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ABSTRACT

Geothermal is one of the important energy sources because it is renewable energy and does not have any significant damage to the environment. The western Anatolian part of Turkey has a high potential in terms of geothermal energy. The study area, which is thought to have geothermal characteristics, is close to Afyonkarahisar province in Turkey. In this study, gravity data with horizontal gradient magnitude (HGM) and tilt angle map (TAM) techniques, and electric resistivity data with vertical electric sounding (VES) technique are used for the reveal of underground structure and location of hot water regions. Thus, locations with excess geothermal energy can be identified and locations of potential hot water areas can be determined. The possible hot areas are characterized with high density contrast and low resistivity values. According to the calculations made, the depth of the target mass for the geothermal source starts from approximately 300 m and continues up to 1100 m. More reliable and accurate results can be obtained by holistic interpretation of gravity and electrical resistivity methods in a geothermal field.

Key words: Geothermal field, gravity, vertical electric sounding, horizontal gradient magnitude, tilt angle.

1 Introduction

Maps created using Bouguer gravity data were generally used for underground illumination (Simpson et al., 1986). Maps prepared using vertical gradient data highlight target masses close to the surface (Jekeli 2004). Horizontal and vertical changes in gravity data generally

give the limits of density variation in these directions. Evjen (1936) was the first to reach useful results in determining target masses using gravity vertical derivative data. Hansen et al. (1987) were able to determine the lateral boundaries of target masses by using gravity data with horizontal gradient magnitude (HGM) and the analytic signal techniques. Miller and Singh (1994) utilized the tilt angle map (TAM) method to determine the masses exhibiting magnetic properties. Oruç and Keskinsezer (2008) showed that TAM values calculated from gravity gradient tensor data can be used to determine lineament structures that present density differences. Oruç (2010) was able to determine the lateral boundaries and depths of target masses presenting density differences by using the vertical derivative values of gravity data with the TAM technique. Depth and resistivity values of the underground target masses were determined using the vertical electrical sounding (VES) method (Pekeris, 1940). Apparent resistivity values determined from electrical measurements made in a specified area can be interpreted with various methods and the resistivity change from top to bottom can be determined in this area (Bhattacharya and Patra, 1968). The theoretical measurement depth in Schlumberger electrode array used in this study is expressed with half opening of the current electrodes.

Many studies have been carried out by Tezcan (1971) and other researchers (Long, et al., 1980; Volpi, et al., 2003; Bibby et al., 2005; Kagel, et al., 2007; Cumming, 2009; Sanliyuksel and Baba, 2011; Zouzias et al., 2011; Flóven, et al., 2012; Gorecki et al., 2015; Kana, et al., 2015; DomraKana, et al., 2015; Tang, et al., 2017; Arzate, et al., 2018; Gültekin et al., 2019; Haklıdır et al., 2020) to determine potential geothermal areas using geophysical methods. Geothermal resources have highly porous and permeable reservoir rock, heat source and fluid components that live the heat to the surface. Around the study area, there are many geothermal wells with a temperature of 55-120 °C (MTA, 2005). The HGM and TAM techniques used vertical gradient data and the VES technique based on the electricity data have been applied to determine the points considered to have geothermal properties and to suggest drilling locations in the field near Afyonkarahisar province, Turkey. With this study, the most efficient geothermal well locations in the area were determined as a result of the calculations made.

2 Methodology

TAM anomalies occur between -90^0 and $+90^0$. In TAM anomaly maps, zero contours are formed on the target mass lateral boundaries. By following these contour lines, the lateral

locations of the target masses can be determined (Miller and Singh, 1994). Applying TAM technique to the vertical gradient ($\partial g_z / \partial z$) of the gravity field procures a tilt angle, ϕ (Oruç, 2010):

$$\phi = \tan^{-1} \left(\frac{\frac{\partial^2 g_z}{\partial z^2}}{\sqrt{\left(\frac{\partial^2 g_z}{\partial x \partial z}\right)^2 + \left(\frac{\partial^2 g_z}{\partial y \partial z}\right)^2}} \right) \quad (1)$$

The denominator part in Equation 1 is HGM for the vertical gradient ($\partial g_z / \partial z$) of gravity field (Oruç, 2010). The HGM is given in equation 2 as;

$$\text{HGM} = \sqrt{\left(\frac{\partial^2 g_z}{\partial x \partial z}\right)^2 + \left(\frac{\partial^2 g_z}{\partial y \partial z}\right)^2} \quad (2)$$

Here, the $\partial^2 g_z / \partial z^2$ is second vertical gradient of gravity data and the $\partial^2 g_z / \partial x \partial z$ and $\partial^2 g_z / \partial y \partial z$ are horizontal gradient of the first vertical gradient data on the x and y direction in Fig. 1, respectively.

Figure 1. The second gravity gradients and tilt angle (modified from Oruç, 2010).

The vertical gradient data has been determined by fast Fourier transform (FFT) equation (Gunn, 1975). The horizontal derivative and vertical derivative of g_z , vital for reckoning of Eq. (1), have been numbered using FFT equation. The zero counts in the TAM anomaly map and the bands formed by the high amplitude values in the HGM anomaly map correspond to the lateral boundaries of the target mass. Moreover, one can designate the depth estimation since half horizontal interval between the $\pm 45^\circ$ contours of TAM is the depth to top of target mass (Oruç, 2010).

Geophysical methods have been applied for many years in the exploration of geothermal energy resources and very successful results are obtained. In geophysical methods, electrical resistivity equation is used in geothermal research. High temperatures and water flow in geothermal areas significantly affect resistivity values. By using the apparent resistivity with Eq. (3), real resistivity and depth information can be obtained for the target masses sought. The geometric factor is found using Eq. (4). A and B represent the current electrodes. M and N represent the potential electrodes inside. O represents exactly the midpoint (Fig. 2).

$$\rho_a = K \frac{\Delta V}{I} \quad (3)$$

$$K = \frac{|AB|^2 - |MN|^2}{4|MN|} \pi \quad (4)$$

In Eq. (3) ρ_a in units of Ohm.m represents apparent resistivity. ΔV in unit of mV represents the measured potential difference, while I in unit of mA represents the applied current. The coefficient of the electrode array is also denoted by K . $AB / 2$ ($L / 2$) in unit of m represents half the gap of current electrodes, while $MN / 2$ is half the distance between potential electrodes. With the VES technique, the depth model of the target masses at an electrical measurement point is given with 1-D apparent resistivity. The electrodes used are opened in a certain order and deeper information is obtained.

Figure 2. Schlumberger electrode array for vertical electric sounding.

As mentioned above, the applied electric current reaches deeper by opening the electrode gaps. Thus, the difference measured in the potential electrodes brings information from deeper. The difference between said potential electrodes is used to calculate the apparent resistivity values. Thus, the location of the target masses being searched is displayed from the surface downwards.

3 Calculations

With this study, it is aimed to determine potential geothermal locations in a selected area near Afyonkarahisar province and to determine the well locations to be drilled (Figure 3). Paleozoic Afyonkarahisar metamorphic units and Pliocene basalt units composed of Schist and Marble are thought to be the aquifer containing hot water. The upper rock of the aquifer is also composed of Neogene units. It is assumed that the source of heat in the area is magma intrusions that form volcanic units.

Figure 3. The study area and the geologic draft map of study area (After from the URL-1)

The study area is 2000 m east-west and 2000 m north-south lengths (Fig. 3). Electricity and gravity data in this study area were obtained from Rasim Taylan KARA. The distance between measurement points is taken as 25 m. The coordinates of the measurement stations were determined in advance in a plan. Gravity was measured at 1681 points in the study area. On the other hand, at 11 points, the electrical VES measurement was taken from the surface downwards (Fig. 4b). The positive anomalies seen in the gravity anomaly map in Figure 4a are thought to be caused by metamorphic rocks that are thought to exist in the study area. This relationship is interpreted as the presence of altered metamorphic rocks that contain hot water. Positive anomalies arising from the locations of metamorphic rocks under alluvium can be seen more clearly in the gravity vertical gradient map (Fig. 4b). By applying HGM and TAM techniques, which are the boundary analysis techniques, to the vertical derivative values of the gravity data measured in the study area, the lateral edges and depths of the metamorphic units containing hot water were tried to be determined. In the gravity anomaly map in Figure 4a, high value gravity anomalies are seen in the central and western parts. It is considered to be a relationship between maxima anomaly locations in the Bouguer gravity anomaly and vertical gradient values of gravity data maps and potential metamorphic rocks belonging to the study field (Figs. 4a and 4b). Initially, using the FFT equation proposed by Gunn (1975), the vertical derivative values of the gravity data measured in the field were determined (Fig. 4b). Then, by applying the HGM technique to these derivative data, the locations of the lateral edges of the possible target masses were tried to be determined (Fig. 4c). Finally, by applying

the TAM technique to these derivative data, both the lateral boundaries and the depths of the target masses were tried to be determined (Fig. 4d). As specified in the method, the depth from the surface of the upper boundaries of these masses is calculated throughout the boundaries of sought mass by using the half length values of horizontal distances remaining between the $\pm 45^0$ contours of the tilt angle in the TAM image (Fig. 4d). While the maximum value contours of the HGM and the zero contours of the TAM give the lateral boundaries of the target masses sought, the depth values of these masses give half of the lateral distance between the $\pm 45^0$ contours of the TAM (Oruç, 2010). Depth of upper surface of the target masses guesses from the intervals are remarked to be around 300 m. It can be seen that this depth value slightly increases from west to east by following the horizontal interval between $\pm 45^0$ contours of TAM map in the figure 4b.

After evaluating the gravity data in the study area, the VES arrogances were made at 11 locations along 2 lines. These are VES 1, 2, 7, 8, 9, 10 and 11 measurement points (Fig. 4b).

Figure 4. **a)** Bouguer gravity anomaly map. **b)** First vertical gravity gradient map, VES locations and electricity profiles. **c)** HGM map. **d)** TAM map. Dashed lines show the boundaries of the possible metamorphic rocks

The $AB / 2 = 1000$ meters theoretical depth were investigated in the VES implementation. At the points where electrical VES measurements were made, apparent resistivity values were calculated from the surface downwards. These apparent resistivity values calculated as a function of depth were processed into log-log graphs and separate graphs were created for each VES point. In these graphs created, there are apparent resistivity values of the formations from the surface to the bottom. The resistivity distributions are shown in the apparent resistivity vertical underground section Fig. 5. There is a relatively low resistivity presence at the intermediate levels of the sections below the profiles (Fig. 5). When the two-dimensional resistivity vertical underground sections are examined, it is seen that the top surface depth of

the altered metamorphic rock, which is thought to contain hot water, is approximately 300 m. This value was approximately similar in calculations using gravity data.

Figure 5. Apparent resistivity vertical underground section

Taking into consideration the economic conditions, the geologic sketch map (Fig. 3), the gravity anomaly map (Fig. 4a), the vertical gravity gradient anomaly (Figs. 4b), HGM anomaly (Figs. 4c), TAM anomaly (Figs. 4d), and resistivity profiles (Fig. 5), drillings are proposed for the most appropriate three different locations that have high gravity and low resistivity anomalies for geothermal sources.

4 Results and Conclusions

Drilling wells were drilled around Afyonkarahisar province for geothermal resource research in three different areas (MTA, 2005; Kervankiran, 2012). In the drillings opened in the first area, the depth is between 60-905 m, the flow rate is between 5-100 (l / s) and the temperature is between 50-98 °C (MTA, 2005; Kervankiran, 2012). In the drillings opened in the second area, the depth is between 50-226 m, the flow rate is between 25-105 (l / s) and the temperature is between 40-70 °C (MTA, 2005). In the drillings opened in the last area, the depth is between 146-394 m, the flow rate is between 7-64 (l / s) and the temperature is between 37-56 °C (MTA, 2005; Kervankiran, 2012). According to the results found in this study, the geothermal resource depth was calculated as approximately 300 m. Thus, it can be said that the results found reflect the general structure of the region.

Regarding the maps, it is accepted that potential geothermal units are connected with the metamorphic rocks in the area. The position of the high gravity and low resistivity anomalies are very important in respect to continuity and dissemination of metamorphic rocks in the study area. It is considered that the high gravity and low resistivity anomalies with east-west direction are associated with the geothermal units in about the west and middle parts of the study area (Figs. 4b, and 5). The edges and depth of possible geothermal units are appointed by HGM, TAM and VES techniques. Looking at Figs. 4c and 4d, the lateral boundaries and depths of the metamorphic units sought for hot water can be determined by using some counters as mentioned above. The results of the gravity and electricity processes stated that the depth of upper surface values have aligned approximately 300 m. The low resistivity values in electricity profiles show that there are geothermal units. The area close by VES-1, VES-2, VES-7, VES8, VES-9, VES-10 and VES-11 points is demonstrated by gravity values that have high amplitudes which are given in Fig. (4a) and resistivity values that have low values which are given in Figs. (5a and 5b). Generally, places where the cover rock is relatively thick is considered to provide geothermal energy. Looking at the Figs. 4d, 5a and 5b, it is seen that the thickness of the cover rock increased slightly from west to east in the study area. In the end, the first drilling location is offered at point ($x=250$ m and $y = 600$ m), second location is offered at point ($x = 280$ m and $y = 1150$ m), and third location is offered at point ($x = 600$ m and $y = 800$ m) (Fig. 4b). According to TAM map and electrical sections, the depth of upper surface of metamorphic units has been found about 300 m. The locations of offered holes were stated with depth approximately 600 meters (Figs. 5a and 5b). In the research of potential geothermal resources, it can be said that consistent results can be achieved by evaluating the gravity data with HGM and TAM techniques and the electrical resistivity data with the VES technique and interpreting the results together.

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Figures

Figure 1

The second gravity gradients and tilt angle (modified from Oruç, 2010).

Figure 2

Schlumberger electrode array for vertical electric sounding.

Figure 3

The study area and the geologic draft map of study area (After from the URL-1)

Figure 4

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Figure 5

Apparent resistivity vertical underground section