wavenumber cutoff = 0.048 cycle/unit for the regional geomagnetic map. Regional anomalies exhibit two distinct zones.

![Regional (lowpass) magnetic anomaly map of Wadi Habuna Area.](image)

The first zone has high magnetic anomalies (high/ zones) in the northeast, south, and west with higher amplitudes (up to 92 nT) and N-S, NW-SE, and NE-SW trends. The second zone reveals low magnetic value, frequency, and amplitude with N-S and NE-SW trends at the center of the mapped area. It is also distinguished by having low and moderate magnetic anomalies.

4.1.5. High-pass (Residual) Magnetic Map

Residual magnetic anomalies are interesting, as they denote shallow abnormalities, which are often weaker and localized. The residual map emphasizes weaker traits obscured by substantial regional influences on the source map. The high-pass (residual) filtered map (Fig. 8) designates shallow magnetic responses at an average depth of 1.4 km. It optimizes shallow-seated source-related high-frequency magnetic abnormalities. The residual magnetic anomaly map shows magnetic narrow closure systems throughout the research area with varying amplitudes and frequencies, mainly attributable to variable composition and depths. This map illustrates various N-S-oriented negative and positive magnetic anomalies. Hydrothermal solutions may alter sills and dykes in these faulted zones.
4.1.6. Tilt Derivative (TDR)

The magnetic data alone will provide insight into the area's general structure. Filtering of magnetic data increases the visibility and sharpness of irregularities and patterns in the data, which aids the analysis. The magnetic data is subjected to a Tilt Derivative Filter. The TDR and the horizontal derivative filter are suitable for mineral exploration and mapping the shallow structures. The vertical derivative is divided by the horizontal derivative to calculate this filter (Verduzco, 2004) as:

\[
TDR = \tan^{-1} \left( \frac{VDR}{THDR} \right)
\]

Where the vertical derivative is \(VDR\), total horizontal derivative is \(THDR\) and the total magnetic intensity is \(T\)

\[
VDR = \frac{dT}{dz}
\]

\[
THDR = (\frac{dT}{dx})^2 + (\frac{dT}{dy})
\]

TDRs have a zero-contour line near the fault/contact spot. Magnetic data TDR map with zero-contour line emphasizes magnetic patterns and reveals that the N–S directed structures are the dominant structural type in the area. Other NE-SW patterns also exist. Therefore, two domain fault systems have been recognized within the research area: the N–S trending and the NNE-SSW trending (Fig. 9).

4.1.7. Euler Deconvolution

Euler solutions are usefully absolved in terms of depths and horizontal positions. Three-dimensional results are presented in map form with various source depths and geometries (different N) distinguished using variations in colour and/or symbol type. The margin of source bodies can be mapped in this way (Dentith et al., 2014). Based on oasis montaj 8.3 software, structural indices (SI) = 0 and 0.5 are used for Euler deconvolution. Euler deconvolution with (SI=0) on RTP magnetic data demonstrate linear clustering of circles, signifying potential rock unit connections (Fig. 10). Faults and contacts at depths from 100 m to 3000 m may cause such linear clustering rings. These solutions are directed in N-
S and NE trend. The magnetic thick step or fault model solves the locations and depths of faults that affect diverse basement rocks at great depths using the structural index model (SI= 0.5). The depths were about 500–1500 m. These solutions exhibit N-S, NW-SE, and NE-SW trends (Fig. 11).

Fig. 9. Tilt Derivative (TDR) map of RTP magnetic data of the study area displays zero contour line.

Fig. 10. Interpreted contact solution depth map using Euler techniques (S.I.= 0).
4.1.8. Trend Analysis

Trend analysis is a highly recommended method in the statistical understanding of geology and geophysics of all data types.

The structural lineaments at shallow and deep depths of the prospect area of study were interpreted from the residual and regional magnetic maps. For best resolution of the azimuths and lengths of the interpreted lineaments, numerical pattern analysis is done here. In order to help identify the major structural patterns in the prospective area of study, rose diagrams are constructed for the perceived structural lineaments.

Results of trend analysis can be deduced from the application of the rose diagram technique on the general directions (trends) of the gradients and anomalies of the residual and regional magnetic-component maps (Figs. 12 and 13). The analysis of these diagrams showed two predominant structural trends, N-S and NNW-SSE, having variable intensities and lengths. Besides, there are also three minor structural trends, including NE-SW, E-W, and NNE-SSW.

4.2. Geoelectrical Data Interpretation

4.2.1 Geoelectrical cross sections

Seven geoelectric cross-sections were prepared from VES data at wadi Hubuna. The final model that represents the layer parameters (thickness and depth) was created using the computer program IPI2WIN. The VES models employ geological information derived from well-log interpretations to visually illustrate the Wadi’s water status, water-bearing stratum, and basement rocks. The results of the geo-electric interpretation for the VES No.1, and VES No.5 measured nearby the two boreholes (Well No.1, and Well No.2) show, agreeable resemblance for the outcomes of the boreholes data (Figs. 14a, and b). However, the RMS % between field curves and calculated curves during interpretation ranges from 1.66 to 4.8.
The results of the geoelectrical interpretation indicate that the subsurface cross-section contains distinct geoelectrical layers (Fig. 15a-g). The first surface layer consists of dry Wadi deposits that encompass the surficial 2 m depth in the Al-Arga and Mahda areas and increases to 4 m depth in the Rafgha area, with an average thickness of 3 m. The resistivity of this layer ranges from 452 $\Omega$.m in the Mahda area to 1353 $\Omega$.m in the Al-Arga area. The thickness of the second layer of dry sand ranges from
2 m in the Al-Arga area to 16 m in the Tanhed area, while its resistivity ranges from 104 Ω.m in the Zafra area to 451 Ω.m in the Sbooha area. The third layer accounts for the water-bearing formation and the upper portion of the weathered basement complex.

**Table 1.** Shows hydrogeological data near the cross sections.

<table>
<thead>
<tr>
<th>Well No.</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Total Depth (m)</th>
<th>SWL (m)</th>
<th>Well Type</th>
<th>TDS (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17°50'31.46&quot;</td>
<td>44°01'35.00&quot;</td>
<td>22</td>
<td>14</td>
<td>Dug</td>
<td>560</td>
</tr>
<tr>
<td>2</td>
<td>17°50'19.93&quot;</td>
<td>44°01'26.18&quot;</td>
<td>58</td>
<td>16</td>
<td>Drilled</td>
<td>1292</td>
</tr>
<tr>
<td>3</td>
<td>17°50'39.26&quot;</td>
<td>44°02'2.80&quot;</td>
<td>24</td>
<td>16</td>
<td>Dug</td>
<td>1000</td>
</tr>
<tr>
<td>4</td>
<td>17°46'19.64&quot;</td>
<td>43°59'24.85&quot;</td>
<td>27</td>
<td>9</td>
<td>Dug</td>
<td>700</td>
</tr>
<tr>
<td>5</td>
<td>17°47'03.67&quot;</td>
<td>43°59'38.16&quot;</td>
<td>21</td>
<td>9</td>
<td>Dug</td>
<td>1349</td>
</tr>
<tr>
<td>6</td>
<td>17°45'44.71&quot;</td>
<td>43°57'27.65&quot;</td>
<td>14</td>
<td>10</td>
<td>Dug</td>
<td>1800</td>
</tr>
<tr>
<td>7</td>
<td>17°45'40.43&quot;</td>
<td>43°57'36.40&quot;</td>
<td>13</td>
<td>11</td>
<td>Dug</td>
<td>1780</td>
</tr>
<tr>
<td>8</td>
<td>17°51'10.10&quot;</td>
<td>43°37'28.50&quot;</td>
<td>14</td>
<td>10</td>
<td>Dug</td>
<td>670</td>
</tr>
<tr>
<td>9</td>
<td>17°51'03.09&quot;</td>
<td>43°37'35.78&quot;</td>
<td>10</td>
<td>5</td>
<td>Dug</td>
<td>770</td>
</tr>
<tr>
<td>10</td>
<td>17°46'25.00&quot;</td>
<td>43°52'38.50&quot;</td>
<td>13</td>
<td>10</td>
<td>Dug</td>
<td>330</td>
</tr>
<tr>
<td>11</td>
<td>17°46'23.80&quot;</td>
<td>43°52'54.10&quot;</td>
<td>17</td>
<td>6</td>
<td>Dug</td>
<td>704</td>
</tr>
</tbody>
</table>

This layer varies in thickness from 5 m in the Al-Arga and Old - Gafa areas to 32 m in the Sbooha area, and in resistivity from 22 Ω.m in the Zafra area to 188Ω.m in the Old-Gafa area. The fourth layer appears after the end of the saturated layer. The resistivity increases with increasing depth in some cases to 31.5 Ω.m at the Zafra area to 4105 Ω.m at the Mahda area, whereas the resistivity decreases sharply to 0.2-0.7 Ω.m at the Zafara, shooha, Al-Araga, and Tanhed areas, due to the presence of shale layers above the basement complex rocks.

Eleven wells were drilled near these profiles and close to some of the VESes locations. The data of these wells are shown in Table 1. According to the hydrogeological data, the static water level changes from 5 m to 16 m, and the total dissolved solids (TSD) also exhibit great variety from 330 ppm to 1800 ppm.
Fig. 15a. Interpreted cross section for Profile A (SW-NE direction).

Fig. 15b. Interpreted cross section for B (S-N direction).
Fig. 15c. Interpreted cross section for Profile C (SW-NE direction).

Fig. 15d. Interpreted cross section for Profile D (SW-N direction).
Fig. 15e. Interpreted cross section for Profile E (W-E direction).

Fig. 15f. Interpreted cross section for Profile F (N-E direction).
4.2.2. Distribution maps

The True resistivity and isopach values of three geoelectric layers (Table 2) are calculated, and their main trends are described below.

Table 2. True resistivity and isopach values for geoelectric layers.

<table>
<thead>
<tr>
<th>Profile</th>
<th>Symbol</th>
<th>Res. of First Layer</th>
<th>H First Layer</th>
<th>Res. of Second Layer</th>
<th>H Second Layer</th>
<th>Res. of Third Layer</th>
<th>H Third Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sbooha</td>
<td>A</td>
<td>784</td>
<td>3</td>
<td>451</td>
<td>14</td>
<td>69</td>
<td>32</td>
</tr>
<tr>
<td>Al-Arga</td>
<td>B</td>
<td>1353</td>
<td>2</td>
<td>176</td>
<td>2</td>
<td>37</td>
<td>5</td>
</tr>
<tr>
<td>Zafra</td>
<td>C</td>
<td>556</td>
<td>3</td>
<td>104</td>
<td>7</td>
<td>22</td>
<td>35</td>
</tr>
<tr>
<td>Tanhed</td>
<td>D</td>
<td>652</td>
<td>3</td>
<td>163</td>
<td>16</td>
<td>32</td>
<td>25</td>
</tr>
<tr>
<td>Rafgha</td>
<td>E</td>
<td>937</td>
<td>4</td>
<td>274</td>
<td>3</td>
<td>128</td>
<td>12</td>
</tr>
<tr>
<td>Mahda</td>
<td>F</td>
<td>452</td>
<td>2</td>
<td>235</td>
<td>6</td>
<td>183</td>
<td>19</td>
</tr>
<tr>
<td>Old Gafa</td>
<td>G</td>
<td>1160</td>
<td>3</td>
<td>385</td>
<td>3</td>
<td>188</td>
<td>5</td>
</tr>
</tbody>
</table>

The true resistivity values of the first geoelectric unit (Fig. 16a), which consists of Wadi deposits, range between 452 Ω.m and 1353 Ω.m, where the greatest value was mainly reported at the main Wadi stream. The thickness of this geoelectric unit varies from 2 to 4 m in the study area (Fig. 16d) and also increases toward the main Wadi stream.

The true resistivity values of the second geoelectric unit, which consists of dry sand, range from 104 Ω.m to 451 Ω.m (Fig. 16b), where the greatest value was mainly reported at the main Wadi stream.
The thickness of the second geoelectric unit varies from 2 to 16 m (Fig. 16e) and increases mainly toward the main Wadi stream.

The true resistivity map for the third geoelectric unit, which consists of water-bearing sands and the upper part of the weathered basement, revealed that the true resistivity values range between 22 Ω.m to 188 Ω.m (Fig. 16c), where the higher resistivity values occurred at the Wadi stream. The thickness of this geoelectric unit varies from 5 to 35 m in the study area (Fig. 17c) and increases mainly at the main Wadi stream (Fig. 16f).

Fig. 16. (a) True resistivity distribution map for the first layer, (b) True resistivity distribution map for the second layer, (c) True resistivity distribution map for the third layer, (d) Iso-pach distribution map for the first layer, (e) Isopach distribution map for the second layer, and (c) Isopach distribution map for the second layer.

5. Conclusions

Aeromagnetic data analysis began with measurements of the total magnetic field intensity, which was then reduced to the north magnetic pole. Afterward, the power spectrum technique was applied to the RTP map to identify the depths of the residual and regional components and to generate appropriate...
maps. The mean depths of regional and residual magnetic sources, which were found to range between 3 km and 1.4 km. The technique of tilt derivative has values close to zero above the borders of the causative bodies with N-S and NNE-SSW trends. The application of Euler deconvolution, with SI=0 and 0.5, to aeromagnetic data signifies the presence of faults and/or contacts with depths ranging from 100 to 3000 meters. The analysis of rose diagrams revealed two distinct structural trends with variable lengths and intensities. These are the north-south and north-northwest-southeast tendencies. On the rose diagrams, various small structural trends are visible, such as the NE-SW, E-W, and NNE-SSW tendencies.

Geoelectrical resistivity soundings were performed according to the Schlumberger configuration with AB/2 spacing reach to approximately 700 m. Most of the sounding curves constituted a four-layer QH curve type. 2 to 4 m thick layer of alluvial deposits having a dry surface and a thickness between 2 and 4 meters. This layer’s apparent resistivity has a wider range of values. The resistivity of the surface layer of Wadi Hubuna ranges from 452 \( \Omega \cdot m \) to 1353 \( \Omega \cdot m \). This discrepancy is attributed to the presence of fine-grained material, such as silt and clay that characterize the surface layer. The resistivity of the saturated zone varied between 22 \( \Omega \cdot m \) and 188 \( \Omega \cdot m \). In general, the highest portions of the Wadis have low resistivity values. However, the highest values were reported from the central portions of the wadis, with values between 100 \( \Omega \cdot m \) and 125 \( \Omega \cdot m \). The resistivity decreases from west to east, and the thickness of the saturated zone varies from location to location. The upper portions of Wadi have thin aquifers with saturation thicknesses between 4 meters and 12 meters. The average thicknesses increase to 14 m in the central portions. In Wadi Hubuna, a clay layer exists beneath the saturated aquifer in the areas of Zafara, shooha, Al-Araga, and Tanhed. The resistivity of this clay layer ranges from 0.2 \( \Omega \cdot m \) to 0.7 \( \Omega \cdot m \).

The ideal areas for drilling wells, according to the interpreted cross-sections, are along the main stream of Wadi Hubuna and other small wadis, as well as the lower portions of the wadi in the extreme east direction.

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