3-D inversion of gravity data to determine the Tulehu geothermal prospect zone, Maluku

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Abstract. The Gravity method is a geophysical method that is widely used for geothermal exploration. The use of gravity data is commonly limited to interpretation of geological structure using 2-D modeling. In this study, 3-D inversion of gravity data conducted to improve 3-D conceptual model of geothermal system. This method was applied in Tulehu geothermal prospect area, which is located in Maluku Province. In 2019, gravity survey was conducted for geothermal exploration in Tulehu by gridding measurement of 130 stations with 500 m spacing. The geological condition of the area is dominated by quaternary volcanic rocks, limestone, alluvial, and metamorphic rocks. The result of CBA and residual gravity indicate the existence of medium gravity anomaly at the Mt. Eriwakang, the high gravity anomalies are found around several structures obtained from Remote Sensing. In the section of gravity 3-D inversion, it shows that the low-density contrast can be seen at 2000–3500 meter and 4500–7000 meter, while high density contrast can be seen at 0–5000 meters and 6500–8000 meters. The low and high-density contrast is associated with the presence of Huwe Fault, Banda Fault, and Banda Hatuasa Fault in the prospect area which is correlated to the geological condition. 2-D forward modeling has a good correlation to confirm the results of 3-D inversion of gravity data.

Keywords: Tulehu, structure, gravity, 3-D Inversion

1. Introduction

Gravity method is one of the geophysical tools that is widely used for exploring geothermal resources. The use of gravity method is commonly limited on the interpretation of geological structure using 2-D maps of Bouguer gravity and supported by First Horizontal Derivative (FHD) and Second Vertical Derivative (SVD) analysis. Recently, 3-D inversion algorithm for gravity data is already developed. The 3-D gravity inversion method is extensively used in the last two decades in mineral exploration works [1, 2]. The 3-D inversion of gravity data is a valuable tool to guide geologists in exploration work as it can provide relevant information related to subsurface condition. One of available 3-D gravity inversion program is VOXI which can perform 3-D inverse modeling of gravity data under Oasis Montaj. The algorithm is developed based on the equation that explained in previous research [2].

In April 2019, gravity data acquisition was conducted for 130 stations in TulehuTulehu geothermal prospect area, Maluku Province, Indonesia. The measurement objective is to delineate some parts of
geothermal systems in Tulehu especially to detect the possibility of heat source [3, 4] and fault structure.

Tectonically, Tulehu geothermal area is mainly controlled by Banda arc. The presence of geothermal systems in this area is indicated by the occurrence of several thermal activities spotted along Banda Fault and Banda-Hatuasa fault, and some manifestations are found at the eastern part of Tulehu.

In this research, 3-D inversion of the recent gravity data was applied to re-evaluate the geological structures that may control the geothermal system in this area.

2. Geological setting and surface manifestations

Ambon Island has a geothermal energy resource, located at Tulehu area in the eastern part of the island, approximately 26 km to the northeast of Ambon Island. The Geothermal activity in Tulehu is mostly situated around the graben structure. There are also exist several normal faults and fractures around the area. Lithology in the area consists of volcanic products, such as lava and pyroclastic of andesitic to dacitic composition which is distributed on high topographic areas (pyroclastics) and in river valleys (lava). There is also exist distribution of metamorphic rocks that possibly become basement or the oldest formation in this area. The rest of rocks formations are sedimentary rocks (limestones and alluvial) which is classified as Quaternary rocks [5].

Several geological structures are detected from remote sensing such as Banda Fault, Banda-Hatuasa Fault, Huwe Fault, and Wayari Fault as shown in figure 1. These faults might act as a channel or pathways for manifestation to appear at the surface. This is supported by the occurrence of several thermal activities spotted along Banda Fault, Banda-Hatuasa Fault, and Huwe Fault in the eastern part of Tulehu. The type of these manifestations is hot spring which is categorized as outflow manifestations [6].

3. Methodology

Gravity survey results are used for a few purposes: modeling the earth’s crustal structure, locating bedrock fractures, buried topographic valley and others. Gravity measurement used density contrast
which leads to a different gravitational force. The density of rocks usually depends on the rock composition and porosity, while the subsurface porosity anomaly is affected by faults and fractures. These faults and fractures usually control geothermal fluid movement in the reservoir until it appears to the surface in the form of various thermal manifestations. In this study, the gravity survey were conducted by gridding measurement of 130 stations with 500m spacing. The raw gravity data was then corrected by drift correction, latitude correction, free-air correction, bouguer correction, and terrain correction. The correction data follows the equation:

\[ CBA = Gobs - Gn + 0.3086h - 0.04193\varrho + TC \]

where, CBA is complete Bouguer anomaly, Gobs is station absolute gravity, Gn is latitude correction 75, and TC is terrain correction. The terrain correction was calculated using DEMNAS data. Moreover, The bouguer density was calculated using the parasnis method [7] and obtained a value of 2.1618 g/cm³. To separate CBA into regional and residual anomalies, the first order of Trend Surface Analysis (TSA) was applied in this study. 2-D forward model and 3-D inversion of gravity data were then applied to generate the subsurface density model which may represent the subsurface geological condition in Tulehu geothermal prospect area.

VOXI Earth Modelling™ is a Geosoft Oasis Montaj cloud and clustered computing module that allows the inversion of geophysical data in 3-D. It utilizes a Cartesian Cut Cell (CCC) and an iterative reweighting inversion algorithm [8]. In this study, 3-D inversion completed as ‘unconstrained’.

3-D inversion of gravity data was conducted with average grid cell space of 250 meters in x and y directions, while 125 meters was applied in z direction for shallow depth and 250 meters for a deeper depth. x, y and z directions respectively have the total blocks of 36, 28 and 17. Therefore, the total blocks for this 3-D inversion of gravity data are 17136 blocks. Before run the inversion, the fit error of field data must be selected. In this research, the fit error is absolute error (10⁻⁵ mgal) [9]. 3-D inversion model was then compared with 2-D forward model which is generated by using GYM-SIS in Geosoft Oasis Montaj.

4. Results and discussion

4.1. Complete Bouguer anomaly

Figure 2 shows Complete Bouguer Anomaly (CBA) map in Tulehu geothermal area. The gravity value of CBA map varies from 87.95 to 120.03 mgal. Low gravity anomaly is found in the northern part of the measurement area. The low anomaly pattern may correlate with the presence of alluvium which has lower density value relative to surrounding rocks. Another low gravity anomaly also found around Mt Eriwakang. The low gravity anomaly in Mt. Eriwakang may be affected by the distribution of limestone which is covering the body of Mount Eriwakang. Moreover, high gravity anomaly can be observed in CBA map and aligned along Huwe Fault and Banda Hatuasa Fault.

CBA Map also shows the distribution of low gravity anomaly in the northern part of the area. The low anomaly correlates with the geology condition, which is consisted of alluvium. The alluvium has lower density than another rocks.

High gravity anomaly is spotted between Mount Eriwakang and Mount Huwe. The anomaly indicates the existence of Huwe Fault. Furthermore, this fault probably controls the occurrence of hot springs as it is coincided with the location of the hot springs. However, the indication is not clear enough since fault contact should be located at high contrast of high and low gravity anomaly.

4.2. Residual anomaly

Residual anomaly was extracted by subtracting CBA with regional anomaly which was calculated by using the first order of TSA. Residual anomaly shows gravity value of shallow anomalous body. The anomaly has a value ranging from -9 to 21 mgal. Generally, the pattern of residual gravity anomaly is
mostly similar to the CBA map (figure 3). Low gravity anomaly was found in the northern part and in the Mount Eriwakang, while high gravity anomaly is located around Huwe Fault. There also medium gravity anomaly in the center of the study area around Mt. Eriwakang. The difference is the gravity anomaly at southwest is low at residual anomaly map, while it is high at CBA Map.

Based on the results, the low-density contrast that is represented by blue to green colour can be seen at 500–2000 meter (at elevation of -2000 meter) and 3800–5500 meter distance. This low density contrast can be interpreted as graben which corresponds to the geological data. While the high-density contrast may correlate to the presence of horst which has higher density. This high-density contrast can be seen at 2000–3800 meters and 5800–6500 meters distance. The contrast of low and high density is associated with the presence of several faults in the prospect area which is correlated to the geological condition (figure 4).

The 3-D model is compared to the model derived from 2-D gravity forward modeling (figure 5). Both models show the distribution of several faults, which are interpreted as Banda Fault,

**Figure 2.** CBA map of Tulehu geothermal prospect.

**Figure 3.** Residual anomaly map of Tulehu geothermal prospect.
Figure 4. Section line from 3-D gravity inversion

Figure 5. Comparison between 3-D gravity inversion and 2-D forward model of gravity data
Banda-Hatuasa Fault, a fault between these two faults, and Huwe Fault. The 3-D model shows more obvious fault location since the boundary of high and low density contrast can be easily recognized. The result can be used to make sure 2-D forward model result since the model was freely adjusted depends on supporting data.

Banda Fault and Huwe Fault form a graben structure. The structures may act as controlling structure of Tulehu geothermal system. Low density anomalies between the faults are interpreted as weak zone which can be interpreted as a graben of geothermal system. Banda Fault acts as a channel that connects the weak zone towards surface. This way, fluid from the system may flow to the surface and form geothermal manifestations such as hot springs along Banda Fault.

5. Conclusion
CBA and residual anomaly result show a correlation between high gravity anomaly with the presence of several structures in the prospect zone. 3-D inversion of gravity data shows the low-density contrast can be seen at 500–2000 meter (at an elevation of -2000 meter) and 3800–5500 meter distance, while high density contrast can be seen at 2000-3800 meter and 5800–6500 meter distance. The contrast of low and high density is associated with the presence of Huwe Fault, Banda Fault and Banda Hatuasa Fault in the prospect area. 2-D forward model of gravity data confirms the presence of those faults in the similar location. Low density anomaly between the faults may indicate weak zone related to a graben of Tulehu geothermal system.

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