# Continuity Reservoir Magnetic Anomaly at Kelud, Kasinan-Songgoriti, and Arjuno-Welirang of Geothermal Area, East Java Indonesia

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***Abstract***

*This research aimed to observe the continuity reservoir magnetic anomaly of the geothermal system at Kelud, Kasinan-Songgorti, and Arjuno-Welirang. The magnetic data was Performed using PPM G-856 on 74 points with a total area of 36 × 40 Km. Manifestation points covered the areas of Kelud, Kasinan-Songgoriti, and Arjuno-Welirang (Cangar and Padusan hot springs). A qualitative interpretation was conducted to the total transformation result of magnetic field anomaly diurnal corrected and referred to IGRF correction (International Geomagnetic Reference Field). The Result of the Research indicated a total magnetic intensity field at a range of -613.62 nT to 722.25 nT. The residual anomaly from the contour map showed that geothermal reservoirs were probably present in areas with a low magnet intensity value around the hot spring area, identified as volcanic breccias and tuffs. A quantitative interpretation was performed by creating 3D inversion modeling and 2D forward modeling. Modeling of residual anomaly showed location distribution, depth, and thickness of geothermal reservoirs. The distribution pattern indicated the existence of secondary structures and flow patterns of fluid from the reservoirs to the manifestations on the surface. This indicated geothermal system in Kelud might have different manifestations from that of geothermal systems in Kasinan-Songgoriti and Arjuno-Welirang.*

**Keywords:** *Magnetic method, Reservoir, Manifestation, Kelud, Kasinan-Songgoriti, Arjuno-Welirang.*

## I. INTRODUCTION

Indonesia is one of the areas crossed by the ring of fire where three large tectonic plates are met. That is why Indonesia has many volcanoes. Indonesia is dominated by volcanoes that can be proportionally linked to energy, hence a geothermal system. There are 331 geothermal locations in Indonesia that have been surveyed and estimated to produce geothermal energy as much as 11,073 MW. However, most of these potentials have yet been used. The utilization of geothermal energy, particularly for new power plant has just reached 7.7% of the total national energy targeted to contribute by 23% or equal to 45 GW in 2025 [1].

Geothermal prospects in Indonesia are mostly located in Java Island, extending from west to east. The geothermal system in East Java consists of a geothermal system associated with volcanoes; such as quarterly volcanoes followed by an outflow system, a geothermal system associated with tertiary volcanoes, and one non-vulcanic geothermal system [3]. Geothermal potential found in East Java is around 1,024 MW (according to the data in the geothermal potential distribution map of Indonesia) [1]. including Kelud, Kasinan-Songgoriti, and Arjuno-Welirang. Because coming from under the cone of Arjuno-Welirang Mountain, the heat source will heat the fluid stored in the reservoir covered by caprocks. Fumarole and solfatara manifestations appearing around the top of Arjuno-Welirang are as big as an up-flow zone; while hot spring water manifestations appearing in Coban, Cangar, and Padusan are interpreted as an up-flow zone in a geothermal system.

Research in areas with general geothermal potentials uses geophysics methods i.e. magnetic method to find the geothermal reservoir [7]. The method is highly sensitive to thermal activities. The magnetic method is able to measure the variation of the intensity value of the natural magnet field based on geothermal activities [11]. This variation is affected by the process of magnetization induction locally producing positive and negative magnet field anomalies. For the geological purpose, anomaly becomes the target of the magnetic survey [4].

According to Kristanto (2019) [5] used a magnetic method to find a geothermal system in Kelud. He found a change in the fault structure with susceptibility value of 0-.38 to -0.019 and andesite in that area with a susceptibility value of 0.3 to 0.33. Moreover, Marwani et al. (2018) [6] used a magnetic method to find geothermal systems identified as reservoir rocks in Kasinan-Songoriti. They found volcanic breccia with the range of susceptibility value from -0.025 to 0.050 and the geothermal reservoir with a depth of more than 500 meters and thickness approximately 1,000 meters. Other researchers, Afandi et al. 2010 [2] analyzed the geothermal system in Arjuno-Welirang with Cangar manifestation. They applied the magnetic method and found the value of its magnetic residual was at a range of -1,000 to 690 nT. The low anomaly was -1,000 Nt located in the north and west of the hot spring water manifestation. The main objective of this magnetic survey is to find continuity in the anomaly distribution of geothermal reservoirs covering the reservoir location, depth, and thickness, estimation of the existence of secondary structure, the flow pattern of fluid to the manifestation. Another objective is to find continuity among geothermal systems in Kelud, Kasinan-Songgoriti, and Arjuno-Weilarang.

## II. REGIONAL GEOLOGY OF RESEARCH AREA

We conducted the research in the volcanic areas of Kelud, Kasinan-Songgority, and Arjuno-Welirang, as shown in the geological maps of Kediri and Malang.

Fig. 1: Geological map in the study area

Kelud Mountain is one of the volcanoes located in East Java with the type of explosive eruption. It is surrounded by several volcanoes; such as Kawi and Butak Mountain in the east and Anjasmoro and Ajuno-Welirang in the northeast [8]. Administratively, Kelud Mountain is located in Kediri, Blitar, and Malang East Java. Geographically, it is in $70^{0}$56’00” S and $112^{0}$18’30” E with the peak height of 1731 above sea level. Additionally, it has a crater lake with a water volume of 40 million $m^{3}$. The temperature was $32^{0}$C -$35^{0}$C with a pH of 5.1 before the eruption in 1990. Kelud Mountain is a quarter-old stratovolcano. It has ten craters and 32 normal faults. The eruption of Kelud Mountain produces pyroclastic rocks and usually destructs the old crater, confirming that it is explosive [9].

Kasinan and Songgoriti have two main hot spring as geothermal manifestations. The coordinate location of Kasinan is in $7^{0}$52’50.51” S and $112^{0}$ 29’47.58” E with the height of 1128 above sea level; while hot spring water Songgiriti is in the coordinate of $7^{0}$52’01.06” S and $112^{0}$ 29’33.45” E with the height of 1002 above sea level. Kasinan-Songgoriti is located in three mountain feet i.e. Panderman-Kawi-Butak, Arjuno-Welirang, and Old Anjasmara. Previous research had revealed that geothermal systems in Kasinan and Songgoriti were controlled by structures orientating to the southwest and northeast. The geothermal systems are formed in the Kawi-Butak volcano area in the East Java Quaternary Volcano Path and in between the Kendeng path in the northern and southern parts of the South Mountain Path. Tectonic and deformation activities of Kawi-Butak have formed a graben zone in the forms of Sandril, Pitrang, and Cemoro Kandang normal faults due to open cracks allowing subsurface rocks to have high permeability.

Arjuno-Welirang is one of the volcanoes administratively located in Malang, Mojokerto, and Pasuruan East Java [13]. Meanwhile, geographically Arjuno-Welirang volcano is in the coordinate of $7^{0}$ 37’56” S and $112^{0}$ 29’12” E. Geological structure found in Arjuno Welirang is categorized according to the fault directions formed; such as north-south, northwest-southwest, southwest-northeast, and west-east [12]. The north-south directed fault is represented by Cangar, Puncung, and Claket faults. The northwest-southwest directed fault is represented by Padusan, Kemiri, and Bakal faults. The later faults may control spring water around Padusan. The southwest-northeast directed fault is represented by Welirang, Kembar, and Butak faults. They may be the main faults affecting the formation of Arjuno-Welirang volcano. The west-east directed fault is represented by Ledug and Ringgit faults. Other geological structures are rim caldera Anjasmoro, a normal fault, and the Amblasan sector. The sector is characterized by Arjuno fault, a normal fault with a distinguished formation of a half circle and neither southeast nor northeast direction [10].

## III. MAGNETIC METHOD

### *A. Magnetic Data Acquisition*

A preliminary survey was carried out before data acquisition. The magnetic survey it aimed to discover the condition of the area used as a research site. Meanwhile, it was also used as a consideration to create a survey design for data acquisition. The data were collected through magnetic data acquisition with a focused area of 36 × 40 kilometer and 74 measurement points. Points to collect the data were determined by following any existing roads with a gap of 5 km. However, the distance might change any time due to bad road conditions. The magnetic survey was performed using PPM G-856 with a sensitivity of 1 nT. Data acquisition was performed using the looping method. In magnetic data acquisition, we found the total value of magnetic field intensity in the research site. Corrections needed by measured magnetic data were both daily correction and IGFR correction (Figure 2).

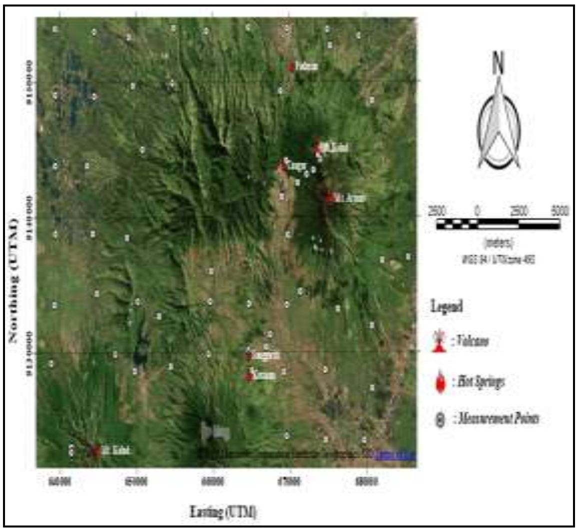


Fig. 2: The measurement data point of study areas

### B. Magnetic Data Processing

Magnetic data processing was performed using the total magnetic anomalies. Parameters used were the value of magnetic field intensity, latitude and longitude position, height, and time. Then, the magnetic data that had been corrected by diurnal and IGRF correction was then followed by the transformation process of the magnetic field. After that, the upward continuation process was performed to eliminate the effect of residual anomaly excluded as the research target. As a result, regional and residual anomaly contours were obtained. Next, the process of reduction to the pole (RTP) was carried out to reduce anomaly so it could be precisely above the anomaly source. The purpose of the RTP was localized in the areas that have maximum anomalies so they can be located right on the body of the causal source [17]. Some of the filters that used in the RTP process consist of Fourier transform that was applied to the data, multiplying by the phase filter, and inverse Fourier transforming the product [18].

### C. Magnetic Data Interprotation

There were two magnetic data interpretations i.e. quantitative and qualitative interpretations. The quantitative interpretation was carried out by determining the total magnetic intensity under the surface from the measured data based on the reading of the pattern of regional and residual anomaly contour maps. Meanwhile, qualitative interpretation had been used to find the depth of subsurface structures i.e. faults and embankments, intrusive rocks, and basement complex of the area under consideration. The quantitative interpretation was performed by creating a 2D inversion and 3D forward modeling data. After that, the susceptibility value of reservoir rocks was obtained. Trial and error were two parameters used to find a compatibility between the anomaly data curve of measurement result and that of modeling result with the least error. Figure 3 presents the flow chart of magnetic data processing.

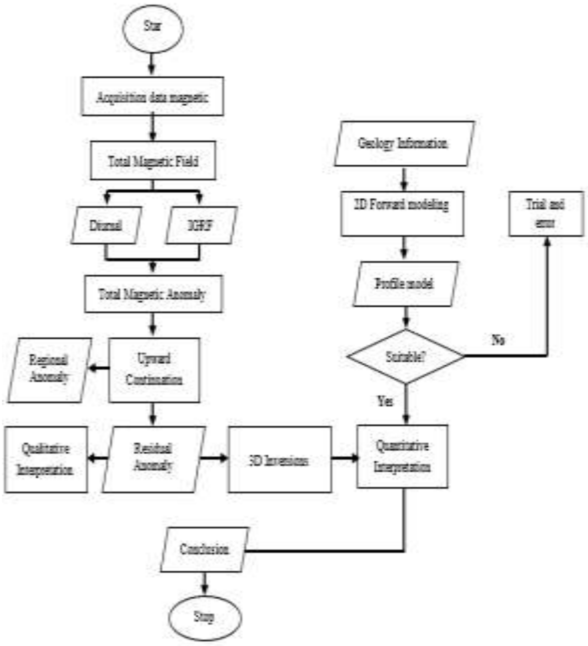


Fig. 3: Flowchart of magnetic data processing.

## IV. RESULT AND DISCUSSION

### A. Total Magnetic Intensity

The anomaly contour map of total magnetic intensity as shown in Figure 4.1 presented the distribution value of measured total magnetic intensity that was around -613.62 nT as the minimum value to 722.25 nT as the maximum value. The different value in this total magnetic intensity was due to different mineral contents under the surface. The contour pattern that was quite close to the positive and negative value indicated that the area had a fracture [12]. This research focused on low magnetic anomaly. In principle, the investigation on the geothermal system using the magnetic method was based on magnetic properties contained in rocks [13]. If there was an increase in temperature, the rocks would experience the demagnetization process where the magnetic properties were lost. As a result, it was assumed that if an area was geothermal, its magnetic field intensity would be lower than its surrounding areas.

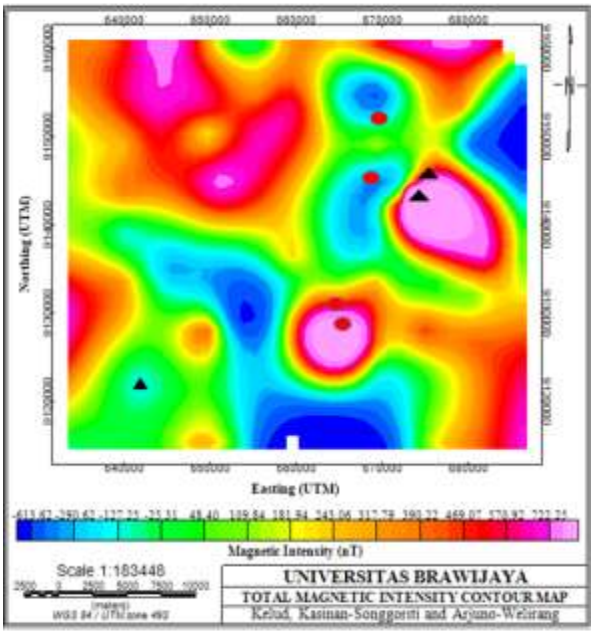


Fig. 4: Total anomaly intensity contour maps

### B. Separation of Regional and Residual Anomalies

Separation of regional and residual anomalies was to eliminate the effect of the magnetic objects on the surface by performing the upward continuation process. A regional magnetic anomaly was caused by wide and geological structures. Meanwhile, residual anomaly described a clearer distribution pattern and a more specific subsurface geological structure. This research used magnetic residual anomaly because due to its effectiveness in magnetic anomaly interpretation and the use of correlation coefficient [12].

After the upward continuation process was carried out several times with several trials of height value, we obtained a regional anomaly contour map as shown in Figure 5.

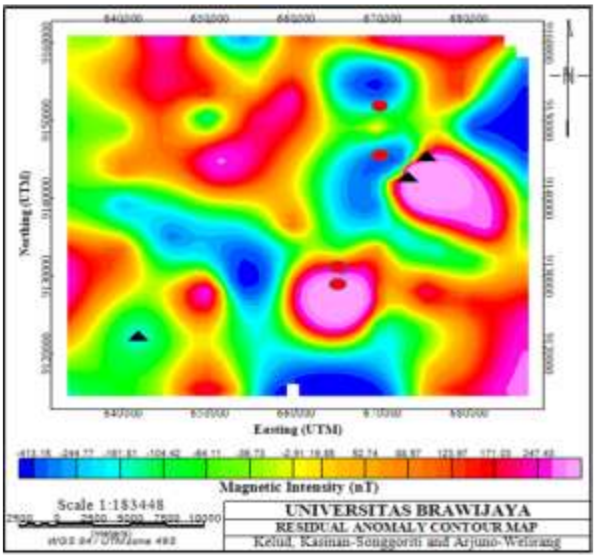


Fig. 5: Residual anomaly contour map

### C. Reduction to Pole (RTP)

RTP process was used to change magnetic survey data from dipole to monopole magnetic. The process was necessary for the data interpretation process. Based on the RTP contour map, magnetic anomalies gathered around Kasinan-Songgoriti, Cangar, and Padusan manifestations in the geothermal system of Arjuno-Welirang. In Kelud, there was a separated anomaly contour between high and low anomalies. A high anomaly showed that the existence of a low magnetic anomaly was related to geothermal activities of RTP contour (Figure 6).

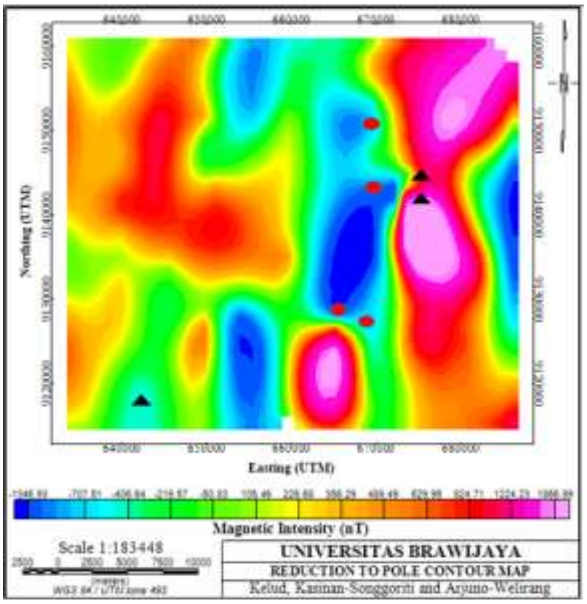


Fig. 6: Reduction to pole contour map

### D. Interpretation Data

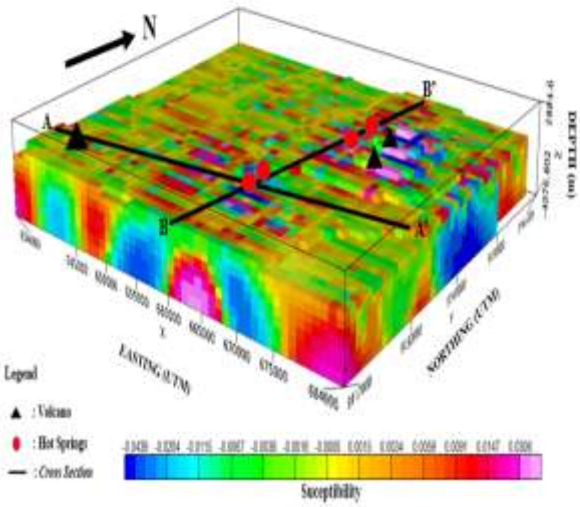


Fig. 7. Model 3D Inversion in research area

Inversion modeling was used on the magnetic residual anomaly contour map to obtain reservoir location distribution, depth, and thickness, to find the presence of secondary structure, and to identify the flow pattern of fluid to the surface. In this research, the modeling consisted of two slices in each manifestation point.

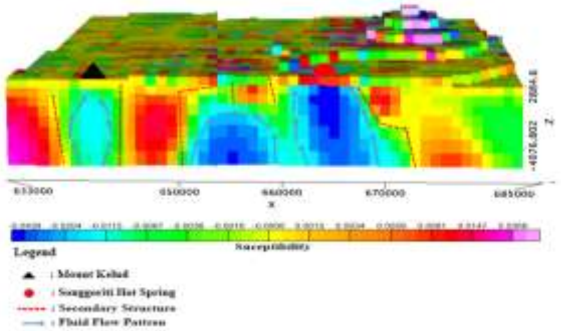


Fig. 8: Data slice on the A-A' axis for Kelud and Songgoriti geothermal system

A-A' directed slice was a slice orientating to the horizontal axis of the geothermal area in Kelud and Songgoriti. It showed a manifestation location in an area with a low susceptibility value. Reservoir rocks were found in the Kelud area in a depth of 1500 meters from the surface and thickness around 2500 meters. Moreover, reservoir rocks were also found in Songgorti manifestation in a depth of 1000 meters from the surface and thickness 3000 meters. Based on the regional geological map, Kediri and Malang were dominated by volcanic breccias, tuff breccias, lava, andesite, clay tuff, agglomerates, and tuffs [15]. One of the reservoir rock properties was having good porosity, so it was important to consider the susceptibility value of the rock type suspected as reservoir rocks in the geothermal system or the volcanic breccia. Above the reservoir rocks, there was a type of rock identified as a cover rock. The rock type was predicted to be tuff and highly impermeable, indicating a geothermal manifestation. Thus we could assume that there was a secondary structure causing the fluid to flow to the surface. This assumption was in line with the previous research on geothermal in Kelud and Songgoriti using derivative analysis. It argued a structure controlling hydrothermal activities there [16]. A tentative model of A-A' slice had found the presence of secondary structure.

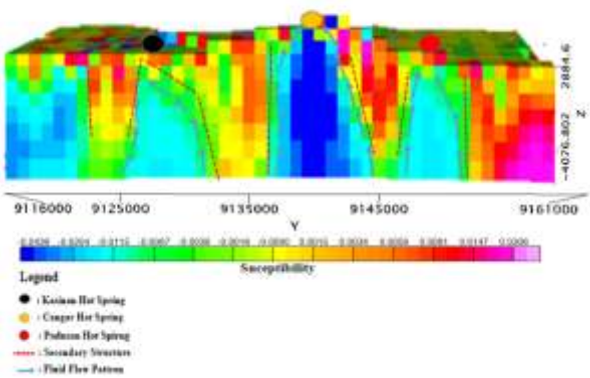


Fig. 9: Data slice on the X-X' axis for Kasinan, Cangar, and Padusan geothermal system

B-B' directed slice was a data slice orientating to vertical axis slicing the manifestation. The slice was to prove the location and type of reservoir rocks causing geothermal manifestations in Kasinan, Cangar, and Padusan. From the B-B' slice, reservoir rocks were found in Kasinan manifestation in a depth of 1700 meters from the surface and thickness around 2300 meters. In Cangar manifestation, reservoir rocks were found in a depth of 300 meters from the surface and thickness around 3700 meters. In Padusan manifestation, reservoir rocks were found in a depth of 1000 meters from the surface and thickness around 3000 meters. B-B' slice data had determined the presence of three, two, and two secondary structures from Kasinan, Cangar, and Padusan manifestations respectively.

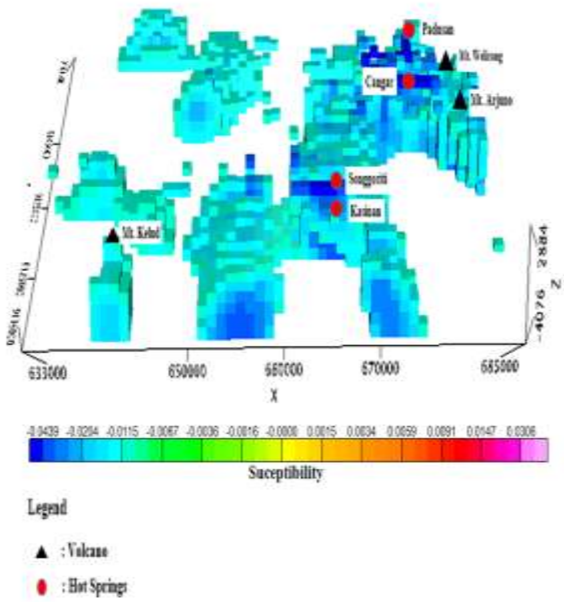


Fig. 10: The continuity between Kelud, Kasinan-Songgoriti and Arjuno-Welirang Geothermal system

Deeper identification in the geothermal reservoir was performed by creating forward modeling presented in Figures 8 and 9. Magnetic data on the Kelud, Kasinan-Songgoriti, and Arjuno-Welirang geothermal systems identified as reservoir rocks are types of volcanic breccia rocks with values ranging from -0.0115 to -0.0439. Whereas for rocks suspected as intrusion is ranging from 0.0091 to 0.0306. The forward modeling was created on a magnetic residual anomaly contour map with a length of A-A' slice of 36 km cutting the geothermal in Kelud and Songgority and of B-B' slice of 33 km cutting the geothermal in Kasinan, Cangar, and Padusan. Based on the result of forward modeling, it was estimated as diamagnetic rocks and intrusive rocks of the subsurface anomaly source in this research.

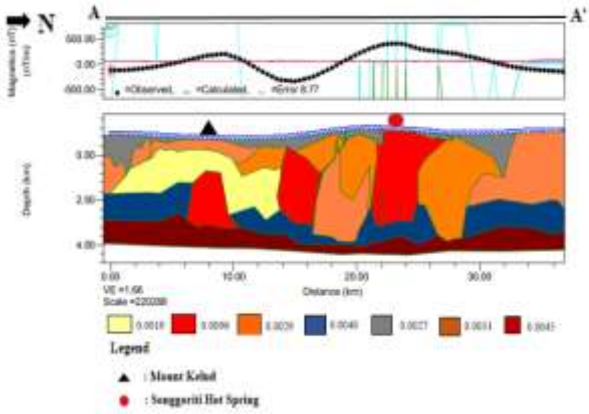


Fig. 11: Forward modeling for the magnetic anomaly in study area Kelud and Sonngoriti

The forward modeling (Figure 11) showed that intrusive rocks would appear due to the secondary structure. These intrusive rocks were identified as an andesite breccia. Besides, there were rocks with low susceptibility value predicted as a geothermal reservoir. It was because the geothermal reservoir could be determined from the susceptibility value of rocks in addition to their porosity. If it was correlated to geological map, these rocks were in the formation of lava deposit (Qvlh), young Kelud volcanic rocks (Qvk), Arjuno-Welirang volcanic rocks (Qwaw), Parasit old volcanic rocks (Qpvp), Kelud old volcanic rocks (Qpvk), Kawi Butak volcanic rocks (Qokb), and Anjasmara old volcanic rocks (Qpat).

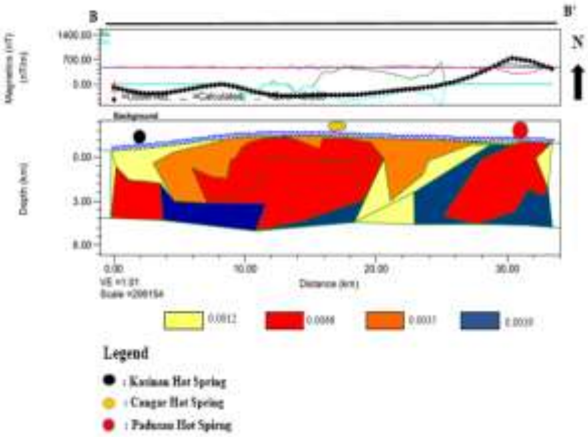


Fig. 12: Forward modeling for the magnetic anomaly in study area Kasinan-Cangar and Padusan

The forward modeling (Figure 12) showed that intrusive rocks would appear due to the secondary structure. These intrusive rocks were identified as tuff breccia. Besides, there were rocks with low susceptibility value predicted as a geothermal reservoir. It was because the geothermal reservoir could be determined from the susceptibility value of rocks in addition to their porosity. If it was correlated to geological map, these rocks were in the formation of upper quarter volcanic rocks (Qv(p)), Arjuno Welirang volcanic rocks (Qwaw), and Anjasmara old volcanic rocks (Qpat).

## V. CONCLUSION

The magnetic method was able to be used to identify the geothermal reservoir. Based on data processing, the total magnetic intensity was around -613.62 nT as the minimum value to 722.25 nT as the maximum value. Magnetic data on the Kelud, Kasinan-Songgoriti, and Arjuno-Welirang geothermal systems identified as reservoir rocks are types of volcanic breccia rocks with values ranging from -0.0115 to -0.0439. Whereas for rocks suspected as intrusion is ranging from 0.0091 to 0.0306. Qualitative interpretation showed that geothermal reservoirs tended to be present in areas with a low magnetic intensity value. The tentative model from the magnetic residual anomaly showed the location, depth, and thickness of the geothermal reservoir. By considering the susceptibility value and information from regional geological maps, the type of reservoir rocks for geothermal systems in Kelud, Kasinan-Songgoriti, and Arjuno Welirang were categorized as igneous rocks identified as volcanic breccia. This Research also showed the flow pattern of fluid to the manifestation on the surface. The presence of secondary structure showed how the hot fluid flowed to the manifestation. The secondary structure could be identified as a fault, intrusion, or crack. Based on 2D and 3D inversion models, the geothermal system in Kelud might not come from one geothermal system from Kasinan-Songgiriti and Arjuno-Welirang.

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