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Full Length Research Paper

Groundwater exploration using geoelectrical resistivity technique at Al-Quwy'yia area central Saudi Arabia

Mohamed Metwaly[1,2]*, Eslam Elawadi[1,3], Sayed S. R. Moustafal[1,2], F. Al Fouzan[4], S. Mogren[1] and N. Al Arifi[1]

[1]Department of Geology and Geophysics, Faculty of Science, King Saud University, Saudi Arabia.
[2]National Research Institute of Astronmy and Geophysics (NRIAG), Cairo, Egypt.
[3]Nuclear Materials Authority (NMA), Cairo, Egypt.
[4]King Abd Alaziz City for Science and Technology (KACST), Saudi Arabia.

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Geoelectrical resistivity surveys were carried out in Al Quwy'yia area, located at the centeral part of Saudi Arabia, to map the acquifer and estimate the groundwater potentuality. The acquired vertical electrical sounding (VES) data sets have been collected along three longitudinal profiles trending East-West, perpendicular to the basment/sedimentary contact. The data sets have been analysed using 1D to obtain the initial figure out of the resistivity layers along the areas. Then, the data were inversion resistivity section using 2D inversion scheme. Information from two boreholes were incorporated during the processing to enhance the results and constrain the resistivity models with geological layers. The results revealed mainly two geoelectric layers represent mainly the basement and sedimentary rocks. The basement rocks dip generally east ward, where the sedimentary section increases in this direction. The depth to the basement is about 50 m in the western part of the area and can not be reached from the acquired data in the eastern part. The contact boundaring between the basment complex and sedimentary rocks can be determined. The static water table is coincident with the limestone rock of Khuff formation as indicated from the comparison between the individual resistivity models and the two wells located at the study area. The thickness of the aquifer is increasing in the north eastern direction where the possibility of the groundwater potentiality is increasing.

Key words: Vertical electrical sounding (VES), arid environment, Al Quwy'yia, 2D resistivity.

INTRODUCTION

Al Quwy'yia area is considered as one of the most promising areas for future sustainable developments in central part of Saudi Arabia. It is located at 160 km to the west of Riyadh city, the capital of Saudi Arabia (Figure 1). The area gains its importance as it is an essential stop for the internal pilgrimages during trips to holly Mecca. Because Al Quwy'yia area is located in the most arid region in the Arabian Peninsula, it has limited groundwater resources. The main charging groundwater resources are coming from the rare rainfall along the basement outcrops that bounds the area from the western side. The rain fall water is charging the aquifers in the Quaternary and the underlain calcareous deposits of Khuff formation, which overlay the basement rocks particularly in the western part of the area. Water demands in Al Quwy'yia area is increasing due to the increasing of population and development activities. However, the groundwater studies of the area are rarely addressed, because it was thought that the area has not any groundwater potentiality and was out of the future development plan. However, most of the carried out work were dealing with the geological and mineral resources as the area is situated very close to the eastern part of Arabian shield (Senalp and Al-Duaiji, 2001). Moreover, there are some works, that have been done close to Al Quwy'yia area dealing with the groundwater recharging source along the shallow and deep aquifer in the eastern and central part of Saudi Arabia (Hoetzel, 1995). Also, Al-Amri (1996) applied the geoelectrical techniques in delineating the groundwater potentiality in the central part

*Corresponding author. E-mail: mmetwaly70@yahoo.com.

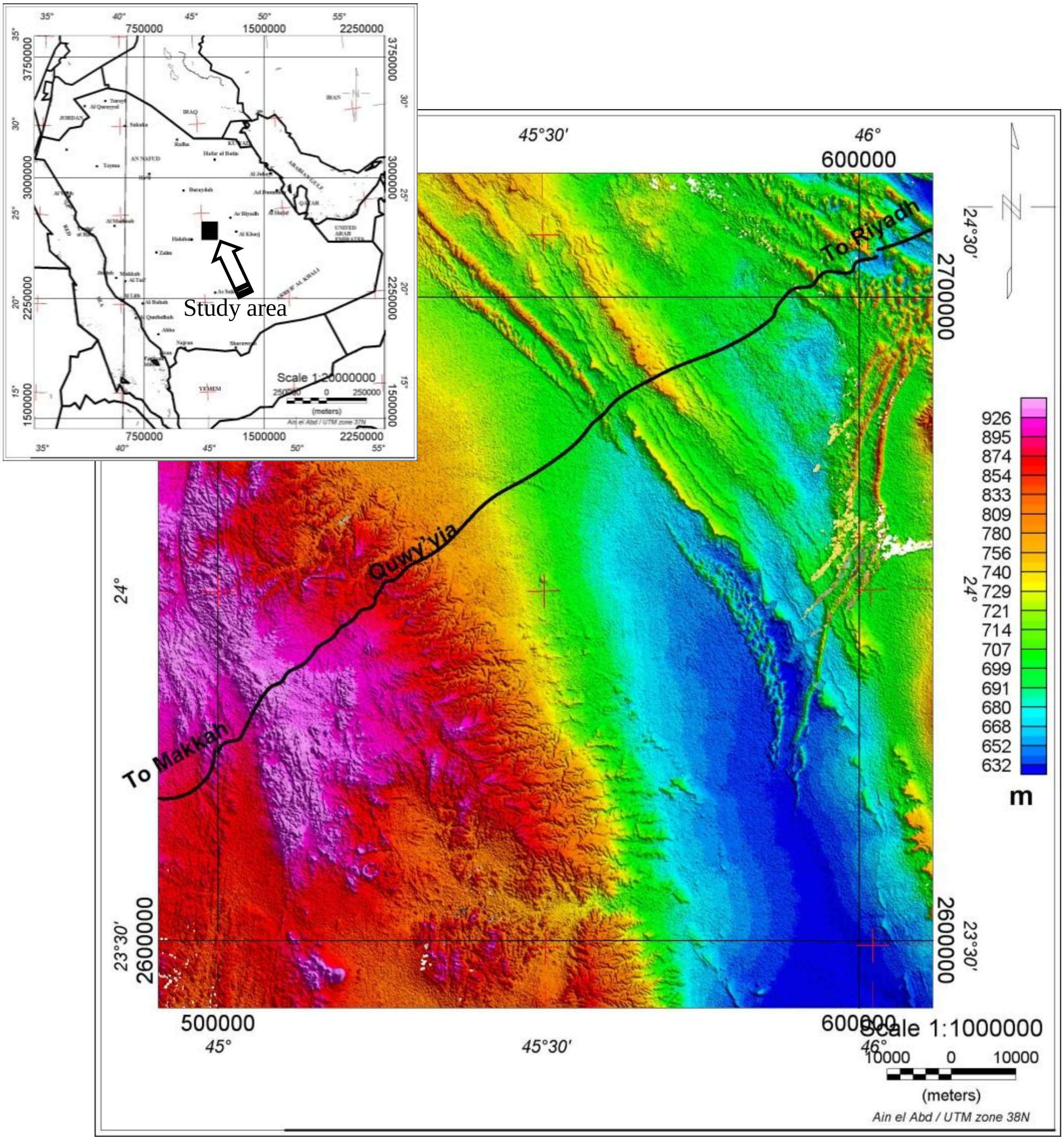

Figure 1. Location map of Al Quwy'yia area.

of Saudi Arabia. Zaidi and Kassem (2010) have applied the electrical resistivity tomography (ERT) in Diriyah area close to Riyadh, for estimating the depth of the water-bearing formations up to 70 m depth.

The present study aims to demonstrate and portray the shallow aquifer, applying surface electrical resistivity measurements in Al Quwy'yia area, along the contact zone with the Arabian shield. In order to achieve this target, geoelectrical resistivity technique has been utilized as it is important exploring tool for studying and depicting the subsurface aquifer in arid areas (Asfahani, 2007; Chandra et al., 2010; Yadav and Singh, 2007). It is based on measuring the contrast in electrical conductivity of the different rock units which is varying according to the rock nature (density, porosity, pore size and shape), water content and its quality and temperature (Parasnis, 1997). The resistivity is more controlled by the water contents and its quality within the matrix of the formation than by the solid granular resistivity value itself. Therefore, the subsurface sedimentary succession may be subdivided into different geoelectrical units according to the different percentage of humidity.

Geological setting

The study area is part of a large plain extending north south over several hundred kilometers, between the Tuwaiq mountains in the east and the basement complex in the west (Figure 2). This plain slopes from the west (950 m elevation) to the eest (632 m elevation) in the east, whereas there are many dry wadis running from the west to the east. The south-west corner of the study area is made up of crystalline rocks with dark rounded hills dissected by white sandy wadis and separated by large sand dune areas. Going to the eastern side, the area is almost flat. The Khuff limestone exposures are dissected by a dense network of wadis, evidencing active erosion during rainy periods. Locally, most Al Quwy'yia area has been covered with Quaternary deposits, which are in the form of alluvium and sand dunes (Figure 2). The thickness of such deposites range from few meters to tens of meters (Figure 3). The Quaternary deposites are followed by calcareous units of Khuff formation (Permian), which is exposed as a hilly belt of 20 km wide at the eastern side of the basement. Going to west and south of Al Quwy'yia, the Khuff formation overlies directly the basement complex as indcated in wells (Qap2-1 and Qap1-1), located at the eastern side of Al Quwy'yia area (Figure 3). The Khuff formation comprises various types of limestone and dolomite, shales and siltstone, sandstone and marl.

ELECTRICAL RESISTIVITY DATA ACQUISITION

Most of the electrical resistivity techniques require injection of electrical currents into the subsurface via a pair of electrodes planted on the ground. By measuring the resulting variations in electrical potential at other pairs of planted electrodes, it is possible to determine the variations in resistivity (Dobrin, 1988; Ozcep et al., 2009; Alile et al., 2011). A conventional vertical electrical sounding (VES) survey was used for quantitative interpretation where the center point of the array remains fixed and the electrode spacing is increased for deeper penetration (Loke, 1999).

The ultimate aim of the resistivity survey is to determine the resistivity distribution with depth on the basis of surface measurements of the apparent resistivity and to interpret it in terms of geology or hydrogeology. Nevertheless, when resistivity methods are used, limitations can be expected if ground inhomogeneities and anisotropy are present (SenosMatias, 2002). Due to large variation in resistivity of the formations, as well as inherent non-uniqueness in the interpretation techniques, the method sometimes results in mis-interpretation of the layer's parameters. The ambiguous interpretation, thus, often makes the results unreliable. It is thus necessary to interpret the soundings data taking parameters from other sources like geological and hydrological information into consideration (Kumar et al., 2007; Yilmaz, 2011) and/or applying the 2D inversion scheme to increase the data consistency. Such 2D inversion scheme reduces the uncertainty, which is common in the 1D inversion (Uchida, 1991).

Using the Syscal R2 acquisition system, operating with the Schlumberger electrode configuration, 16 VES data sets were recorded along three profiles passing through Al Quwy'yia area (Figure 2). For each VES, the current electrodes (AB/2) were varied from 3 to 1000 m and the potential electrodes (MN) were extended from 0.5 to 200 m in successive steps. Long steel electrodes (about 0.75 m) were used to optimise coupling between the electrodes and the ground particulary in the dry and friable sediments areas. At several locations, measurements were repeated or the current electrode positions were changed to improve the quality of the acquired resistivity data, which have been often checked during the data acquisition. Two VES (B2 and B3) have been carried out close to two boreholes (Qap2-1 and Qap 1-1). The geological data obtained from the wells were used in calibration process of the geoelectrical models and increase the constrains to minimize the uncertainties of the 1D inverted models (Figure 3).

Processing of VES data in 1D mode

Inspection of the acquired resistivity data curves (Figure 4) reveals certain properties that characterize the two distinct principal geological environments in the study area. The apparent resistivity curves are mostly of H-type, whereas the resistivity values are high at small AB/2 offsets due to the dry surface conditions. Then, the resistivity values decrease gradually due to the presence of aquifer saturated limestone rocks. With increasing AB/2 offsets, the apparent resistivity values increase again, probably due to the effect of bedrock.

Typical examples of 1D resistivity models obtained by iteratively inverting (IPI2win, 2000) code, which provides the opportunity to choose a set of equivalent solution and among them, select the best one with less fitting error between observed and calculated data. The routine is utilizing a least squares approach to minimize the difference between the input data and the theoretically derived curve. The quantitative interpretation has been applied to determine the thicknesses and resistivities of

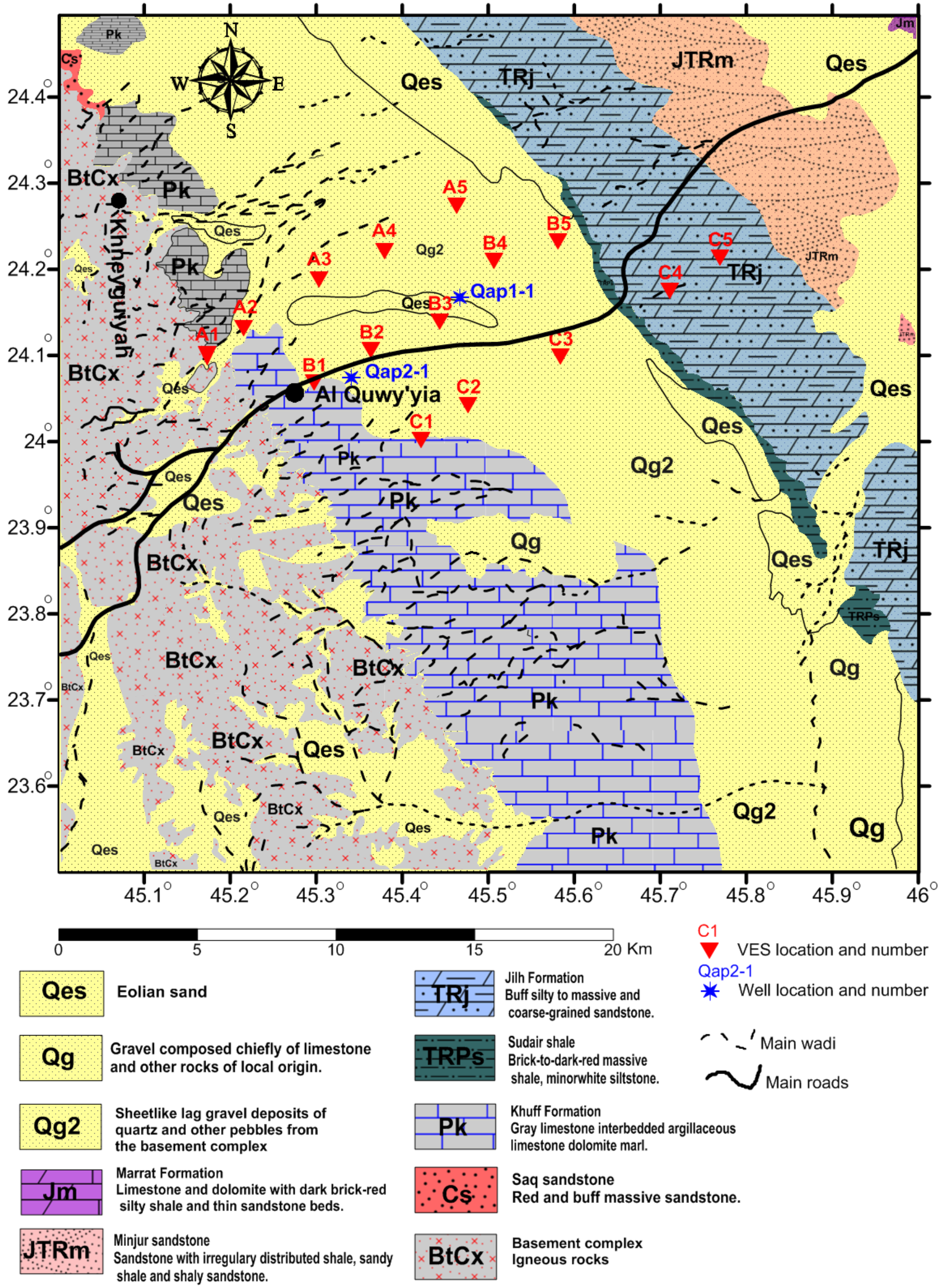

Figure 2. Location of VES and wells along the survyed site at Al Quwy'yia area superimposed on the geological map.

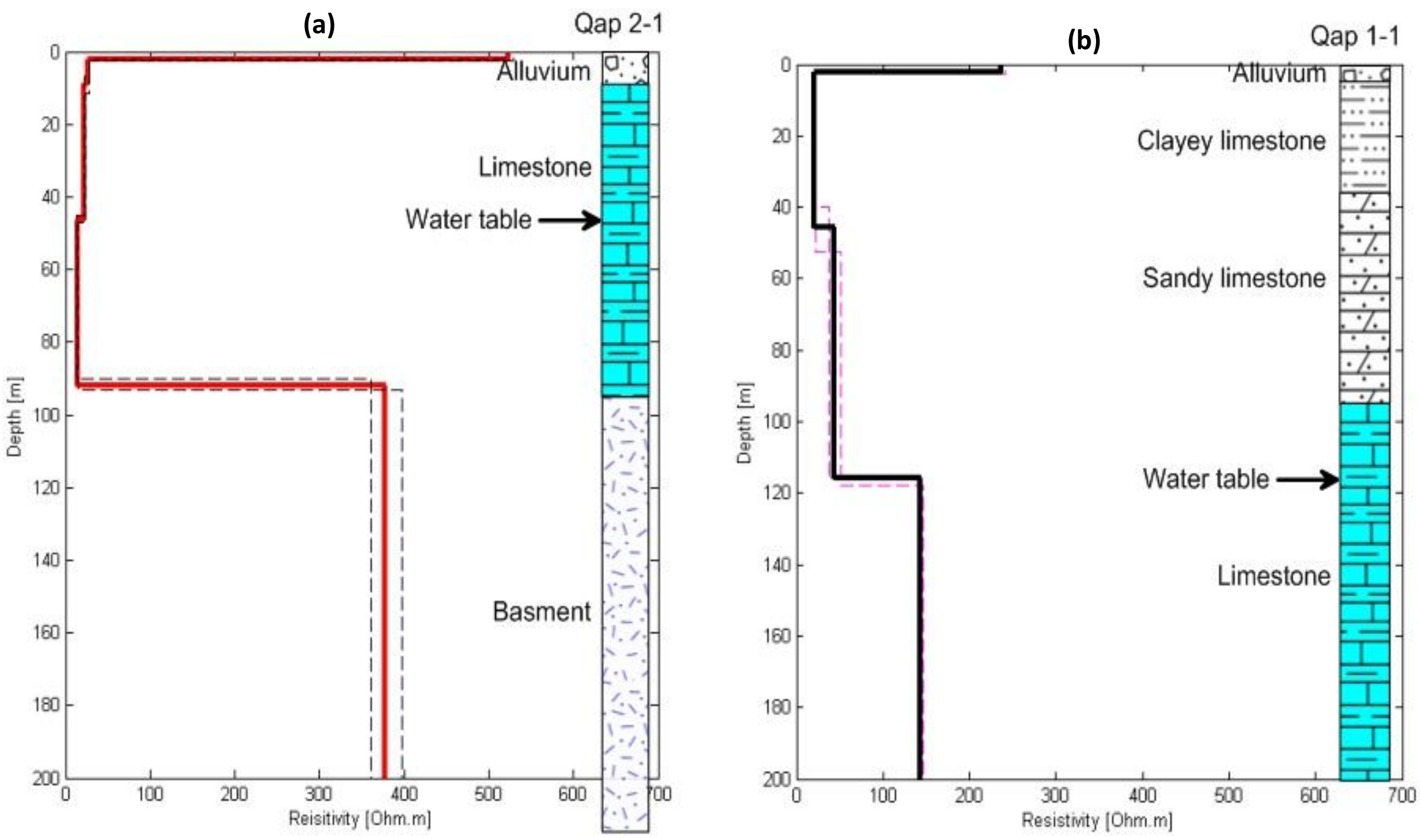

Figure 3. The layered resistivity and equivalent models constrained with the geological boundaries at two wells along profile B; (a) VES (2) and well (Qap2-1); (b) VES (3) and well (Qap1-1).

the different lithological units below each VES station (Figures 3 and 4). Resistivities are controlled primarily by the pore water conditions and ionic content rather than the lithological variation particularly in the sedimentary succession (Loke, 1999; Mohamed et al., 2011); therefore, there are wide ranges in resistivity for any particular subsurface matrix material. Accordingly, calibration of the resistivity model with the lithological layers is essential in such a case to reduce the non-uniqueness problem. During the processing of the 1D VES, it was essential to constrain the depths relative to the corresponding lithological boundaries of the two wells, whereas the resistivity values remain free during the inversion process. After some iterations, it was possible to achieve a good consistency between the resistivity model and the well lithological contacts explaining the changes in subsurface succession. The resistivity models in the two wells show a high resistivity at the shallow part due to the arid and dry condition of the alluvium layers. The thickness of this layer is less than 4 m. Then, the resistivity values decrease in both VES at the front of limestone layer in well (Qap2-1) and clayey sandstone, sandy limestone and limestone succession in well (Qap1-1). Then, resistivity increases sharply against the basement complex in well (Qap2-1), while the maximum depth of penetration does not reach the basement in well (Qap1-1). Small changes in resistivity values in the second layer are referring to the variable amount of clayey and sand content in the limestone layer. The static water level has been marked in both wells and the saturated limestone layer is located at depth about 42 m in well (Qap2-1) and 118 m in well (Qap1-1) (Figure 3).

It is not possible to constrain the depth of each resistivity layers all over the surveyed site on the basis of borehole logs. It is, however, possible to derive trial-and-error models that match well VES data sets based on the behavior of the two models, concident with the two wells. The 1D models for all VES aquired along the three profiles have been ploted in Figure 4. Most of these models follow up the same characters obtained near the available well (Ministry of Water and Electricity, Saudi Arabia, Personal Comunication, 2011). However, there are some minor changes due to the different content of calyey matrials in limestone layer and the location of each VES relative to the basment of the Arabian scheild (Figure 2). The modeled layer for the VES along profile (B) are more systematic in comparison to other profiles. The corresponding equivalnce for each model have been ploted and only the minimum and maximum equivalences have been presented for simplicity (Figure 4). The

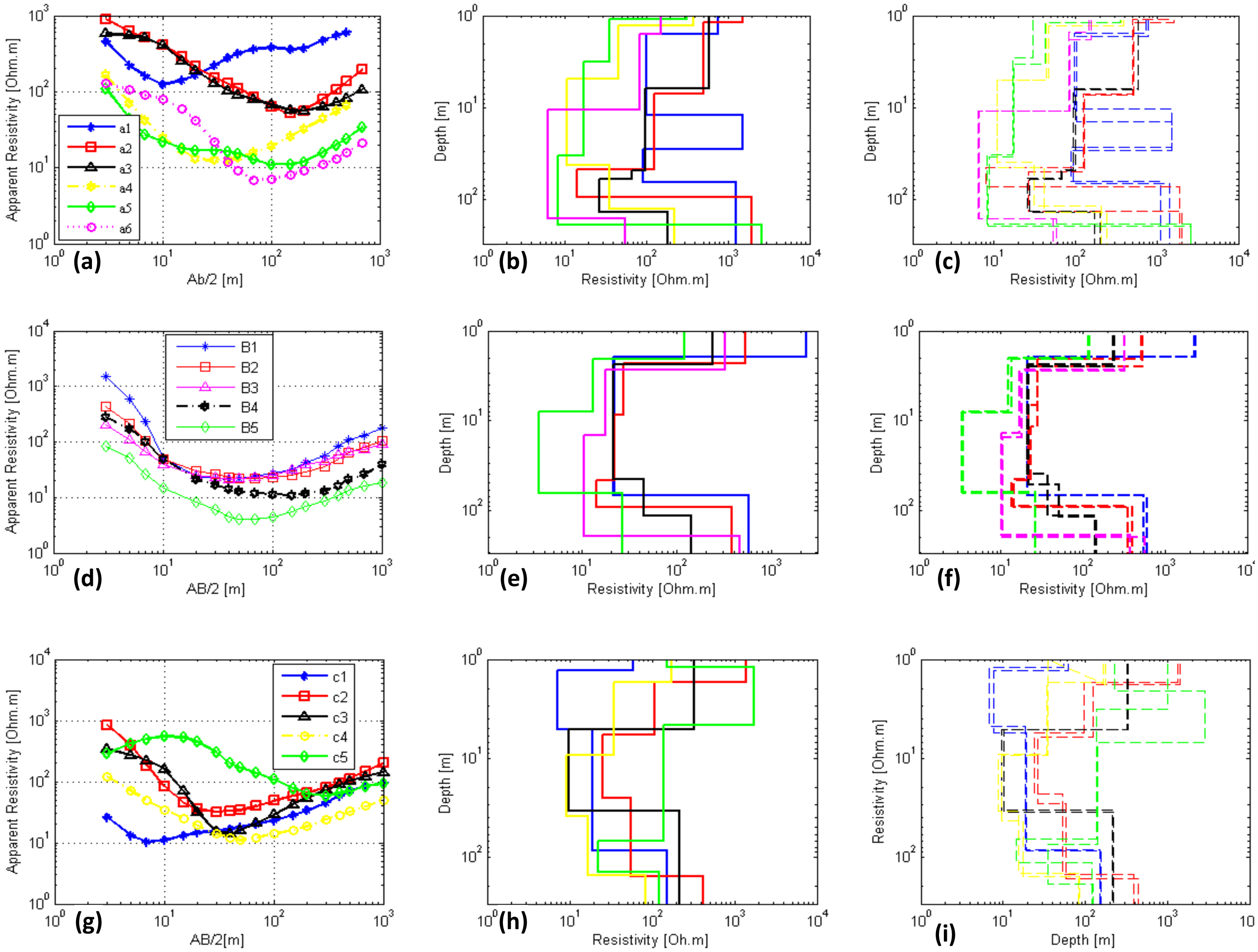

Figure 4. The acquired resistivity curves and the corresponding layered models with the equivalent mdoeıs along the study area; (a, b and c) at profile a; (d, e and f) at profile b; (g, h and i) at profile c.

equivalence models are consistent with the layer model with small deviation refering to the uncertianty of the 1D inversion process.

Processing of VES in 2D model

Since most of the VES data points were recorded along quasi-linear profiles, it is possible to process the acquired data in form of 2D subsurface models (Sasaki, 1989; Uchida, 1991). Applying the Uchida's (1991) algorithm, 2D resistivity models were derived for the available VES profiles. The algorithm is based on the Akaike Bayesian Information Criterion (ABIC) and utilize finite element calculation mesh (Sasaki, 1981; Tripp et al., 1984; Shima, 1990). The subsurface medium was represented by numerous rectangular blocks shown by the 2D mesh (Figure 5). The numbers of blocks in the vertical and horizontal directions are functions of the number of VES sites and the extension of AB electrodes. Resistivity values were assigned to each block of the mesh individually. The model is obtained under the assumption that the data error and roughness (spatial derivatives of the parameters) are normally distributed with zero mean. The optimum smoothness is also obtained in the process of the likelihood maximization. For the least-squares inversion with smoothness regularization, we seek a model, which minimizes both the data misfit and model roughness.

In the first step of an inversion, Uchida's (1991) algorithm, outputs seven models based on different inversion parameters. The best of these models, according to the root-mean-square (RMS) misfit values and the smoothing factors, is then used as the initial model for

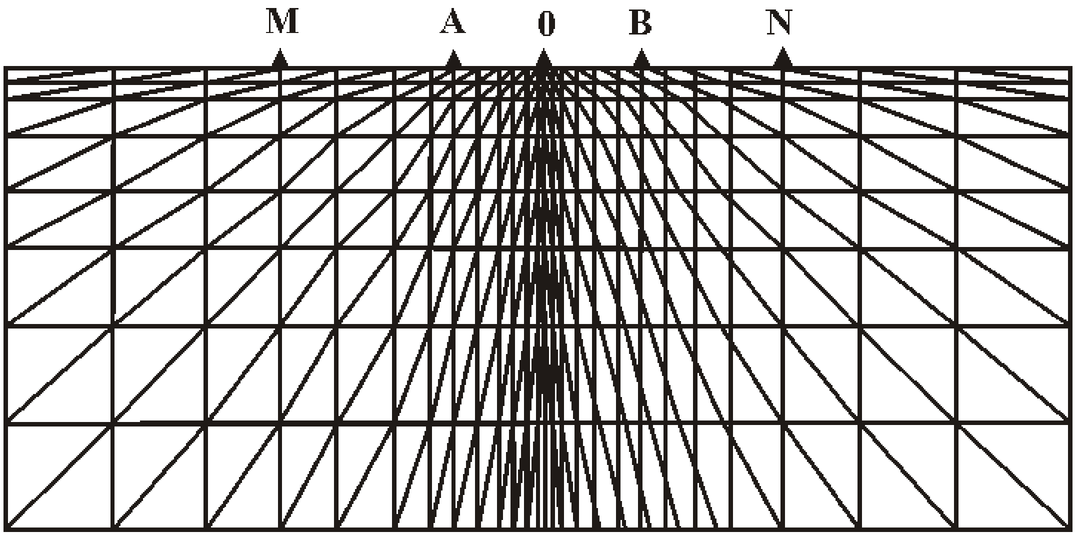

Figure 5. Sketch of the finite-element mesh used in the 2D inversion process. A and B are the current electrodes; M and N are the potential electrodes; O is the centre of the Schlumberger array.

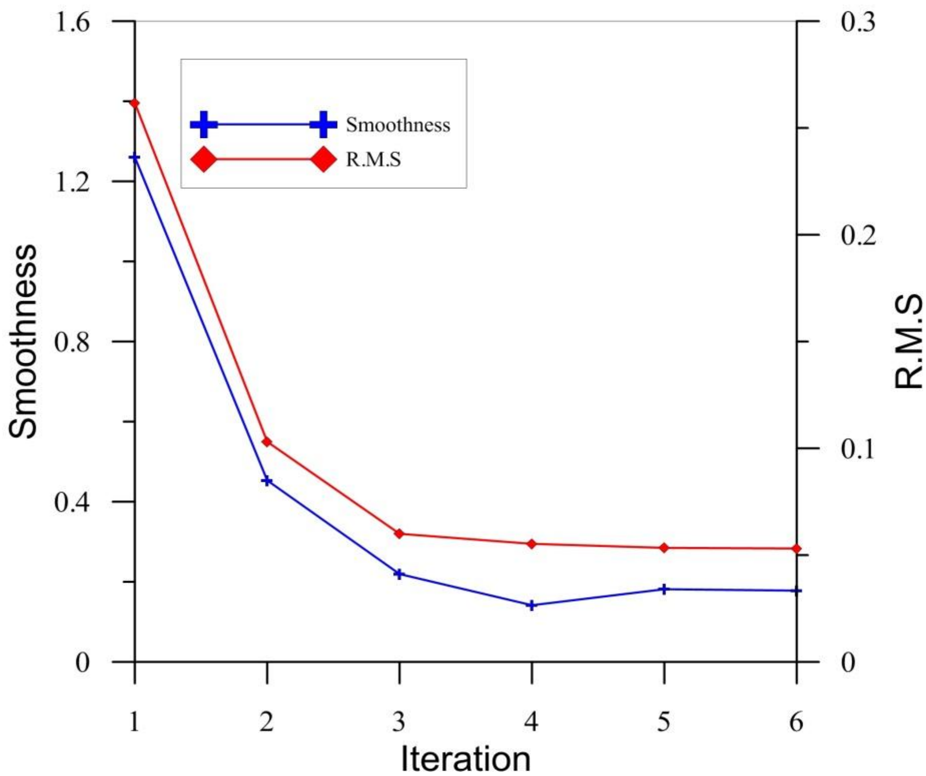

Figure 6. The inversion parameters (Smoothness and RMS) for profile (a).

the next iteration. Subsequently, the algorithm outputs seven new models. The process is repeated until the RMS misfits and smoothing parameters reach relatively stable minimum values. A typical example of the rate of convergence achieved by this procedure is presented in Figure 6. For profile (A), this figure shows that improvements in the RMS misfits and smoothnesses do not occur after the third iteration. For all VES profiles, convergence between the observed and predicted data was obtained by the third and fourth iteration.

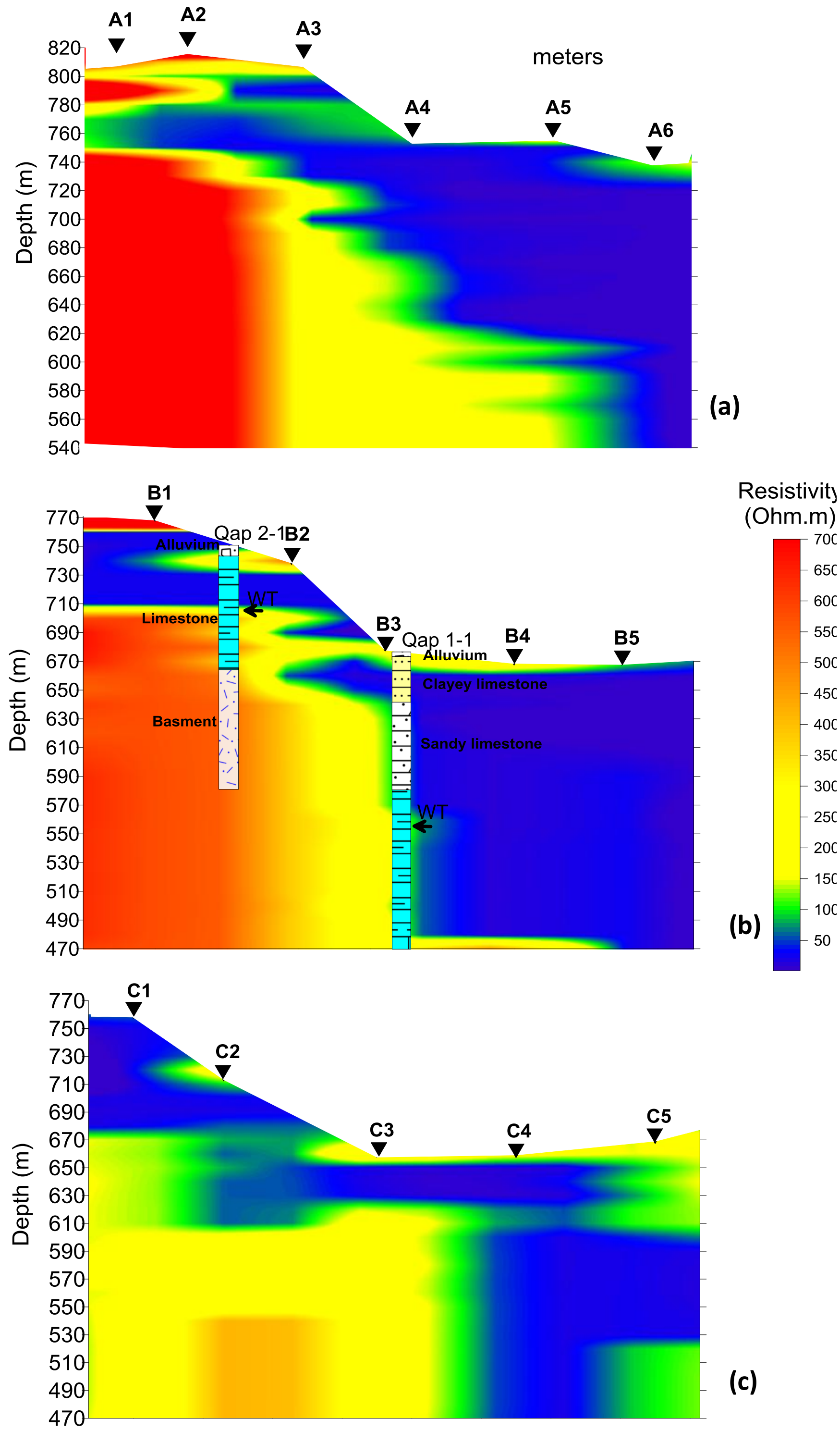

Figure 7. Geoelectrical cross sections deduced from 1D inversion models along profiles a, b and c.

INTERPRETATION

Based on the resultant 1D model of VES data, the electrical resistivity data are set of multi-layered models; each of them fit the observed field curve and describes the electrical properties of the subsurface medium. These models have been used to prepare 2D view of the electrical resistivity variation (Figure 7). Powerful geostatistical

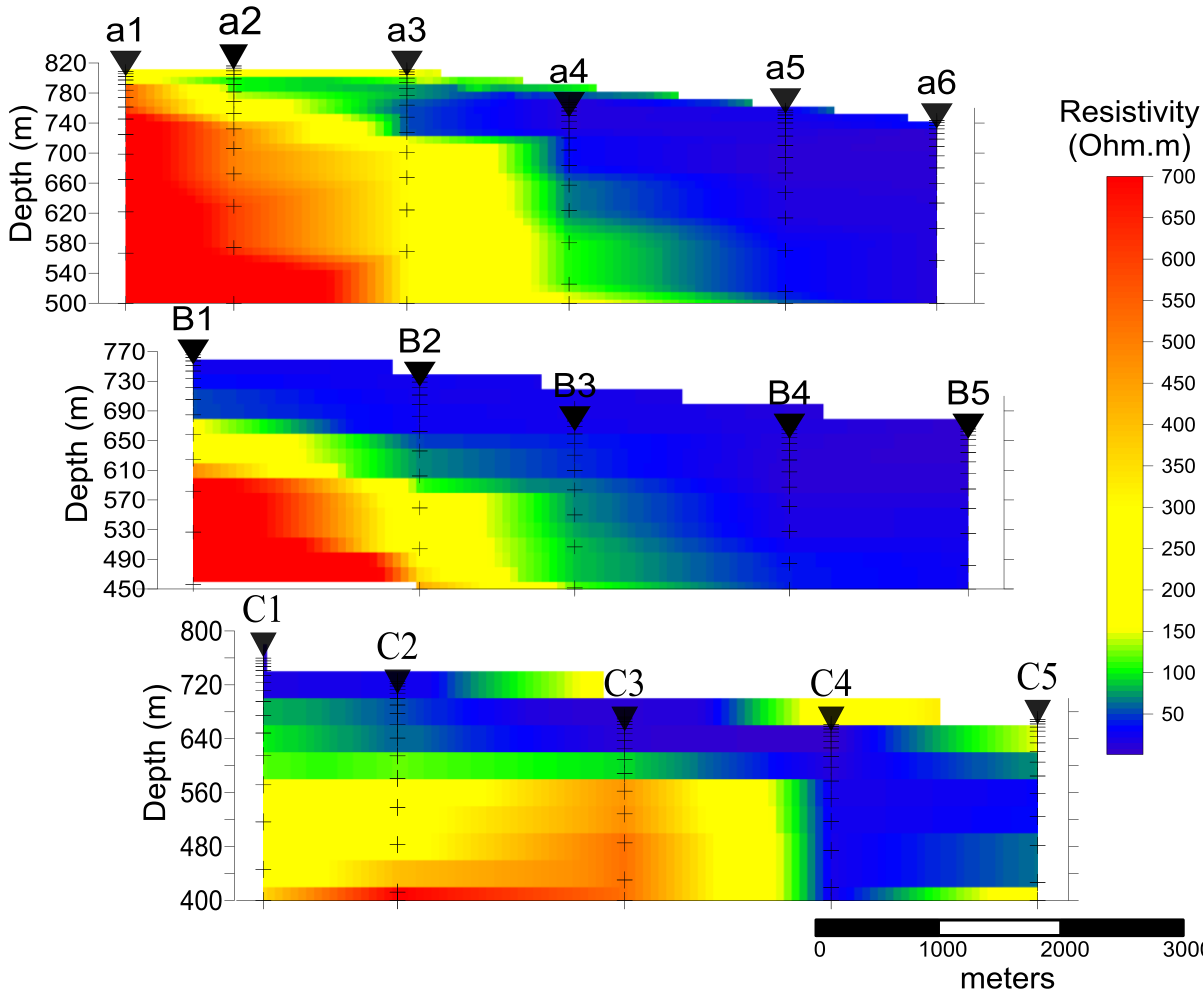

Figure 8. 2D Geoelectrical cross sections deduced from 2D inversion.

gridding (kriging) method has been applied to smoothly interpolate the inverted data. Linear color scale has been used to visualize the limited resistivity range (1 to 700 Ω/m). Generally, there are many features that can be interpreted from the resistivity cross sections. Firstly, underneath the most topographically elevated area in the south western side, the resistivity values are relatively high (> 500 ohm.m) and represent the occurrence of basement complex at shallow depth (Figure 7). This fact has been confirmed by the correlation between the well (Qap2-1) and the coincident VES (B2) (Figure 3a). Overlay the basement rocks, sedimentary cover exist with resistivity lower (<70 ohm.m) and variable thickness depends on the topography of the basement complex. Going to the eastern side, the topography is slightly flat and the resistivity values have relatively low values. This is due to the occurrence of limestone of Khuff formation, which has variable contents of clayey and sandy materials (Figure 7). The clay contents in the limestone rocks are increasing to the eastern direction as indicated by the lower values of resistivity. It is noticeable that the boundary of basement can be identified in both resistivity sections (A and B), whereas it is located deeper in the southern west in profile (C). The static water table is coincident with the top boundary of limestone unit, giving an indication that the subsurface aquifer is increasing in depth and thickness eastward. However, there are small potentiality of groundwater underneath the elevated stations in the south western side due to the small thickness of the limestone unit and also, due to the moving of groundwater eastward with dipping of basement.

The 2D inversion results for the data sets have been presented in the form of 2D geoelectrical cross sections (Figure 8). The data which gave the lower RMS values have been presented and compared with the equivalent 1D sections based on the 1D VES inversions. Although, there are matching between the 2D and 1D inversion schemes in the general trends of increasing and decreasing resistivity values, some details can be observed only in the 1D inversion results particularly in the shallow parts of the sections. This is due to the difference of the inversion schemes where the 2D inversion scheme is concentrated on the general trend of the resistivity variations along the profile. However, the main trends of locating the basement trends and thickness of sedimentary cover are resolved as well as the contact between the basement and limestone sediments of Khuff formation (Figure 8). The depth of investigation is more deeper in the 2D inversion results. Such results of 2D inversion can be achieved without any kind of direct constrains with the boreholes like the 1D inversion.

Conclusion

Resistivity surveys were carried out in Al Quwy'yia area at the centeral part of Saudi Arabia to map the acquifer and groundwater potentuality in promising area close to Riyadh. The results of 1D and 2D resistivity data interpretation indicated the depth to basement at the south western part of the study area as well as the contact boundary between the basement complex and sedimentary rocks. The static water table is found to be matching with the limestone rock as indicated from the comparison between the individual VES and the two wells in the study area. The thickness of the aquifer is increasing in the north eastern part where the possibility of the groundwater potentiality is increasing. The result of 1D data set were confirmed by 2D section interpretation. The difference between the two data sets are observed only in the shallow parts as the 1D inversion is collected in dense manner and conistrained with the available geological information. Collecting more data sets using deep VES and time domain electromagnetic are recommended for more analysis of the acquifer in the eastern part of the study area.

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