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Geothermal study using modelling of magnetotelluric data - A case study: Sabalan region, Iran

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SUMMARY

This research aims to examine subsurface structures in Sabalan geothermal region, northwest of Iran using three-dimensional (3-D) modelling of magnetotelluric (MT) data. For this, we have used MT data of 27 stations acquired along 4 survey lines in the northwest part of the region, namely Moeil valley. These MT data have been acquired by EDC Company in 2007. Since the real earth has three dimensions, 3-D inversion has obvious advantages over two-dimensional (2-D) inversion, and therefore, we have used 3-D inversion of MT data to obtain a 3-D electrical image of the subsurface structures of the region. In this research work, WSINV3DMT code has been employed for 3-D inversion of the acquired MT data. As a result, apparent resistivity and phase cross-sections have been obtained. Furthermore, dimensionality analysis of the MT data has been carried out by using polar diagrams of the impedance tensor. The results of this dimensionality analysis indicate that shallow subsurface structures can be considered as one-dimensional (1-D) or 2D structures, however, deep structures should be considered as 3-D structures. After preparing the model parameters and designing the suitable modelling blocks, 3-D Occam's inversion of the MT data has been made. The location of the geothermal reservoir in the region is determined from the results of the 3- D Occam's inversion. Moreover, the results of the 3-D inversion of the MT data have been compared with the results of the 2-D models, and then, the results have been interpreted using geological information from the region. From the interpretation results of this study, we have found that the geothermal reservoir is located at the depth of 800 to 2562 meters.

Key words: 3D inversion, magnetotelluric data, Occam method, geothermal structures, WSINV3DMT algorithm.

INTRODUCTION

One of the most important applications of the magnetotelluric method is its use in the exploration of geothermal resources. Since geothermal resources produce large changes in subsurface resistivity, they are ideal targets for magnetotelluric methods (Fanaei and Oskooei, 2011; Didana, 2010). In recent decades, inversion methods in quantitative interpretation of magnetotelluric data have become very important. By using inversion methods, a model of physical properties can be obtained from geophysical data that defines the subsurface structures. Two-dimensional (2-D) inversion methods are still the most common tools for modelling magnetotelluric data due to their higher speed and cheaper price compared to three-dimensional (3-D) inversion methods. There are many 2-D inversion methods, which calculate the basic features of resistivity models. In some cases, by using 2-D inversion, an accurate interpretation of 3-D structures can be obtained, but the disadvantage of 2-D inversion is that they are very complicated in 3-D structures, and thus, the obtained 2-D models are not logical and suitable for 3-D structures as we need 3-D inversion to obtain an ideal model that contains sufficient information of the investigated area. Geothermal energy is thermal energy inside the earth. Its surface effects are in the form of hot springs or water fountains, and it is mostly concentrated along the tectonic plates and in known volcanic and seismic areas. Since geothermal sources are usually accompanied by thermal changes, as a result, they produce metamorphic products (clay minerals, etc.) with low resistivity above and around geothermal sources that have higher resistivity. For this reason, in this study, magnetotelluric method has been used to identify and explore geothermal sources after preliminary geological and geochemical surveys, and before any exploratory drilling. Magnetotelluric surveys have been carried out three times in the region in 1998, 2007, and 2009. In this study, 27 magnetotelluric soundings that were collected in 2007 by Iran's Renewable Energy and Electricity Efficiency Organization, were used. The mentioned data were collected using the Phoenix MTU-5A device with a frequency range of 0.0005 to 320 Hz from Moeil valley located northwest of Sablan Mountain. The data of the region were subjected to impedance analysis with the help of WinGLink software. Then, by using 2-D inversion, the electric resistivity model along the 4 survey lines was obtained and the results were compared with the available geological information. Furthermore, 3-D inversion of magnetotelluric data using WSINV3DMT code was carried out to determine the possible location of the geothermal reservoir. 2-D inversion modelling of magnetotelluric data can be made with any of the TM or TE modes or a combination of these two modes. Meanwhile, the TM mode is more suitable for examining 2-D structures and lateral changes of resistivity. Moreover, according to the studies carried out by

Berdichowski et al. (1998) and Wanamaker et al. (1984), the response of the TM mode is more stable compared to the effects of 3-D resistive structures, and this mode has a greater ability to depict 3-D structures as well (Alborzian , 2014). Therefore, in the present study, this mode has been used for 2-D inversion of magnetotelluric data.

Geology of the region

From the geological point of view, the investigated area is a part of the northwestern slopes of Sabalan or a part of the high plateau of Azerbaijan. The tectonic activity of the region has been affected by the movement of the tectonic plates at the meeting place of the Iranian, Caspian, Eurasian and Arabian plates. The old activity of Sabalan started from the Eocene, but what created Mount Sabalan started in the Pliocene and continued until the evening after the last ice age. The building materials of this volcano are obtained from deep magma, but it has been affected by complex processes, the most important of which are partial crystallization, digestion, and mixing of two magmas. After the Eocene, the next stage of activity of this mountain belongs to the Miocene. Therefore, magmatic evolution has taken place over a long time (Didon and Germain, 1976). In the study area, extensive magmatic activities from Eocene to Quaternary can be seen. The structure of the main fractures has been built on a region between two big old faults, and during its growing stages, the crater has created a 12-km-diameter collapse.In addition, there is no evidence of magmatic activities of the Upper Cretaceous period. The Eocene lavas have come up through deep fractures (Noorallahi et al., 2007). The geological map of the region is shown in Figure 1.

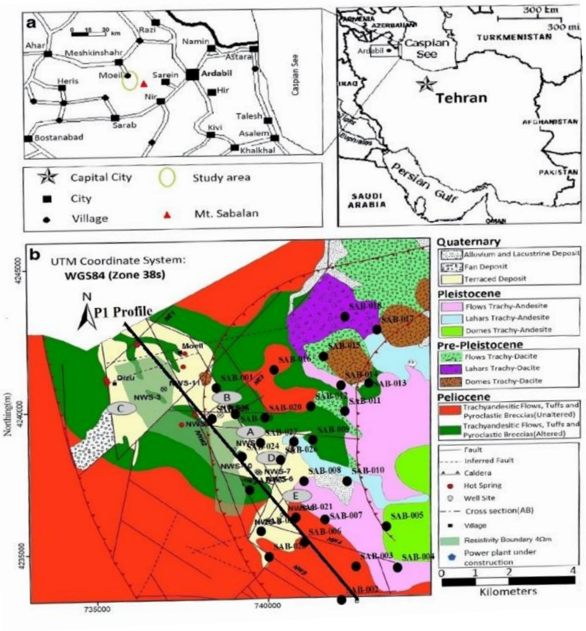

Figure 1. Geological map of the study area. (Seyedrahimi-Niaraq et al., 2017) The black line segment indicates the *P1* survey line or profile.

The resistivity model can be as a result of 2-D inversion of magnetotelluric data. For this purpose, after correcting the static displacement, 2-D inversion of the data of the magnetotelluric stations located along 4 survey lines was performed using non-linear conjugate gradient method in WinGLink software. For the P1 profile, a half-space with a resistivity of 150 ohm meters was selected as the initial model, and the apparent resistivity and phase data in 15 stations located along the P1 profile were used for inversion. Moreover, floor error for apparent resistivity and phase data was 20% and10%, respectively. The maximum number of iterations of 50 was considered in the inversion process. Figure 2 shows the estimated resistivity model resulting from the TM mode inversion. The RMS error value of 2.874 for this model was obtained.

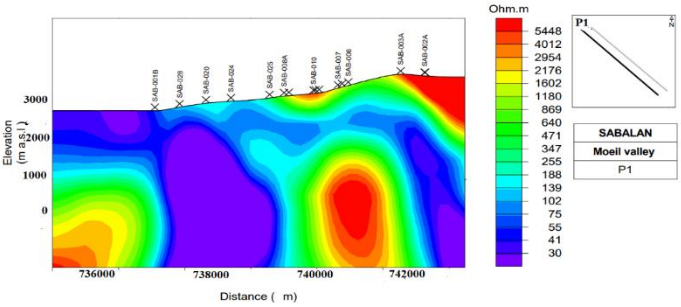

Figure 2. The model resulting from 2-D inversion of magnetotelluric data along the *P1* profile (soundings 3, 2, 6, 23, 7, 21, 22, 10, 8A, 8B, 20, 25, 24, 28, and 1) RMS = 2.874.

Figure 3 shows the geological section of the Sabalan region based on the study made by Seyed Rahimi Niark et al. (2017) along profile P1. Comparing this Figure with the resistivity model obtained in Figure 2, it seems that the relatively conductive layer visible in Figure 2 is equivalent to pyroclastic and porous rocks, in which the presence of hydrothermal solutions and hot water causes low resistivity of these rocks. In addition, this decrease in resistivity can be caused by the presence of argillic alteration and clay formation due to the alteration of igneous rocks in the reservoir area. The subsurface geothermal reservoir is located at a depth of 800 meters with a thickness of 1500 to 2000 meters along the profile. Moreover, a surface resistive layer with a resistivity of more than 350 ohm-meters can be seen. Considering the geological map (Figure 1) and the geological section of the region (Figure 3), this surface resistive layer probably is the surface volcanic lavas of andesite type. Furthermore, below the conductive layer, the resistivity has increased to more than 4000 ohm-meters that can be an indicator of intrusive and hot igneous rocks, which are probably the origin of thermal currents.

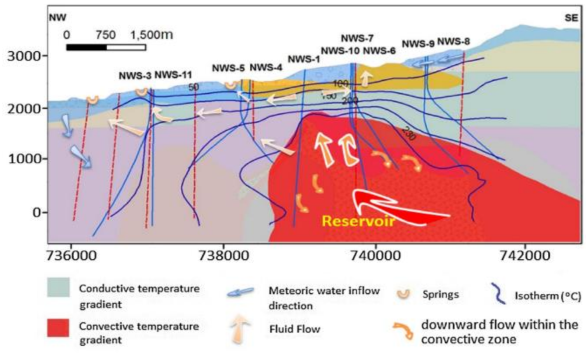

Figure 3. Geological section of Sablan region (Seyedrahimi-Niaraq et al., 2017).

The resistivity sections obtained as a result of 2-D inverse modelling of the magnetotelluric data along P2, P3, and P4 survey lines haave been shown in Figures 4, 5, and 6, respectively.

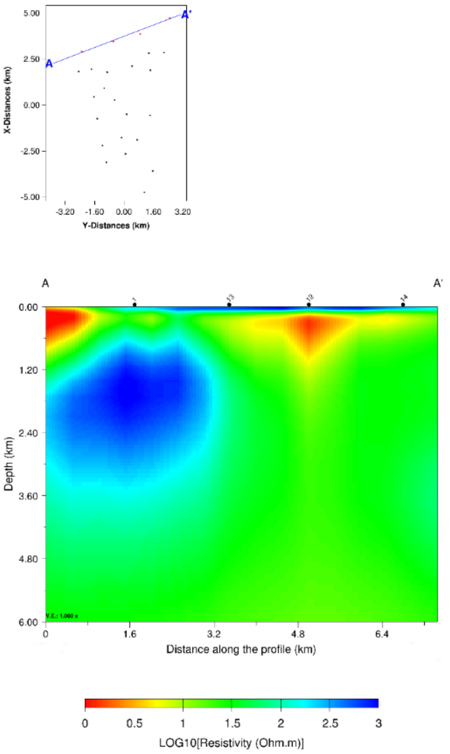

Figure 4. The resistivity section obtained as a result of 2-D inversion of magnetotelluric data along *P2* survey line comprising of sounding points 1, 13, 12, and 14.

As can be seen from Figure 4, there is a resistive zone at the beginning of the P2 profile that can be verified based on geological information. At the beginning of the profile, from the surface to a depth of 800-700 meters, there is a conductive zone, and below station 12, there is a conductive zone with a resistivity of less than 10-ohm meters, while the ground surface in this part of the profile is resistive.

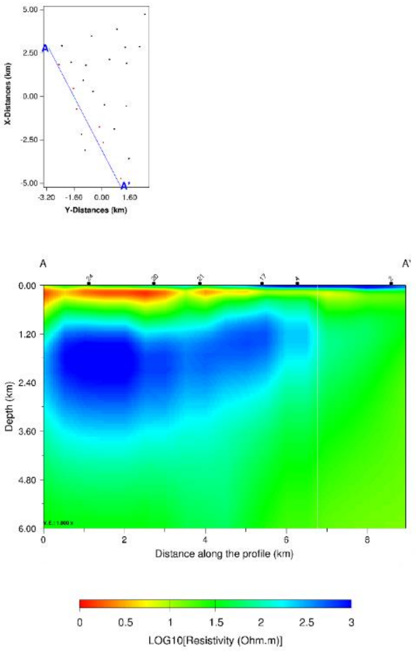

Figure 5. The resistivity section obtained as a result of 2-D inversion of magnetotelluric data along *P3* survey line comprising of sounding points 24, 20, 21, 17, 4, and 2.

According to Figure 5, there is a conductive zone extending from the beginning of profile P3 to a shallow depth of approximately 600 meters. In the middle of the profile, there is also a surface conductive zone that its depth is not more than 200-300 meters. A resistive zone can also be seen at the last part of the profile. A very large and relatively deep resistive zone is also found at the resistivity section along this profile as evident in Figure 5.

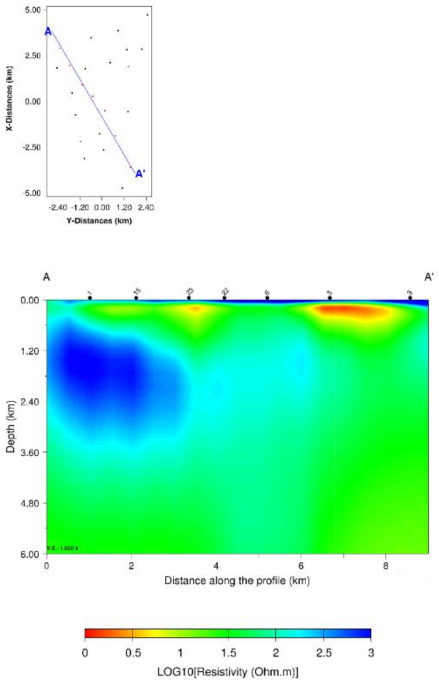

Figure 6. The resistivity section obtained as a result of 2-D inversionof magnetotelluric data along *P4* survey line comprising of sounding points 1, 15, 23, 22, 6, 5, and 3.

According to Figure 6, there is a resistive zone at the beginning of the P4 profile in which its lateral extension is about 3000 meters and its depth extension is 1500 to 2000 meters. In the middle of the profile, there are 23 conductive zones in the subsurface. The wider conductive zone is at the end of the profile and below thestation 5. This conductive zone extends 200-300 meters in depth. There are also resistive surface zones with resistivity of 1000 ohm meters, and depth of less than 100 meters.

3-D inversion

For 3-D inversion of the magnetotelluric data in the study area, a model was built. The considered primary model (Figure 7) has dimensions of 34×34×37 in x, y and z directions, respectively. Out of the total of 37 blocks considered in the Z direction, 7 blocks form the air layer. The central block has dimensions of 500 × 5030 meters, and the increase factor for the blocks outside the central part in x and y directions is 1/3. The thickness of the first layer in the z direction is 20 meters. The resistivity of the initial model is equal to 10 ohm-meters. The inversion has been done with all impedance components and 5 iterations.in which the final RMS is equal to 2.734. The resistivity sections in the x and y directions have been taken up to a depth of 7850 meters (Figures 8 and 9)). Three cross-sections have also been obtained in the x and z directions.

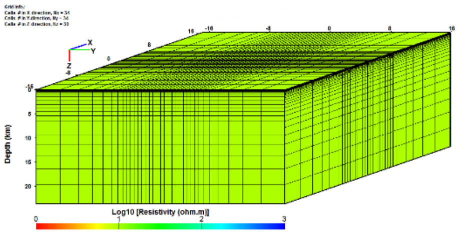

Figure 7. A part of the initial model to start the inversion in three directions of *x*, *y* and *z*. The dimensions of the model is 34×34×37.

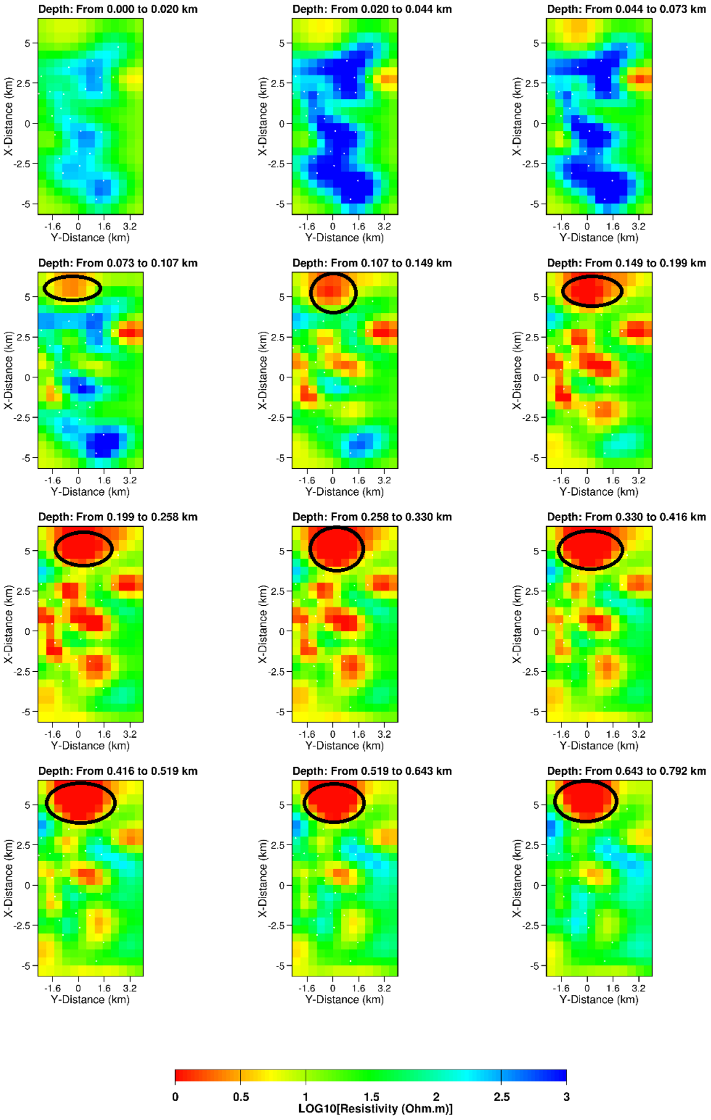

Figure 8. The resistivity sections at different depths from 0 to 0.792 km obtained from 3-D inversion of magnetotelluric data.

Figure 8 shows the subsurface resistivity distribution at different depths from the depth of 0 to 792 meters. Different conductive zones are observed in the resistivity sections shown in the Figure. As the depth increases, the conductive zones marked by ovals in the Figure increase. Alteration of rocks increases the conductivity of the rocks asthe formation of clay in the rocks is one of the alteration products that causes to have lower resistivity or higher conductivity of the rocks. In this Figure, the conductive zones, marked by the ovals, correspond to the top surface of the geothermal reservoir.

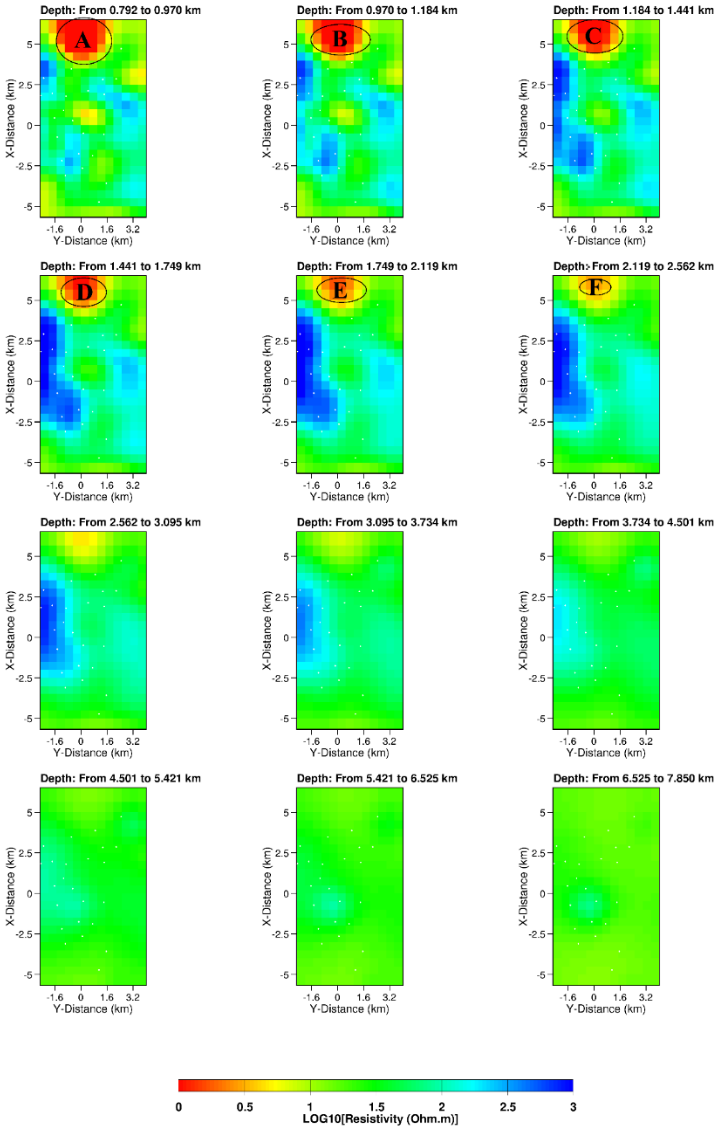

Figure 9. The resistivity sections at different depths from 0.792 to 7.850 km obtained from 3-D inversion of magnetotelluric data.

Figure 9 demonstrates the subsurface resistivity sections at different depths from the depth of 792 to 7850 meters. The geothermal reservoir, indicated by conductive zones and marked by ovals in the Figure, has expanded in depth well from the depth section of 970 to 1184 meters up to the depth of 2562 meters. It is noted that the location of the geothermal reservoir at different depths is shown by English letters in the Figure.

CONCLUSIONS

As can be seen from the results of 2-D, and especially 3-D inversion of the acquired magnetotelluric data in the study area (Figures 8 and 9), the conductive zone, representing the geothermal reservoir, starts from the depth of 800-1200 meters and continues to the depth of approximately 2500 meters. This deep zone can be associated with fluid flow within subsurface areas of higher density. This zone is located just below the brittle metamorphic surface, and it probably indicates the fluid continuity along the fracture boundary. In other words, the higher flow in these areas can be explained by lower porosity (higher density) or generally lower resistivity of the pore fluid. Furthermore, areas with higher resistivity can be interpreted as having higher porosity (lower density). Considering the existence of numerous faults in the study area and their intersection (geological map), the above hypothesis that this zone with high conductivity may be related to fracture zones, is confirmed. The results of the interpretation of the resistivity sections, shown in Figure 9, imply that the conductive zone representing the geothermal reservoir is located below a surface or a conductive mass in Figure 8 that is due to alteration of rocks and formation of clay as a product of the alteration in the rocks.

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