INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
W.M. Maubana et al., Vol.9, No.2, June, 2019

Reservoir Magnetic Anomaly at Geothermal Area of Mount Pandan, East Java, Indonesia

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Received: 14.02.2019 Accepted:04.05.2019

Abstract- The magnetic method has been applied to identify the geothermal reservoir in the mount Pandan East Java, Indonesia. The magnetic survey was performed using PPM G-856 and measured on 80 magnetic stations that cover an area of 9 x 10 km². The magnetic stations cover two hot springs, Jari and Banyukuning in the mount Pandan. The magnetic data were processed by 2D and 3D data modeling. The results showed that total magnetic intensity ranged from -446.7 nT to 526.3 nT. The residual anomaly of contour map revealed that geothermal reservoir was suspected in an area with the low magnetic intensity value around the hot spring and identified as the volcanic breccia and tuffaceous sandstone. The tentative model from magnetic residual anomaly can show location, depth, and the thickness of the geothermal reservoir. The flow pattern the reservoir to manifestation, show the alleged presence of a secondary structure. This indicates that Jari and Banyukuning manifestation have different reservoirs.

Keywords- Magnetic method, Geothermal, Reservoir, Manifestation, Mount Pandan.

1. Introduction

One of the biggest natural resources in Indonesia is geothermal. Indonesia has around 256 geothermal areas with a potential of 27.441 MW distributed over Indonesia, however only seven geothermal fields that have been utilized optimally [1]. The advantages of geothermal energy in addition to providing electricity in the future, this energy does not affect pollution to the environment. Geothermal energy is formed naturally through the interaction of rocks and heat flow beneath the earth's surface. In general, geothermal systems in Indonesia consist of five types. The complex of volcanoes and graben-caldera volcano cones is the biggest geothermal energy potential source in Indonesia [2-3]. According to the Directorate General of EBTKE (2017), mount Pandan is an area that has geothermal potential, identified by the presence of hot springs in several locations. This area is estimated to have geothermal energy potential of around 60 MW, with a surface temperature of more than 35°C and a neutral pH of 7 [4]. The areas that have geothermal energy potential need to be investigated further in order to assess the geothermal systems. The identification of geothermal reservoir is the important stages and has a very significant influence on the identification of geothermal system [5].

Generally, there are several geophysical methods used to identify geothermal reservoirs, one of them is the magnetic method. This method is very sensitive to a thermal activity. The magnetic method is applied to measure variations in the value of magnetic field intensity. The variation of magnetic intensity is caused by the distribution of rocks and magnetization under the earth's surface which can be caused by changes in the geological structure under the earth's surface. The ability of rocks to magnetize depends on the magnetic susceptibility of each rock. Rocks with the content of certain minerals can be known as an anomaly. For geological purposes, anomalies are targeted by magnetic surveys [5-6]. Based on previous studies, [7-12] this method is proven reliable in analyzing geothermal reservoirs. This research has been conducted in the Western Desert, Egypt [13], Turkey [14], several locations in Indonesia, Aceh [15] and several other areas. The main purpose of this magnetic survey is to identify geothermal reservoirs includes of the reservoir location, depth and the thickness of geothermal reservoirs, the presence of the secondary structures, and fluid flow patterns from the reservoir to manifestation.

2. Regional Geology in the Study Area

Mount Pandan is located in the southern part of Bojonegoro Regency, East Java, Indonesia. The physiography of the study area is the Kendeng line in the south, which consists of rough hills with steep slopes [16]. In the Pleistocene Period in Kendeng Mandala, removal and dispersion occurred, thus at the end of the Pleistocene, land was formed which then followed by sedimentation of land-based sediments until now. In the late of Pleistocene-Holocene period, intrusive rocks appeared in the form of andesite pyroxene (Qia) and Pandan breccia, which is a young volcanic activity [16]. Mount Pandan has two main hot spring as the geothermal manifestation, Jari and Banyukuning. Jari hot spring has the coordinate position on 7°26′48.16″ S and 111°48′28.12″ E and located on the elevation of 270 mdpl, while Banyukuning hot spring has the coordinate position on 7°24′57.80″ S and 111°49′05.27″ E with the elevation is 500 mdpl [16].

Based on the geological map, (Figure 1) it is known that the study area is dominated by pandan volcanic eruption rocks namely Pandan Breccia (Opv) and intrusive rocks in the form of Andesite Pyroxene (Qia). Pucangan Formation (QTp) including volcanic breccia, claystone, and Tuffaceous Sandstone. Sonde Formation (Tpso) consists of the alternative of claystone, tuffaceous sandstone, and limestone intercalation. Klitik Formation (Tpk) in the form of clastic limestone, with marl and claystone intercalation. Kalibeng Formation (Tmpk) in the form of marl locally with intercalations of tuff, tuffaceous sandstone, and calcarenite. While, Kerek Formation (Tmk) consists alternation of sandstone, claystone, tuff, marl, and limestone. There are two types of geological structures that develop, normal faults and horizontal faults. In general, the mount Pandan's geological structure orientation is dominated by the NE-SW and NW-SE directions, although there are several faults in the W-E direction [16].

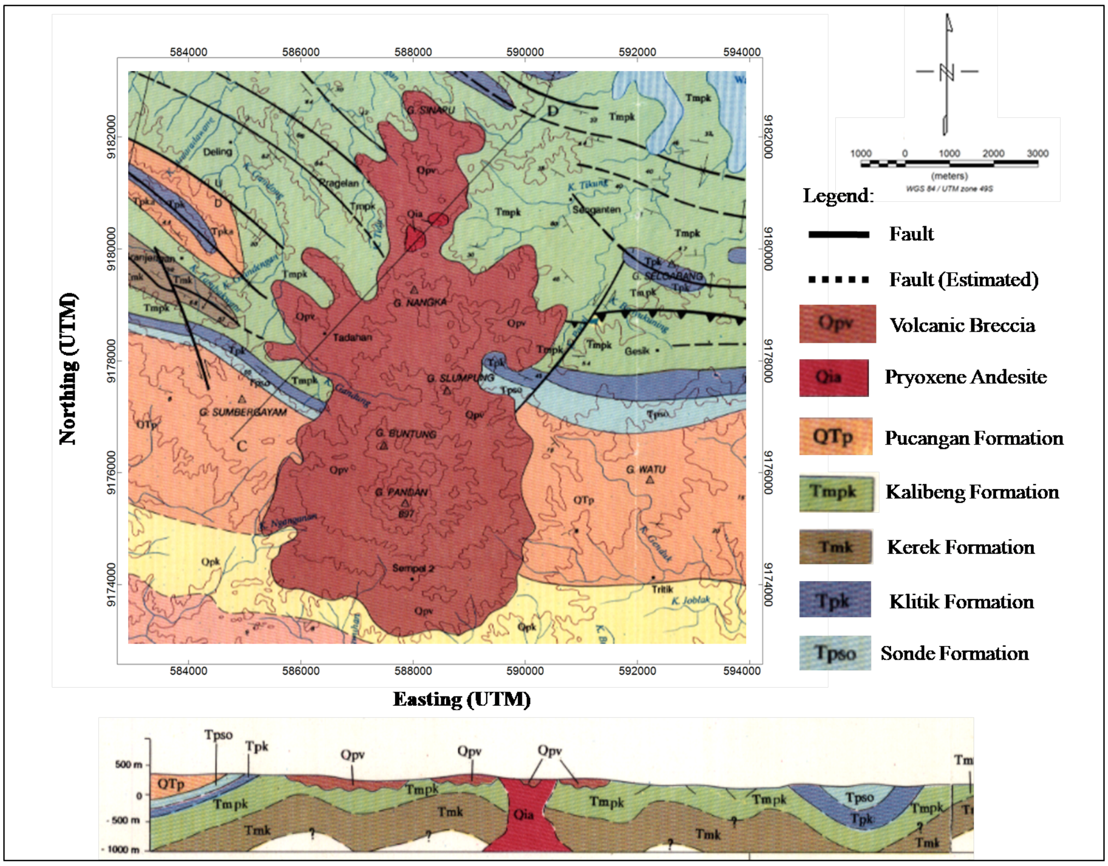

Fig.1. Geological map in study area [16].

3. Research Method

3.1. Magnetic Data Measurement

A preliminary survey is needed before the data acquisition in order to identify the condition of study area and used as a consideration for design survey for data acquisition. Magnetic data acquisition was carried out in the area of 9 x 10 km^2. The magnetic survey was performed using PPM G-856 with 1 nT of sensitivity and measured on 80 magnetic stations with the space range between each station is 1000 meter, depending on the topography condition. The data acquisition was done by looping method. Data were obtained in the form of total magnetic intensity, time, latitude, longitude, and elevation. The necessary corrections for the measured magnetic data have been applied, which were diurnal correction and IGRF correction. The figure below shows all the measurement data points (Figure 2).

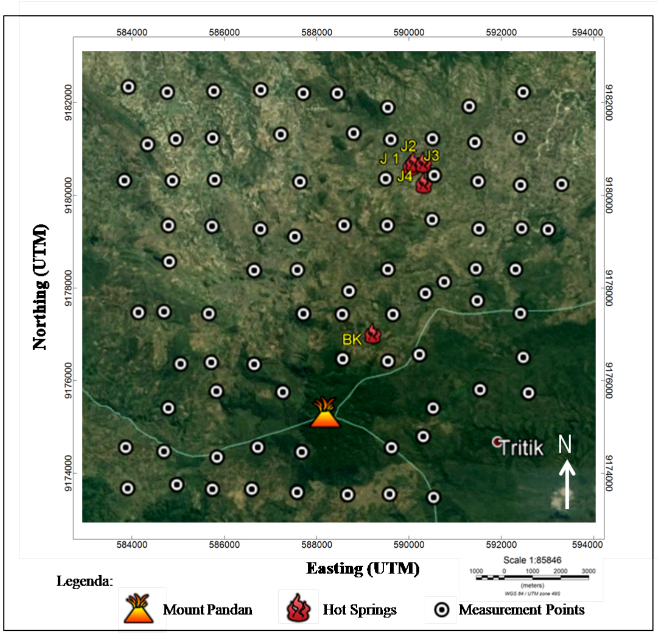

Fig.2. The measurement data point of the research in the study area.

3.2. Magnetic Data Processing

The magnetic data that has been obtained in the field were then processed in order to obtain the total magnetic anomalies. There were several corrections applied, the diurnal correction and IGRF correction. Diurnal correction must be done in order to eliminate the differences in measurement time and the effect of sunlight in a day which causes a deviation in the intensity of the earth's magnetic field. The formula for calculating the diurnal correction is shown by formula 1 [6]:

$$H_D = \frac{t_n - t_{Base}}{t - t_{Base}}\left(H - H_{Base}\right) \quad (1)$$

Where H_D is diurnal correction, t_n is time at point n, t_{base} is time at the start and end point, H is the magnetic field value at the end point and H_{base} is the magnetic field value at the starting point.

IGRF (*International Geomagnetic Reference Field*) correction is needed to eliminate the effects of internal earth by using magnetic field calculators in the website NOAA (*National Oceanic and Atmospheric Administration*), IGRF value 44984.1 nT, inclination -30.26 and declination 4.92.

The magnetic data that has been corrected by diurnal and IGRF correction then followed by upward continuation. The upward continuation process aims to eliminate the effects of local magnets originating from various sources of magnetic objects scattered on the surface of the topography. Upward continuation process has resulted in the regional anomaly and residual anomaly. These anomalies have been used in the interpretation and delineation of the subsurface structure of the study area. The information from the residual contour map used as the consideration to determine the position of the slicing data for interpretation process.

The interpretation of this study consists of qualitative and quantitative interpretations. The qualitative interpretation has been carried out to determine the value of the subsurface magnetic intensity of the data we have measured, based on reading patterns from regional and residual anomaly contour maps. Meanwhile, quantitative interpretations have been used to investigate the depth of sub-surface structures such as faults and dikes, intrusive rocks, and basement complex from the area under consideration. Quantitative interpretation is done creating by 3D inversion model and 2D forward modeling data in the area suspected of being the location of a geothermal reservoir from magnetic residual anomaly contours. Furthermore, the susceptibility value of reservoir rock is obtained. Forward modeling was constructed by build the estimation of the body shape. The main parameter is to observe at the shape of the data curve in the form of a magnetic anomaly curve and modeling curve. The parameters were determined by trial and error method in order toobtain a match between the two curves. Figure 3 shows the flowchart for magnetic data processing.

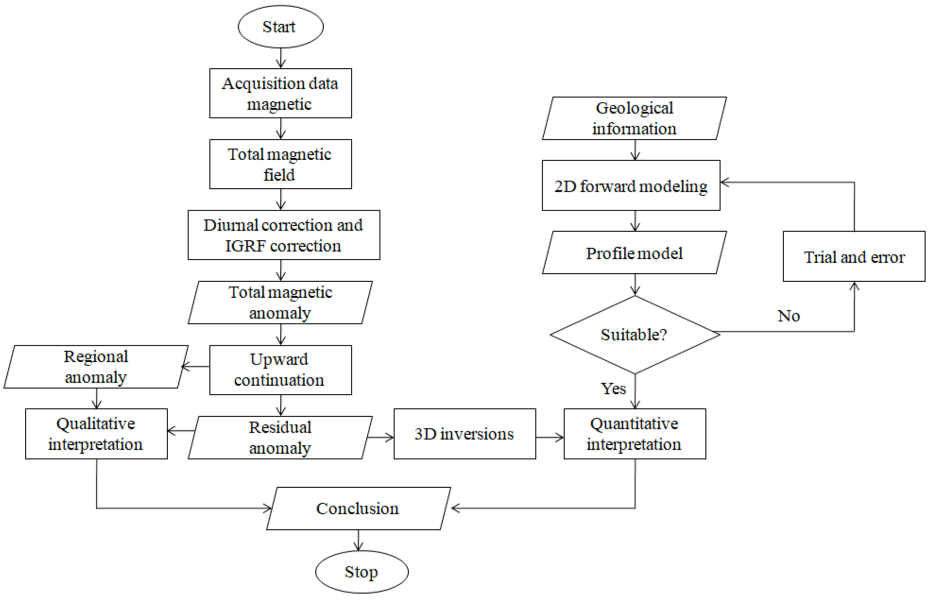

Fig. 3. Flowchart for processing magnetic data

4. Result and Discussion

Figure 4 showed the distribution of the total magnetic intensity of the study area ranged from -446.7 nT to 526.3 nT. The difference in these total magnetic intensity value was caused by the differences in the mineral content in the subsurface. A positive-negative pattern and a rather close contour pattern can be indicated that the area has a fault [5]. The low magnetic anomalies is become our research focus since the investigation of geothermal systems using magnetic methods that based on the magnetic properties of rocks. If the rocks are located around a heat source, then the rock will experience a degradation in magnetism [5-6]. Therefore, in areas where there is a heat source, the intensity of rock magnetic field will be lower than the surrounding area.

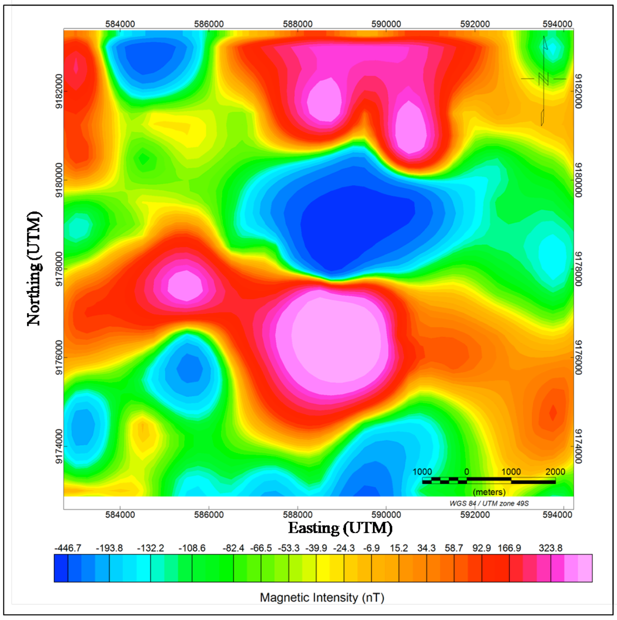

Fig.4. Total magnetic anomaly contour map in study area.

The purpose of the separation process is to obtain regional magnetic anomalies and residual magnetic anomalies. Regional magnetic anomalies are thought to be caused by extensive and deep geological structures. Residual anomalies explain the distribution of clearer and more specific sub-surface geological structures. In this study, residual magnetic anomalies were used because they were considered the most appropriate for the interpretation of magnetic anomalies because the resulted are correlated using the correlation coefficient [5]. The residual contour map showed in Figure 5.

Figure 5 shows that low magnetic intensity ranges from -79.2 nT to -16.2 nT which is oriented to the NE and SE of the map. This value decreases for the area around the Jari and Banyukuning manifestations. We estimated the negative anomalies are due to the presence of grabens and hydrothermal activity below the surface, whereas positive anomalies can be assumed to be mount Pandan intrusive rocks and high magnetic susceptible materials. The anomaly used as a focus for geothermal reservoir study is an area with a low-intensity magnetic value pattern. The map of residual anomalies shows that magnetic intensity may be very low compared to non-magnetic rocks. Therefore, it makes a strong assumption that rocks within the subsurface have undergone a demagnetization process.

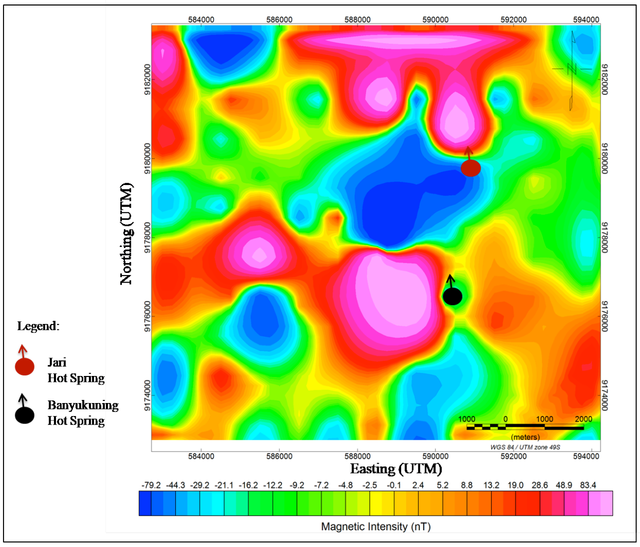

Fig.5. Residual anomaly contour map in the study area.

Inversion modeling was carried out to obtain residual magnetic anomaly contour maps. Furthermore, this process was used to obtain the distribution of subsurface susceptibility values, reservoirs location, the depth and thickness of the geothermal reservoir, to determine the presence of the secondary structure, and also to identify the fluid flow pattern from below the surface in the study area. The result of inversion modeling is presented in Figure 6. There are two hot spring groups namely Jari and Banyukuning which are separated by 3 km. The Jari hot spring group has a higher temperature than Banyukuning, with temperatures ranges from 40ºC to 58ºC while the Banyukuning, the temperature is 37ºC. From the inversion modeling result, we can make a slice that cut off the two manifestation points.

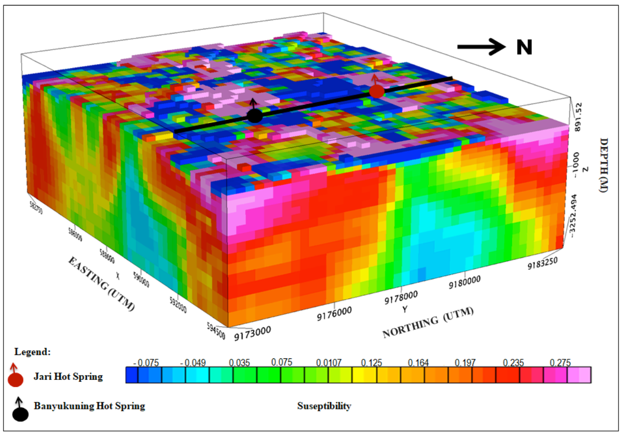

Fig. 6. Model 3D inversion in study area.

BY-JY is a slice oriented to the S-NE direction of the Jari and Banyukuning manifestations. This snippet shows that the manifestation is located above the area with a low susceptibility value. The reservoir rock is found at a depth of 500 m to 3252.5 m from the surface, with a thickness about 2752.5 m. Based on the BY-JY model it was found that the main faults were trending NE-SW and two secondary structure are located in the SW and NE of the study area. This structures is suspected as a structure that affect the appearance of hot water manifestations. The formation of the main fault is estimated to cause the formation of a secondary structure. This secondary structures is estimated to affects hydrothermal activity in the study area. This secondary structure is estimated to be the outlet of the fluid to the surface and appears as a manifestation in the villages of Jari and Banyukuning. This assumption is consistent with results the geology survey and gravity method of previous studies that found a structure which controls a hydrothermal activity in the study area [17].

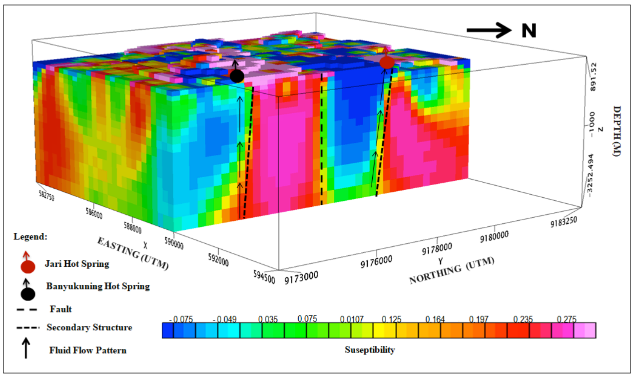

Fig.7. 3D inversion model that shows BY-JY slice in study area.

Figure 7 shows that the Jari and Banyukuning manifestations have different reservoirs rock. This shows the difference in the origin of hot water in each manifestation. These results are in agreement with the results from geochemical data analysis. Depending on the Cl-Li-B diagram were used to find out the water flow's direction it has been revealed that the samples from the Jari manifestation indicate that the water originates from the different reservoir with Banyununing manifestation. To strengthen this assumption confirmed by the results of clipping data in inversion data the model shown in Figure 8. To clip inversion data, the data selected is low data susceptibility values which are interpreted as a part of the heat source and part of the reservoir rock.

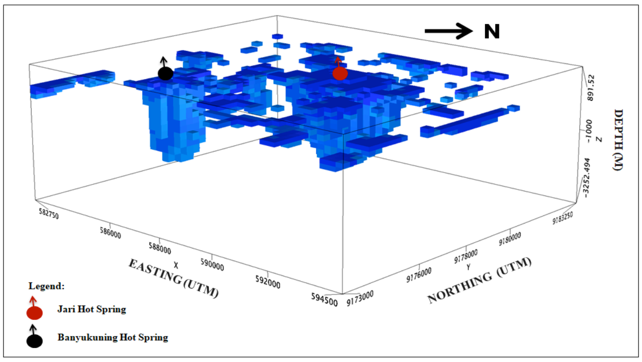

Fig. 8. 3D inversion model of clipping data in study area.

The deeper identification of geothermal reservoir was made by forward modeling that shown in Figure 9. The forward model was made on magnetic residual anomaly contour map with a slice length of 6 km that connecting Jari manifestation and Banyukuning manifestation. Based on the results of the forward modeling (Figure 9), it shows that estimated as diamagnetic rocks and intrusive rocks are the sources of subsurface anomalies of the study area.

Forward modeling shows that there are intrusive rocks that expected to arise due to the presence of secondary structures. This intrusion rock is considered as andesite pyroxene (Qia). In addition, there are rocks with low susceptibility values in the third layer which are estimated to be geothermal reservoirs. Since we can also consider the geothermal reservoir from its susceptibility value of rocks beside its porosity. If we correlated with the geological maps, these rocks are estimated to be in the Pucangan Formation (QTp) located in the Southern part of the research area and the Kerek (Tmk) Formation located in the North which are volcanic breccias and tuffaceous sandstone sills. The second layer is estimated to be in the Pucangan Formation (QTp) located in the south of the research area and the Kalibeng (Tmpk) Formation in the North where is clay rockies. This rock is indicated as a cap rock from a geothermal system in the study area, while the first layer is considered as Pandan Breccia (Qvp).

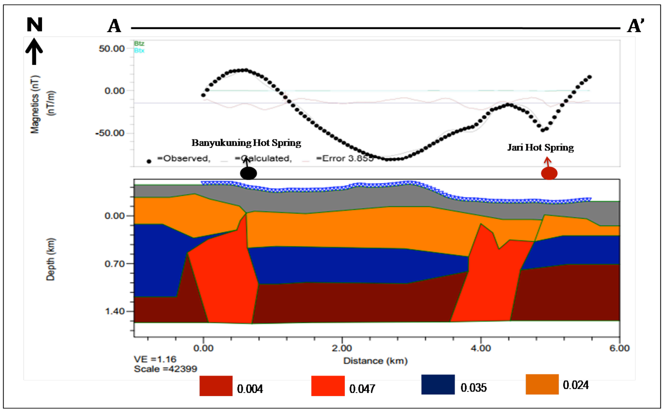

Fig.9. Forward modeling for magnetic anomaly in study area.

5. Conclusion

The magnetic method is capable to identify the geothermal reservoir. The data processing shows that the total magnetic intensity ranged from -446.7 nT to 526.3 nT. Qualitative interpretations indicate that the geothermal reservoir tend to lie in an area with a low magnetic intensity value. Quantitative interpretation based on the 3D inversion and 2D forward modeling, shows that the reservoir rocks are found at a depth of 500 m to 3252.5 m from the surface, with a thickness of 2752.5 m. By considering the range of susceptibility value and the information from the regional geological map, the type of reservoir rock for Mount Pandan geothermal system are volcanic breccia and tuffaceous sandstone. The presence of the secondary structure act as pathway of the hot fluid to move up to the manifestation. Based on the inversion data modeling, we expected that Jari and Banyukuning manifestations have different reservoir rocks.

Future research is expected to use other geophysical methods that magnetetolluric method to provide information about the geothermal system in the mount Pandan complex which is more accurate and varied. A motivating topic of future research is as literature in the field of science, additional information on geothermal potential in the mount Pandan complex, East Java and next geophysical survey reference.

Acknowledgements

The author wishes to thank the Team of Mt. Pandan which help in the data acquisition process, and also to the member of Brawijaya Volcano and Geothermal Research Center, Physics Department, University of Brawijaya Malang, Indonesia and Center of Energy & Natural Resources, Universitas Brawijaya for all of supports during the research. Authors also thanks to Universitas Brawijaya for partially financial support through Research Grant Priority Program No. 3095/2019.

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