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Electromagnetic Insights: 3D Subsurface Modeling of Al-Hassa, Saudi Arabia

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Abstract

Al-Hassa area features Saudi Arabia's largest oasis and one of the world's largest naturally irrigated land. Moreover, Al-Hassa area is very close to Ghawar, known as the largest conventional oil-field in the world. Additionally, more than 280 natural springs were used in the past to water the farmland, and the water in some of the springs used to be warm. Water quality also exhibits spatial variations, hinting at a complex subsurface that must be characterized. Finally, the available geological information from outcrops is very limited since most of the study area is covered by a sand layer. Based on the above, it seems that this important for its natural resources (oil & gas, groundwater, low-enthalpy geothermal) area is partly unexplored, or the data are not available. This work aims to reconstruct the study area's 3D subsurface geophysical structure by combining different geophysical electromagnetic (EM) methods. Thus, three EM geophysical methods were applied to construct a detailed 3D model of the subsurface. Specifically, 46 magnetotelluric (MT) stations, 6 audio magnetotelluric (AMT) stations, and 35 transient electromagnetic (TEM) stations were acquired within Al-Hassa National Park. The EM findings were confirmed by gravity measurements conducted in the same area. The geophysical results uncovered lateral discontinuities in resistivity, a complex structure, and fracture zones acting as pathways or barriers to groundwater flow. This comprehensive modeling approach offers invaluable insights into the subsurface dynamics, enhancing our understanding of the complexity of the study area.

Background

The Al-Hassa region in eastern Saudi Arabia is renowned for hosting the world's largest oasis and the most expansive naturally irrigated lands globally. With a historical reliance on over 280 natural springs and some yielding warm water for agricultural irrigation, the area's varied water quality suggests the presence of complex subsurface geological structures warranting meticulous examination [1,2].

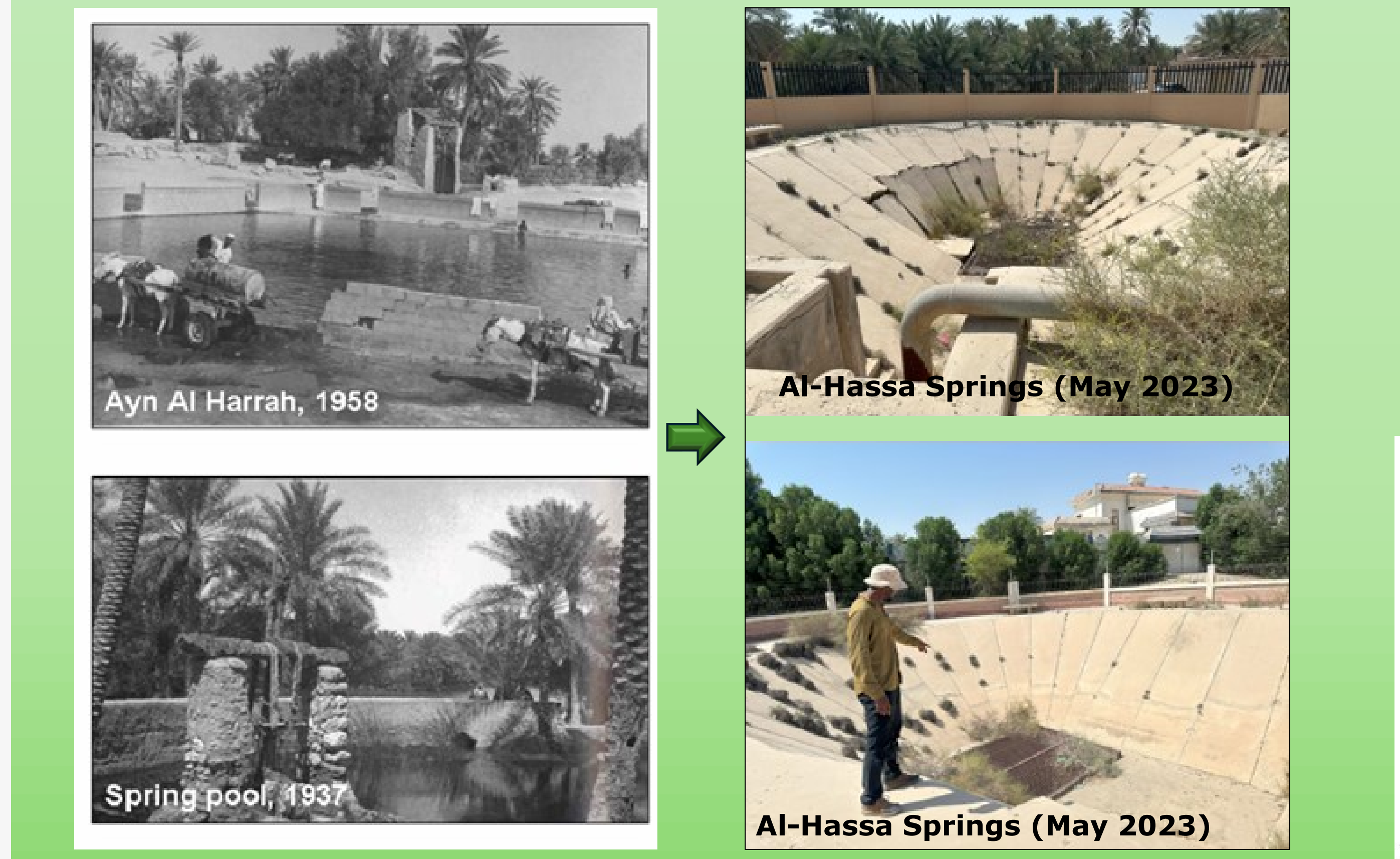
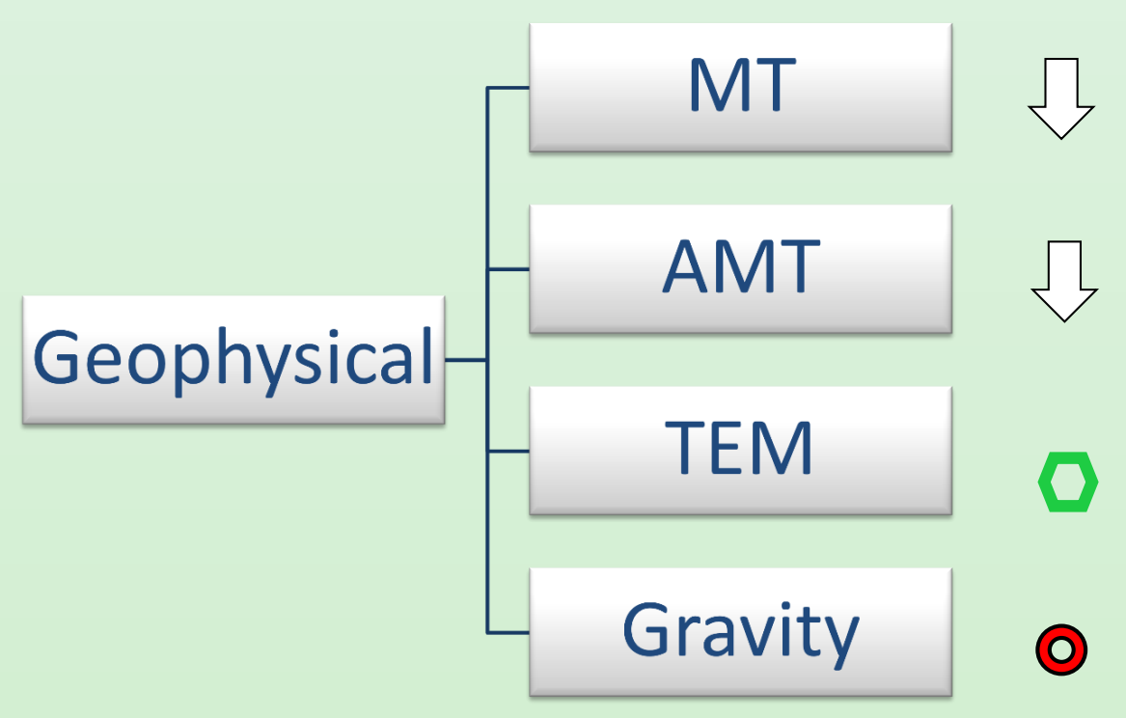


Fig. 1. The Al-Hassa springs in the past (left) (fromAl Tokhais and Rausch, 2008 [1]) and the current situation (right).

Methodology



Geophysical
- MT
- AMT
- TEM
- Gravity

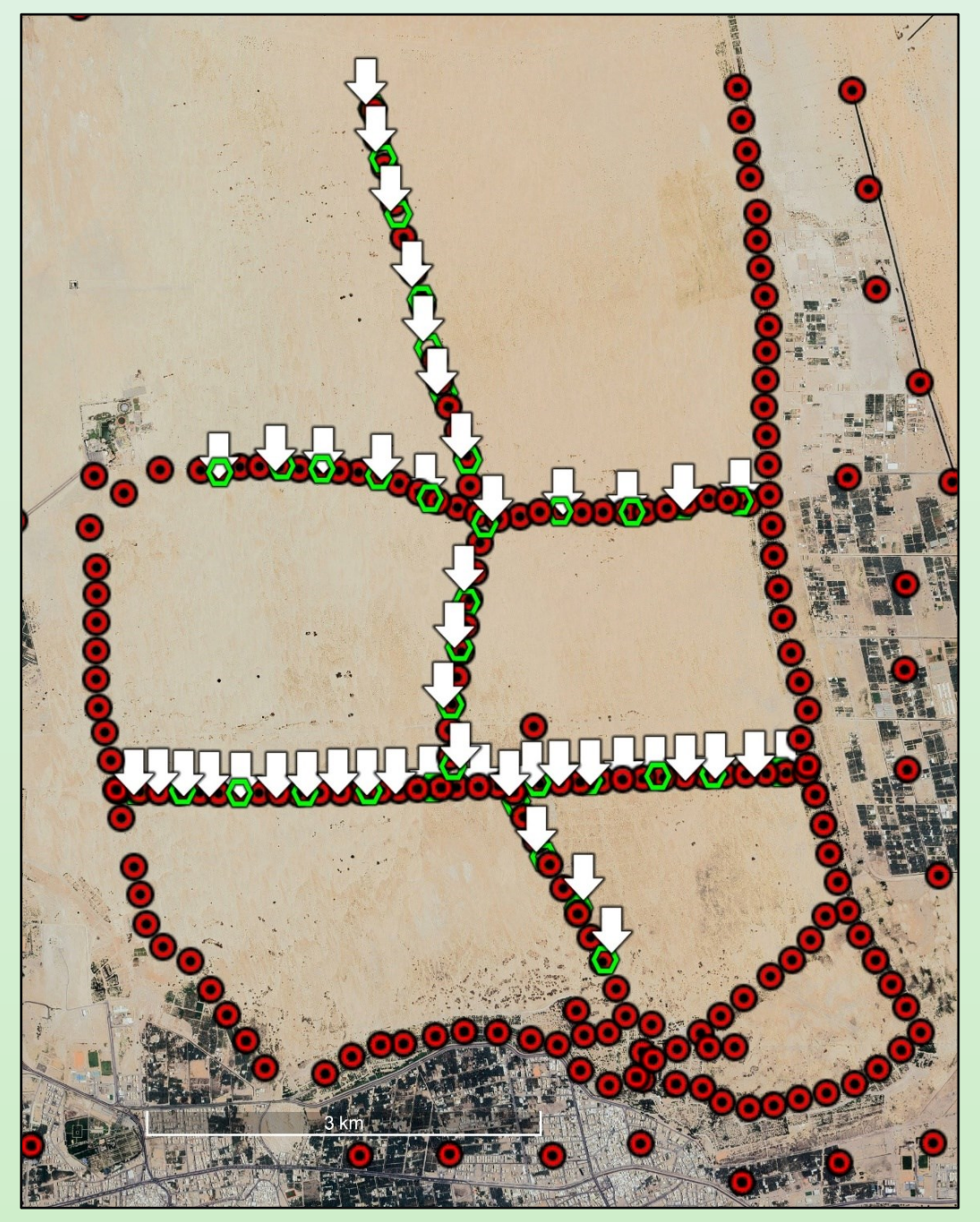


Fig. 2. location of the different geophysical methods

Results

The pseudo-3D MT resistivity model is shown in Figure 3, while resistivity depth slices from 171m to 2161m and 3 2D resistivity profiles are shown in Figure 4. The resulting depth slices from the TEM are shown in Figure 5. The full Bouguer anomaly map and the residual Bouguer anomaly map are shown in Figure 6.

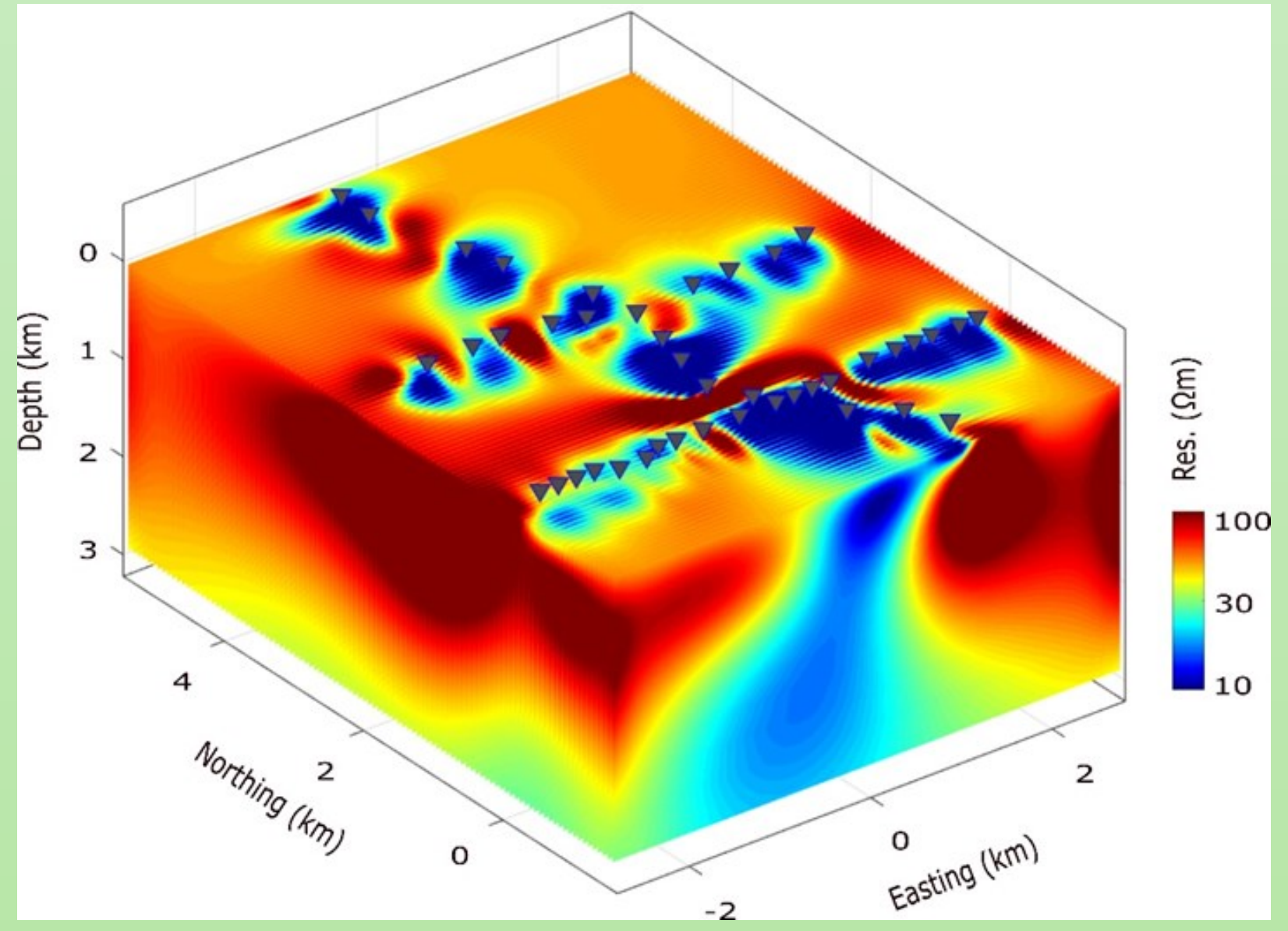


Fig. 3 The 3D resistivity model for the study area

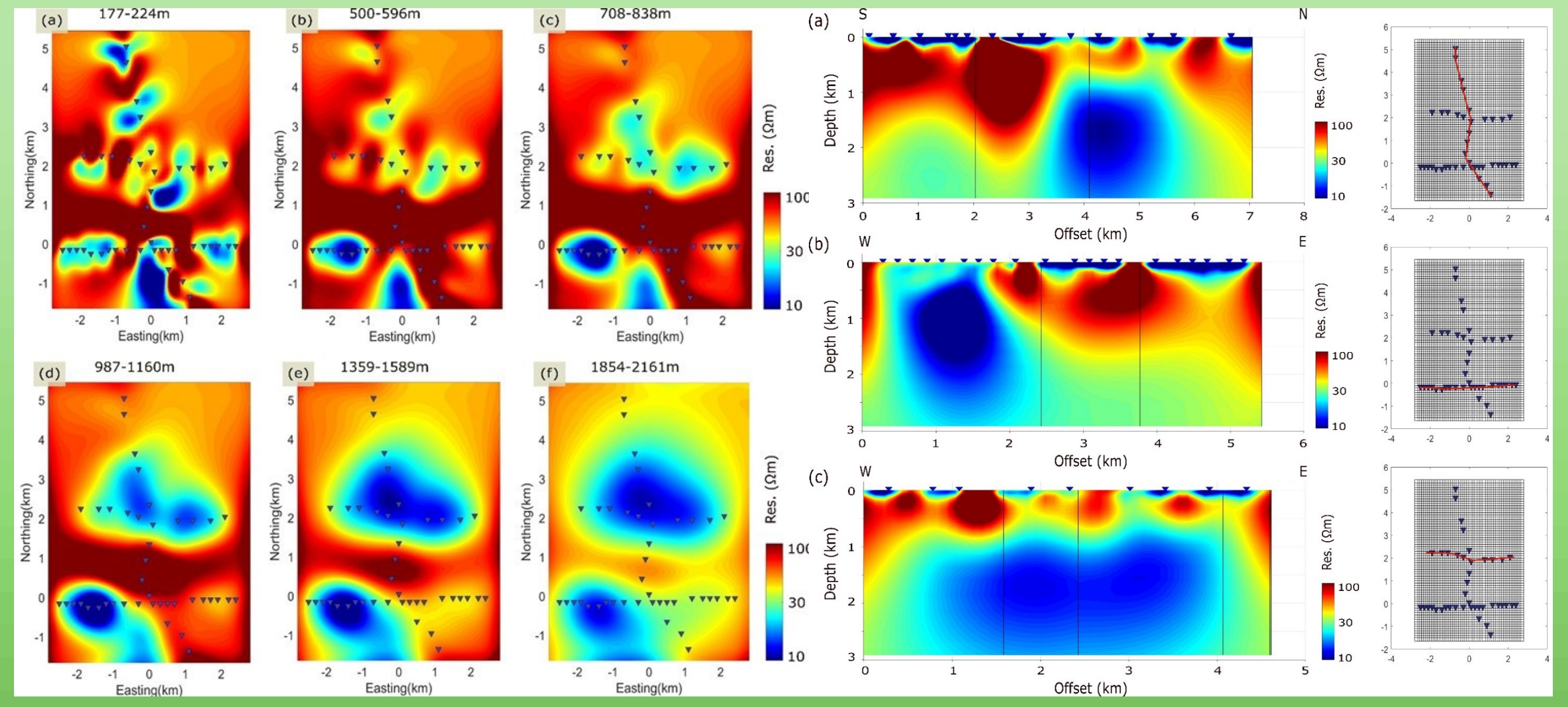


Fig. 4. xy-sections for different depth ranges (left). MT data along three MT profiles. Each section line's location is shown on the plan view of the survey area given on the right side of the related 2D section (right)

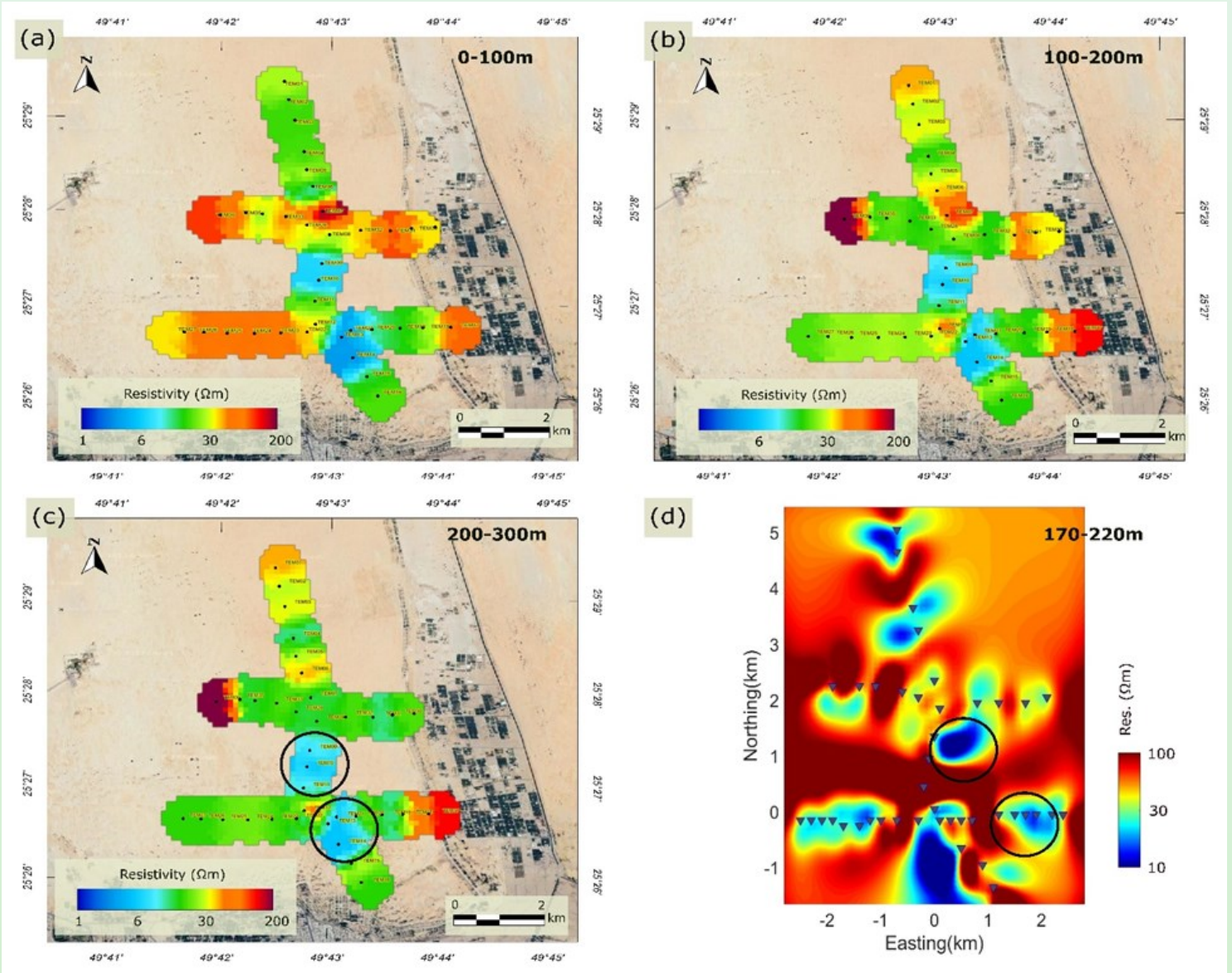


Fig. 5. Quasi-3D TEM modeling. The depth slices for the depths of (a) 0-100 m, (b) 100-200 m, and (c) 200-300 m. (d) The depth slice for the depth of 170-220 m below the ground surface from the 3D MT data inversion.

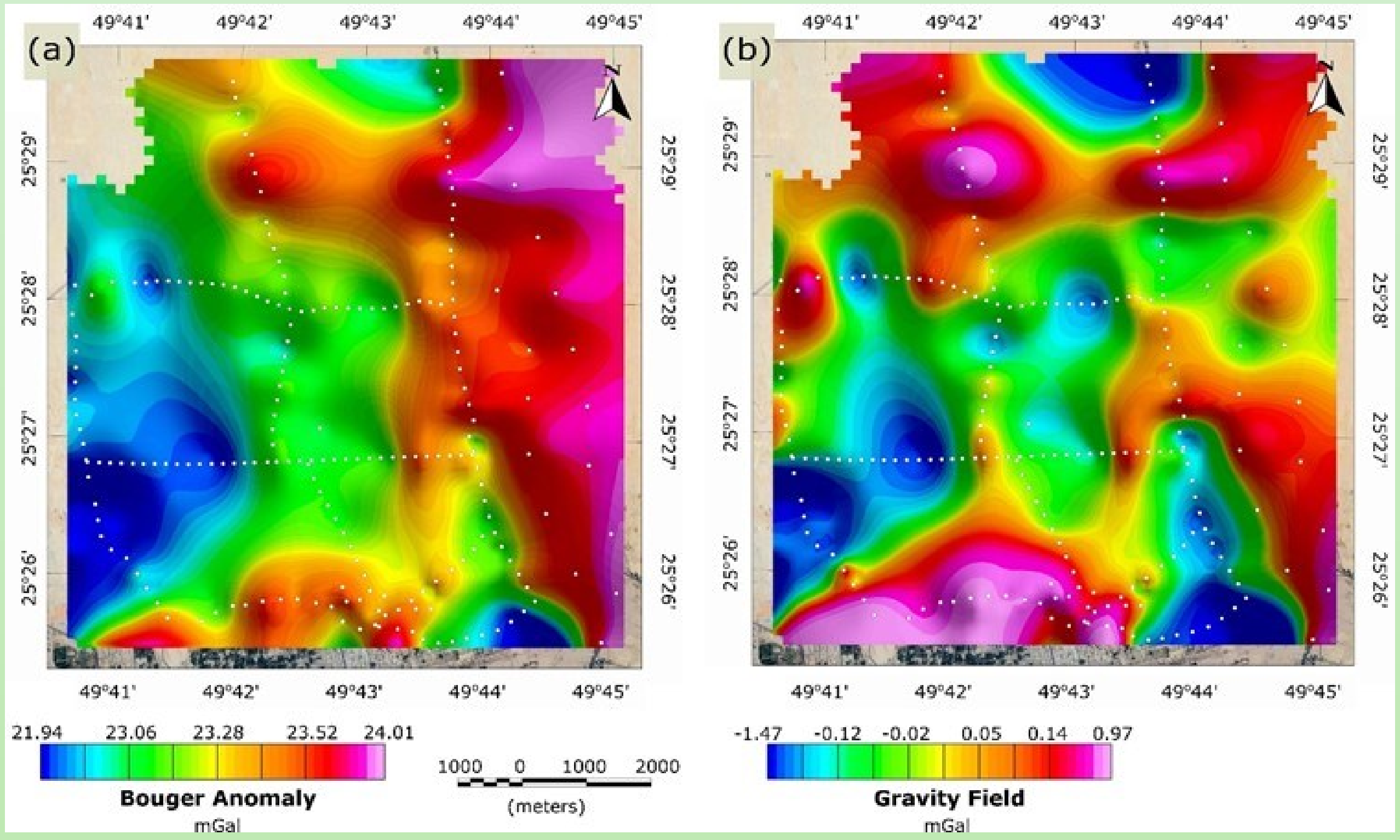


Fig. 6. The results of the gravity data processing. The white dots correspond to the measured gravity stations. (a) The complete Bouguer anomaly map. (b) The residual gravity field map.

Discussion

Four different geophysical methods were applied over the Al-Hassa National Park to characterize the subsurface. Most of the data were very valuable, and their interpretation helped me understand the complexity and uniqueness of the study area.

3D inversion of the MT data achieved high accuracy for the shallow layers (around 200 m depth) till the maximum depth of 2.1 km below the ground surface (Figure 3). Several scattered low-resistivity (below 20 Ωm, blue colors) anomalies were identified in the first depth slice, between 0.177 and 0.224 km (Figure 4). These low-resistivity areas are connected and becoming more extensive as we move deeper, from 0.5 to 0.838 km. After the depth of 1 km, these low-resistivity anomalies cover the central and southwestern parts of the National Park until the maximum depth of 2.161 km. The first anomaly, in the southwest part of the survey area, has its top part at a depth of 500m and average lengths in the x, y, and z directions of 200 m, 600 m, and 1300 m, respectively; thus, an average volume is 0.156 km3 (Figures 4). The second deep low-resistivity anomaly can be seen in the center of the area, with its top part at a depth of 980 m and average lengths in x, y, and z directions of 1400 m, 900 m, and 1350 m, respectively (Figures 4).

The TEM models are presented as three depth slices, separated every 100 m, and reach a maximum depth of 300 m (Figure 5). Lateral and in-depth resistivity variations were observed where the main resistivity features are two low-resistivity (below 20 Ωm) anomalies depicted from the surface (Figure 5a) till the last depth slice (Figure 5c) and are shown as black circles. By comparing the third depth slice (200-300 m, Figure 5c) with the depth slice from the 3D MT resistivity model (177-224 m, Figure 5d), it is shown that there is a good agreement between the final resulted model by the different geophysical methods.

The residual gravity field (Figure 6), shows low gravity (low-density, LD) anomalies in the western, southern, and northern parts of the National Park, while high gravity (high-density, HD) anomalies are encountered mainly in the north and the southeastern parts. Mid-to-low gravity anomalies characterize the largest extent of the National Park. LD anomalies are basins/valleys filled with loose materials of unconsolidated sediments that follow a general N-S orientation and are interrupted locally by HD saddles. The MT data consists of four main units: a very low-resistivity clayed sand layer, a low-resistivity (less than 20 Ωm) suprasalt formation, the resistive (around 100 Ωm) salt body and low resistivity, around 20-50 Ωm, subsalt formation. The other possible geologic scenario is that the observed low resistivity zone, ranging from 20 to 50 Ωm, could be attributed to geothermal fluids circulating through fractures induced by tectonic activity on the broader region. Both gravity and electromagnetic results are in a good agreement.

Conclusions

- EM and gravity experiments were performed in the Al-Hassa National Park area to reconstruct the area's deep and complex subsurface model under investigation.
- The integration of EM and gravity methods in such environments (desert areas) can yield more accurate data regarding the characteristics of subsalt sediments.
- The results defined a complex subsurface structure with NNW-SSE and W-E linear discontinuities, which can be considered fracture zones.
- Lateral resistivity and density variation agree with the suprasalt and subsalt of a salt dome.
- Geological, logs, geochemical, or other geophysical, mainly seismic, information could be useful to confirm the resulted 3D model for the study area and revise the final conceptual model

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