Employing 3-D inversion of geomagnetic data to identify demagnetized rock associated with reservoir zone of Blawan-Ijen geothermal prospect area

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Abstract. Blawan-Ijen geothermal prospect area is placed at Bondowoso, East Java. Geologically, the presence of geothermal system in this field is controlled by the huge ancient Kendeng caldera complex structure. The heat source of the geothermal system is predicted to be situated at the base of Kendeng caldera. Geomagnetic method was used for detecting the presence of the heat source. The high temperature zone as the main target of geothermal exploration mostly situated around the heat source location. The geomagnetic method was applied because of its ability to identify the magnetic variation of rocks such as the demagnetized zone which is caused by the high temperature condition in geothermal area especially in the center of geothermal reservoir. Geomagnetic survey was conducted in 2017 and 2018 with the total of 151 stations. The 3-D inversion of geomagnetic data was then carried out to image the subsurface magnetic variation which is representing the complex structure of geothermal system in this area. The subsurface magnetic variation structure revealed by 3-D inversion showed the distribution of demagnetization reservoir rock inside the Kendeng caldera which has low magnetic susceptibility. In the upper part of this layer that is a higher magnetic susceptibility layer which may associated with the clay alteration that is overlaying the geothermal reservoir in this area. Moreover, the very low magnetic susceptibility anomaly can be observed start from -1000 m elevation, which is interpreted as the heat source of the geothermal system in this area.

Keywords: 3-D inversion, geomagnetic, geothermal

1. Introduction

Blawan-Ijen area is known has a hidden geothermal resources. It is situated in the Bondowoso, East Java, Indonesia. A very few thermal manifestations appeared in the surface such as Blawan hot spring and sulphate water on Ijen crater. Prior to this study, the first magnetic survey has been conducted over Blawan-Ijen geothermal area in 2017 to measure magnetic field variations associated with the existence of geothermal prospect area [1]. The study gives a result that the geothermal prospect area was probably located around the northern side and heading to center and the southern area. This result was obtained from Reduce to Pole (RTP) which indicated the presence of low magnetic value.
However, the previous result has not been able to show in detail the location of reservoir center of Blawan-Ijen area. Therefore, in 2018, we conducted further magnetic investigation to improve the subsurface imaging for understanding the geothermal system. Besides that, an additional approach is performed in this study using 3-D inversion of magnetic data. By applying 3-D inversion of magnetic data, we can obtain an image of magnetic susceptibility distribution with a depth estimation which lead to the prediction of geothermal system and the reservoir depth. Several studies to determine the geothermal prospect zone using magnetic methods have been successfully carried out by Daud et al. [2] and Soengkono [3]. However, the previous geomagnetic research in Blawan-Ijen [2] could only determine location of a suspected reservoir area. In order to strengthen the interpretation and to figure out depth of the reservoir zone, it is necessary to employ 3-D inversion of geomagnetic data.

2. Geological condition

Ijen Volcanic Complex (IVC) is placed at the eastern boundary of Java Island in the Quaternary volcanic front of the Sunda arc. According to Demets, it is formed by subduction of the northward Indo-Australia plate beneath the Eurasian plate [4]. After Plinian eruption in 200,000–50,000 years ago, materials volcanic was ejected around 80 km$^3$ leaving huge caldera structure as seen today [5]. The size of this huge caldera is estimated around 20 km$^2$. Nowadays, the remain of this huge caldera only appears in the northern part of IVC, while the southern part has been replaced with younger volcanoes. These younger volcanoes are divided in two groups: Intra Caldera (IC) and Caldera Rim (CR) [6]. Moreover, the presence of volcanoes ranges and river alignment indicates the existence of faults at IVC. Figure 1 shows several faults, such as, Krepekan fault, Cemara-Kukusan fault, Kawahwurung fault, Kalipahit-Banyuilinu fault, Djampit fault, Rante fault, Blawan fault, Pawenan-Blau fault, and Kendeng-Merapi fault [2]. The fault structure tends to form a permeable zone leading to the occurrence of geothermal manifestation.

![Figure 1. Geological structure map of Blawan-Ijen area.](image)
3. Magnetic data acquisition and processing
The detailed magnetic acquisition was conducted by PITTA 2018 team from about 79 stations over Blawan-Ijen geothermal prospect area. This acquisition was done to enhance the result of previous measurement in 2017 from 72 magnetic stations. The data were collected by applying Precision Magnetometer (PPM) from GEM System series GSM-19T along several gridding points with 1 to 1.5 kilometers spacing. For each measurement, the data retrieval was repeated 5 and 6 times to get the stable data. Then, the observed magnetic data was corrected for IGRF and long-lasting variation. Moreover, to ease the interpretation, Reduction to Pole (RTP) technique was applied to transform the total magnetic force anomalies into magnetic pole which can immediately indicate the existence of body source beneath the earth [7]. It was cut with the inclination angle of -32º. After that, the upward continuation of 500 m was achieved to obtain a regional magnetic contrast resulting from deep sources. Finally, the result from upward continuation was processed by using 3-D inversion of magnetic data to image the variety of magnetic susceptibility with depth of complex geothermal system at Blawan-Ijen. Therefore, it could give more clearly interpretation of the prospect zone location.

4. Magnetic anomaly
The result of magnetic anomaly involving data both 2017 and 2018 is shown in figure 2. It shows that the study area is covered with magnetic value ranging from -1800 nT to 1800 nT. The low magnetic presented in blue color mostly appeared in the eastern part of the study area while the high presented in red color is distributed in the western area. The high and low magnetic were separated because of the bias of bipolar characteristic of magnetic data. Furthermore, at the southern area also could be found several bipolar anomalies which are probably correlated with the presence of considerable volcanoes, like Mt. Lingker or Mt. Cemara-Kukusan.

5. Reduce to pole (RTP) and upward continuation
Magnetic anomaly would be reduced to pole to transform bipolar magnetic poles into a form of magnetic pole; so that it could be interpreted directly where the location of the prospect zone was.
In other words, the RTP process aims to removes asymmetry caused by inclination and locates anomalies above the causative bodies. Moreover, to get a better image of RTP beneath the earth surface by reducing a shallow effect, the upward continuation of 500 meter was done. Figure 3 shows the presence of low magnetic (blue color) which associated with hydrothermally demagnetized rock. The demagnetized rock usually occurred because of the interaction between host rock with a high temperature from the heat source [3]. So, it could be used to delineate the location of high temperature of geothermal prospect zone. Generally, the result of RTP shows that the distribution of low magnetic is spreading over the northern of study area and heading to the southern area. The result leads to the possibility that the up flow zone is in this area. Furthermore, to find the center of the reservoir zone, 3D magnetic inversion will be conducted.

6. Results and discussion
The research used 3-D inversion method developed by Li et al.(1996) [8] to obtain a 3-D model of the magnetic susceptibility distribution in the subsurface. 3-dimensional of magnetic method was carried out by using a grid cell of 250 m in the x and y directions, while the grid cell in the z direction was 125 meters used for shallow depth and 250 meters for a deeper depth. The number of blocks in the x, y and z directions were 49, 50 and 34, respectively. Thus, the total number of model blocks was 83,300 blocks.

The model objective function be,

$$
\phi_m(m) = \alpha_x \int_{V} w_x (w_x (m(r) - m_0))^2 dv + \alpha_y \int_{V} w_y \left( \frac{\partial w(z)[m(r) - m_0]}{\partial x} \right)^2 dv + \alpha_y \int_{V} w_y \left( \frac{\partial w(z)[m(r) - m_0]}{\partial y} \right)^2 dv + \alpha_z \int_{V} w_z \left( \frac{\partial w(z)[m(r) - m_0]}{\partial z} \right)^2 dv
$$

where functions $w_x$, $w_y$, $w_z$, and $w_z$ are spatially dependent weighting functions while $\alpha_x$, $\alpha_y$, $\alpha_y$, and $\alpha_z$ are coefficients that affect the relative importance of different components in the objective function. Here, $w(z)$ is a depth weighting function.

![RTP Magnetic Anomaly](image_url)

**Figure 3.** RTP anomaly after applied by Upward Continuation to 500 meters.
3-D magnetic data inversion processing was run by using the upward continuation (figure 3). The result is shown in a 3-D model of magnetic susceptibility distribution as shown in figure 4a. Generally, the pattern of magnetic susceptibility in the surface showed the same result with upward continuation. It indicates that the demagnetized rocks are distributed over the northern to southern of the study area. Then, a slicing on the N-S direction crossing the indicated prospect area was done (figure 4b). This line was selected to image the geothermal system associated with the distribution of hydrothermally demagnetized rock to a depth of 3000 meters. Furthermore, the location of a possible reservoir zone in the Blawan-Ijen geothermal area could be determined.

Result of the 3-D magnetic inversion was visualized as a cross-section of susceptibility distribution in N-S direction (figure 5). The subsurface condition of Blawan-Ijen geothermal prospect area is dominated by low susceptibility rocks to a depth of 3000 meters. It indicates that the hydrothermal demagnetization occurred in this area. A layer with the susceptibility about 0.01 nT, which represented in light blue, is interpreted as a claycap of Blawan-Ijen geothermal system. Moreover, below the claycap layer is found a very low susceptibility layer with the value ranging from 0–0.005 nT.

**Figure 4.** 3-D model of magnetic susceptibility: (a) at the surface, (b) at the slicing line (N-S direction) of prospect area.

**Figure 5.** Susceptibility distribution of 3-D magnetic inversion along N-S section. The position of the N-S section can be seen in figure 4.
The very low susceptibility layer is interpreted associated with the presence of heat source. Heat source having high temperature when interacting with surrounding rock caused a more intensive demagnetization process. Consequently, the susceptibility between reservoir rock and heat source could not be clearly distinguished and both are represented in dark blue. However, the boundary between bottom of claycap and top of reservoir is well indicated from the up dome shape and marked by red dashed line. Thus, the top of reservoir is probably located at 0 meter elevation.

7. Conclusion
From the study of magnetic method with the total of 151 data points in Blawan-Ijen geothermal prospect area, the RTP result shows that the prospect zone which associated with the presence of demagnetized rock is located slightly in the northern and distributed to the southern area. For further analysis related to the location of reservoir zone, 3-D inversion of magnetic data was carried out by slicing the interpreted prospect area from RTP result in the N-S direction. Furthermore, 3-D inversion result shows the presence of indicated claycap layer with a low susceptibility about 0.01 nT. The claycap layer followed by predicted reservoir layer and a heat source which is indicated by a very low susceptibility rock. The top of the reservoir is estimated to be at an elevation of 0 meter.

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