Combination study of magnetic method and 3-D inversion of gravity data to determine the Blawan-Ijen geothermal prospect zone

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Abstract. Integrated measurements of magnetic and gravity methods were carried out over Blawan-Ijen Geothermal Prospect area to discover the indication of prospect zone location more convincing. The acquisition was first conducted in 2017, followed by recent measurement in 2018 with a total of 151 stations for each method. In this research, Reduce to Pole for magnetic data was applied to identify the distribution of demagnetized rock which associated with reservoir zone. The prospect zone is usually indicated by low magnetic susceptibility value. Furthermore, to support the interpretation of prospect zone which usually located overlying the heat source, then 3D inversion of gravity data was conducted. Thus, by applying 3D inversion of gravity method, the distribution of density variation beneath the earth surface which represents the location of heat source can be obtained. The result of Reduce to Pole of magnetic data shows demagnetized zone with low magnetic susceptibility value located in the centre to the southeast at the study area. Moreover, 3D gravity data inversion delineates the existence of heat source indicated by high gravity anomaly which corresponds with demagnetized zone shown from magnetic data.

Keywords: Magnetic, gravity, 3-D inversion, geothermal

1. Introduction

The study was taken place at Blawan-Ijen geothermal area which typically a caldera-hosted geothermal system located at Bondowoso Regency, East Java, Indonesia. The Ijen Volcano Complex (IVS) which has a complex geological history contribute to the complexity of the system itself. In order to recognize the character of the geothermal system in Blawan-Ijen area, several geophysical methods such as gravity and magnetic methods were conducted in 2017. In 2018, further investigation by using these methods was carried out to infill the previous station's measurement. Joint interpretation of several geophysical methods is useful to improve the accuration in delineating the reservoir boundary, especially relating to the prospect zone.

In this study, a combination between magnetic and gravity method are applied as an attempt to determine the geothermal prospect zone at Blawan-Ijen geothermal area more accurately. There have
been several efforts to determine the geothermal prospect zone using magnetic and gravity methods [1-3]. Low magnetic anomaly caused by hydrothermal demagnetization in a geothermal prospect phenomenon is harnessed in the magnetic method by imaging this magnetic anomaly. Meanwhile, the 3-Dimensional inversion of gravity data is applied to image the density variation of the prospect area by detecting the presence of intrusive body which might be associated with a possible heat source of the geothermal system. Integration of both methods will provide a better understanding of the geothermal system in this area.

2. Geological setting
The geothermal system in Blawan-Ijen Complex, East Java (UTM Easting 180,000–200,000 and Northing 9,100,000–9,120,000) is hosted by Quartenary andesitic volcanic rocks [1]. The old Ijen volcano is thought to form around Pleistocene and erupted in Plinian eruption [4]. The eruption product is partially outcropped in the northern part, while young volcanoes are covering the southern part. The post-caldera volcanoes consisted of Caldera Rim Volcanoes and Intra Caldera Volcanoes. The magma chamber has been recharged after the huge explosion, shown by the young volcanoes along the caldera rim.

Figure 1 shows the structures and the location of surface thermal manifestations [5]. The presence of manifestations in the northern part is probably controlled by geological structures around the caldera rim. These geological structures composed of several faults e.g. Blawan fault, Krepekan fault, Kawahwurung fault, Cemara-Kukusan fault, Djampit fault, Kalipahit-Banyulinu fault, Pawenan-Blau fault, Rante fault and Kendeng-Merapi fault.

3. Geomagnetic method

3.1. Data acquisition and processing
Magnetic data was acquired by putting 151 magnetic stations inside the Kendeng Caldera. 72 magnetic stations were measured in 2017 and another 79 stations were measured in 2018. Spacing between magnetic stations is about 1–1.5 km. In each acquisition period, magnetic diurnal variation was also acquired by a base station.

Magnetic raw data recorded in this study consisted of magnetic field amplitude and recording time. While the magnetic field amplitude is the inclusion of the main field (known as IGRF), magnetic diurnal variation and local magnetic anomaly. To obtain the local anomaly, the total magnetic

Figure 1. Geological structures and surface thermal manifestations of Blawan-Ijen geothermal prospect area, Bondowoso Regency, East Java, Indonesia.
data from the measurements was removed from IGRF and diurnal variation. Afterwards, the total magnetic force anomalies will be transformed into the situation that would be observed locally if the causative agent source is located in the magnetic pole by applying the RTP [6]. The studied area is located near the equator in the southern hemisphere with the inclination of -32, thus the RTP was applied by adjusting the inclination value of -32.

3.2. Magnetic anomaly
The magnetic anomaly obtained from the measurements in 2017 and 2018 is shown in figure 2. The eastern part of the study area is dominated by low magnetic anomaly presented in blue colour while the western area is covered by high anomaly presented in red colour. This high and low magnetic anomaly was interpreted as a pair of a bipolar magnetic anomaly in this area. Several bipolar anomalies could also be found in the southern area that might be associated with the presence of other volcanoes (e.g. Mt. Lingker, Mt. Cemara-Kukusan, etc).

3.3. Reduce to pole (RTP)
In order to get a better understanding of magnetic anomaly by reducing the shallow effect, Reduce to Pole (RTP) and upward continuation of 500 meters has been done as seen in figure 3. The result shows that a low magnetic anomaly is accumulated from the northern area to the southern area. This low magnetic anomaly usually correlated with the location of prospect zone due to the presence of hydrothermally demagnetized rock. The result leads to the possibility that the upflow zone is located in the centre of the southern area, coincidence with the emergence of Kawah Wurung.

4. Gravity method

4.1. Data acquisition and processing
The gravity survey was conducted by using Scintrex Gravimeter CG-5. Gravity data processing was done in several steps, which is started from gravity data corrections to obtain Complete Bouguer Anomaly (CBA). The gravity data was corrected by the drift, tidal, latitude free-air, Bouguer and

![Figure 2. The local magnetic anomaly map.](image-url)
The density value used for Bouguer calculation is about 2.87 gr/cc which was obtained from parasnis method. The regional and residual anomaly is then being separated by using TSA Polynomial 1st order.

### 4.2. Complete bouguer anomaly (CBA) and residual anomaly

Figure 4 shows the Complete Bouguer Anomaly (CBA) with the gravity value from 40–78 mGal. The high gravity anomaly could be observed over the centre to the southwest of the studied area and also in
the northeast area. This high gravity anomaly value might be associated by the occurrence of other volcanoes (e.g. Mt. Lengker, Mt. Leker, Mt. Lingker and Mt. Genteng) as the intrusions. Furthermore, regional and residual anomalies were separated using first order of TSA. Generally, the pattern of high gravity anomaly is also found in residual anomaly at centre of the area to southeast area and northwest area, shown in figure 3 with ranging value -18 to 20 mGal.

5. Results and discussion

5.1. Gravity data 3D-inversion

Average grid cell space of 250 meters in X and Y directions, and 125 meters was applied in the Z direction for shallow depth and 250 meters for a deeper depth to run 3-D inversion of the gravity data. X, Y and Z directions respectively have the total blocks of 49, 50 and 34. Therefore, the total blocks for this 3-D inversion of gravity data are 83,300 blocks. 3-D gravity data inversion processing was run using the residual anomaly shown in figure 5. By applying 3-D inversion, the prediction for the depth (related to topography) of each anomalous object at the study area can be acquired. The gridding area in 3-D inversion is given larger than the study area in order to avoid the edge effect which may lead to misinterpretation.

From the calculation of residual anomaly, high gravity anomaly pattern in the centre to the southwest is predicted as the potential heat source location in Blawan-Ijen geothermal system. This result also is shown from 3-D inversion data (figure 6). In figure 6, high massive density contrast can be seen in the southern part. While from the residual anomaly, on the surface of the southernmost area shown high gravity anomaly (figure 7).

Figure 8 is a line which represented the presence of high gravity anomaly in the southern area. This trajectory has south-north direction as shown on the index map at bottom left corner. The analysis of this result will be interesting which described in the next part.

Figure 5. Residual gravity anomaly map.
5.2. The combination of gravity and magnetic anomalies

3-D inversion results of gravity data are shown in figure 8. The anomalies which have diverse density contrast from low to high values can be seen, but these anomalies are very local and tend to be close to the surface. Gravity inversion result shows the depth of local anomalies up to about 0 meters of elevation.

The heat source at Blawan-Ijen geothermal system predicted came from a plutonic body that has very high-density value. The existence of heat source through 3-D gravity inversion is shown quite clearly on this prospect’s trajectory. A yellowish green high anomaly is seen at a distance of 1000-6000 meters at an elevation of ± 1000 m. Also seen in 3-D gravity inversion result, the presence of a low anomaly at a distance of 7000-9000 meters which is likely to be associated with another volcanic caldera which tends to have low anomalous values than the surrounding. A high anomaly around a distance of 11.000 is associated with the structure of the Blawan Caldera rim in the northern part of the study area.

**Figure 6.** Result of 3-D gravity inversion

**Figure 7.** 3-D inversion results in the prospect area.
Figure 8. 3-D gravity inversion result in the prospect area.

Figure 9. Combination results between gravity and magnetic crossing the prospect area (from south to north). The low magnetic anomaly area corresponds to the high gravity anomaly.

The relationship between gravity and magnetic anomalies is more easily illustrated through the cross-section of the prospect path shown in figure 9. As explained in 3-D inversion results, there is a potential heat source at distances of 1000–6000 meters with high gravity anomalies. This well correlates with magnetic anomalies which have low (negative) anomalies thought related to the strongly demagnetized zone.

6. Conclusion
Joint interpretation of magnetic and gravity methods is conducted to improve the accuracy in delineating reservoir boundary, especially relating to the prospect zone in Blawan-Ijen geothermal area. RTP result shows that a low magnetic anomaly is accumulated from the northern area to the southern area which correlated with the location of prospect zone. Furthermore, it is supported by the
result of 3D gravity inversion. The existence of heat source through 3D gravity inversion is shown quite clearly on this prospect's trajectory.

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