3D Gravity Data Modelling for Determining a Subsurface structure of The SDP Geothermal Field

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Abstract. The SDP geothermal research area geographically located in eastern Indonesia where there are geothermal manifestations of hot springs. 3D modeling and vertical-horizontal gradient analysis are used to determine the presence of subsurface structures of the study area. Separation of complete Bouguer anomaly data to obtain regional and residual anomalies has been done by upward continuation. The results of the horizontal and vertical gradients indicate that the presence of the geothermal manifestation of MAP 1 hot spring is controlled by the presence of trending northwest-to-southeast fault. We interpret the emergence of manifestations due to the presence of a permeable zone in the form of the fault structure. 3D modeling shows the existence of alluvium sediment, sedimentary rocks, limestones, ultrabasas (peridotite), granite, metagranite, gneiss and the presence of trending northwest trending to the southeast fault.

1. Introduction

Indonesia is reported to have 40% of the world's potential geothermal energy resources. To optimally utilize the geothermal energy potential, researches are needed to be conducted to find out the location of the geothermal system using geophysical research.

The geophysical method which is being used in this research is the gravity method. Gravity method can detect the location of a structure underneath the surface as layers and fluid line which is known as recharge area and discharge area as a term of a geothermal system to be formed. The basic principles in the geothermal case are the differences in rocks density where the thermal sources and accumulation area underneath the earth’s surface can cause density differences between the surrounding rocks.

The SDP research area is one of the non-volcanic area located in eastern Indonesia where there are geothermal manifestations. According to the Department of Mines, in SDP area there are geothermal manifestations of hot springs. The SDP geothermal area is formed over several rock units, from the new rock units to older rock units that consists of Alluvium (Ql), Breccia and Sandstone Igneous Rock Pakuli formation (Qp), Granite (Tmpi (g)), Gneiss Gumbasa Complex (TRjgg) and Peridotite Rock Wana Complex (TRw), which structurally touches each other [1].

Based on the manifestations of hot springs, research is conducted using gravity method and 3D modeling the structure underneath the surface of SDP geothermal research area. Hopefully, this will provide more information to Everyone that Indonesia has a lot of energy resources to be explored and able to replace oil, natural gas and coal which eventually run out.

2. Basic Theory
2.1 The Concept of Gravity Method

Gravity method is one of the geophysical methods based on the variety of earth’s gravitational field. This variety of the gravitational field is the distribution of uneven mass on the earth’s constituent rock. The uneven mass distribution is caused by density differences between rocks underneath the surface. This uneven mass distribution indicated that there is a geological structure underneath the earth’s surface. The variety of earth's gravitational field isn’t caused by uneven mass distribution only but also caused by the point of observation on earth’s surface. This is due to earth’s surface being uneven [2].

2.2 Geology of the Research Area

The SDP geothermal research area which located in eastern Indonesia has geological information that stratigraphically formed over several rock units, from the new rock units to older rock units which consists of Alluvium (Ql), Breccia and Sandstone Igneous Rock Pakuli formation (Qp), Granite (Tmpi (g), Gneiss Gumbasa Complex (TRjgg) and Peridotite Rock Wana Complex (TRw), which structurally touches each other [1].

1. Ql
   This deposits of Alluvium dan Beach (Ql) is surface deposits which formed over alluvium and beach’s deposits.

2. Qp
   This Pleistocene aged rock is formed from Pakuli formation, coral limestone, and lake’s sediment. The pakuli formation consists of conglomerate, breccia, and sandstone, local carbonate claystone, is a land sediment on the fan-shaped mountain slopes and river terraces.

3. Tmpi (g)
   This Miocene-aged igneous rock is formed by metamorphism and formed a batolite body with a granite-granitoid type which is one type of igneous rock which has a bright color, coarse grain, composed of dominant minerals such as quartz and feldspar and a small amount of mica and amphibole minerals.

4. (TRjgg)
   This major component of the Gumbasa Complex is Triassic-aged metamorphic rocks, and it includes diorite gneissic, gneiss, schist and amphibolite. Gneiss rock is one of the metamorphic rocks.

5. (TRw)

Figure 1. Geological map of the SDP research geothermal area
This is an Ultrabasa rock, consisting mainly of concentrated peridotite rocks, dark green, showing a layered structure, and in certain places containing nodules and chromite lenses.

The geological structure that developed in the survey area shows the presence of faults that are scattered at several points in the study area, which directed from northwest to southeast. It is possible that manifestations come out through the fracture zone or rock gap so that the hot springs appear on the surface. Geothermal manifestations in the study area are hot springs.

2.3 Gradient Analysis

Gradient analysis used is 4 methods, namely FHG (First Horizontal Gradient), SHG (Second Horizontal Gradient), FVD (First Vertical Gradient), and SVD (Second Vertical Gradient) [3]. Horizontal gradients are used to emphasize the high anomalies contained in gravity data, because the maximum values that show lateral density in contrast are indicated as faults. Horizontal gradient is divided into two stages, namely FHG (First Horizontal Gradient) and SHG (Second Horizontal Gradient). The size of the horizontal gradient (x, y) is defined by equations (2.1) and (2.2).

\[ HG_y = \frac{\partial g}{\partial y} = \left(\frac{\partial g}{\partial y}\right)^2 \]  
\[ (2.1) \]

Then the magnitude of the horizontal gradient (x, y) in equation (2.2) becomes

\[ HG (x, y) = \sqrt{\left(\frac{\partial g(x)}{\partial x}\right)^2 + \left(\frac{\partial g(y)}{\partial y}\right)^2} \]

With \( \Delta g \) is the total gravity Bouguer value, \( x \) is the gradient value of the x-axis and \( \partial g \) is the y-axis gradient value.

Vertical gradient method can be used to assist the interpretation of the type of structure against Bouguer anomaly data caused by the existence of a downward fracture structure or a rising fault [4]. The potential field U with the source not in it will satisfy the Laplace equation according to equation (2.3) [3].

\[ \nabla^2 U = 0 \]

\[ (2.3) \]

For the gravity method, the equation corresponds to equation (2.4) and (2.5)

\[ \nabla^2 \Delta g = 0 \]

\[ (2.4) \]

\[ \frac{\delta^2 \Delta g}{\delta x^2} + \frac{\delta^2 \Delta g}{\delta y^2} + \frac{\delta^2 \Delta g}{\delta z^2} = 0 \]

\[ (2.5) \]

For SVD the equation corresponds to equation (2.6)

\[ \frac{\delta^2 \Delta g}{\delta z^2} = -\left(\frac{\delta^2 \Delta g}{\delta x^2} + \frac{\delta^2 \Delta g}{\delta y^2}\right) \]

\[ (2.6) \]

2.4 3D modeling

3D modeling illustrates the distribution of mass and geomaterials of sub-surface objects based on rock density contrast. To get subsurface structural patterns from gravity data, the Bouguer anomaly of the measurement results is modeled with the forward model or inverse model. The aim is to find out more clearly the distribution of density and the structure below the surface. Based on the density distribution, interpretation is done by combining existing geological information in the research area [5].

The inversion method is used to determine the physical parameters of rock from the results of observational data based on mathematical models [6]. The inversion process is a field data processing process that involves mathematical and static solving methods to obtain useful information about the distribution of subsurface physical properties. In the inversion process, an analysis of field data is
carried out by curve fitting (matching curves) between mathematical models and field data. The purpose of the inversion process is to estimate the physical parameters of rocks that are unknown [7].

3. Methods
This research has been carried out for approximately 5 months. The research location is in the SDP geothermal area with an area of research around 8.04 km x 12.00 km. Data processing was carried out at the Geophysics Laboratory of Diponegoro University from December to May 2018. The type of data used is secondary data obtained from the Bandung Mineral and Coal Resource Center (PSDMBP) of 230 points.

From the data obtained in the data collection process, data processing is then carried out. Data processing is done by tidal correction and float so that the gravitational field value of observation is obtained. The gravitational field value of the observation is then carried out by the correction of latitude, free air, Bouguer and field so that the complete Bouguer Anomaly (ABL) is obtained. Complete Bouguer Anomalies are then separated using continuation upward so that regional and residual Bouguer anomalies are obtained. Bouguer anomalies are also used for the horizontal gradient (first horizontal and second horizontal gradient) and vertical analysis (first vertical and second vertical gradient). Complete bouguer anomalies are also used to do 3D modeling using Grablox. The contours resulting from anomalous separation, gradient analysis, and 3D modeling results are then interpreted together with geological information to determine the subsurface structure of the SDP geothermal area.

4. Results and Discussion
4.1 Topography of the research area
The topography of the study area. This research area has a topography ranging from 570 m to 1025 m above sea level. Based on the topographic map of the west to the northwest the study area is a lower plateau while the southwest and northeast to the east are the higher plains which are hilly areas.

![Figure 2. Topography map of the SDP geothermal research area](image)

4.2 Complete Bouguer Anomaly
Bouguer contour anomaly which shows the range of anomalies between -19.3 to -5.9 mGal. With this range anomalies are grouped into low anomalies, moderate anomalies, and high anomalies. Low anomalies are shown in blue with a range of values of -19.3 to -14.3 mGal which are scattered in the southeast to south and some points in the southwest of the study area. This low complete Bouguer anomaly is indicated as an area that has a dense density distribution of low rock types. Medium
Anomalies are located in areas with a range of values of -14.3 to -7.7 mGal located north of the study area and several points in the eastern area of the study. High anomalies are shown in red to purple with a range of -7.7 mGal to -5.9 mGal and in the southwest and northeast of the study area it is indicated that the area originates from rocks that have high density.

![Figure 3. Complete Bouguer Anomaly map of the SDP geothermal research area](image)

4.3 Upward Continuation
Separation of complete Bouguer anomaly was conducted to determine the distribution of anomalies that dominate the study area. In this study, the Upward Continuation method is used. On the upward continuation, the trial and error process is carried out and gradual at each altitude, so that the contour images of regional anomalies are obtained which have no effect on the residual anomaly value and show a fixed anomaly contour pattern.

Anomalous values of -15.37 to -8.40 mGal. Low anomalies are in the range of values of -15.37 to -14.10 mGal located in the southeast to southwest of the study area. Moderate anomalies are in the range of -12.59 to -10.34 mGal which cross from east to west of the study area. High anomalies are in the range of -9.34 to -8.40 mGal in the northwest to northeast of the study area. Based on the contours of regional anomalies it can be seen that there is a low to high anomaly spread in the south to the north of the study area. The form of anomaly illustrates that the northern region of the bedrock is deeper than the south of the study area.

The residual anomaly has a significant increase in value, having a range of values between -4.65 to 3.23 mGal. The difference in positive and negative values is caused by three things, namely rock density, position, and the size of the rock body that produces anomalies[8]. The slight difference in anomalous values is interpreted as a reduction in value because the residual effect is very shallow.
4.4 Gradient analysis

Horizontal gradients can be used to emphasize the high anomalies found in gravity data; this maximum value shows the lateral density of the contrast identified as a geological structure. The calculation process using Geosoft Oasis Montaj software produces first horizontal gradient and second horizontal gradient contours.

The distribution of the first horizontal gradient value in the SDP geothermal area is illustrated in Figure 4.8 with the horizontal gradient value distribution in the range 0.0004 to 0.0098 mGal / m. The first horizontal gradient contour map shows several fault structures that spread to the northwest to the southeast of the study area.
The results of the second order gradient analysis show the distribution of values in the study area with a range of 0.0000 to 0.00004 mGal / m. Several fault structures that spread in the northwest to southeast of the study area were shown by horizontal gradient contour maps. From the point of manifestation found in the SDP geothermal area, the existence of the manifestation namely MAP 1 is correlated with the maximum anomalous value of the horizontal gradient and interpreted as a fault. This shows that SDP geothermal manifestations are structurally controlled.

Anomalies caused by the existence of a geological structure will have minimum absolute, and maximum absolute values which are limited to zero or close to zero is a gradient analysis with vertical derivatives [9]. Distribution of first vertical gradient values of SDP geothermal areas. SDP geothermal area has a value of first vertical gradient between -0.011 to 0.006 mGal / m. The results shown by vertical gradient contours have a fairly clear color difference. A zero value is indicated on the yellow contour so that the presence of rock contact can be identified.

Figure 8. First vertical gradient map

Figure 9. Second vertical gradient map

The distribution of the value of the second vertical gradient of the study area with the distribution of values ranges from -0.00053 to 0.000018 mGal / m. The vertical value of the zero derivative mGal / m is shown on the yellow contour so that the presence of rock contact can be identified. The results of the vertical gradient contour map of the study area show several rock contact limits that spread in the northwest to the south. The existence of the MAP 1 manifestation is correlated by the zero value of vertical derivatives interpreted as rock contacts which should be geologically occupied by granite lithology which has a high density value. This is possible as a fracturing zone.

4.5 The 3D modeling

Subterranean modeling is performed using 7 incision paths in Bouguer anomalies. Limitation of modeling incisions and north to south, on incisions that are lines A-A', B-B', C-C', axis there are 2 incisions lines, F-F', G-G'. On the x-
4.5.1 Y-axis incision
The subsurface modeling results in the A-A incision have rock density values from low to high. The results of high density values have a range of 2.95 to 3.3 g/cm³ which are gneiss rocks, Schist rocks, amphibolite rocks of Gumbasa Complex (TRjgg) and peridotite rocks (Ultrabasa) Complex Wana (TRw). The results of the low to medium density values have a range of 2.2 to 2.9 g/cm³ which is a breakthrough granite-granitoid (Tmpt), Alluvium (Ql) and Pakuli Formation (Qp) sedimentary rocks consisting of sandstones, conglomerates, breccia, carbonate claystone. The A-A incision indicates the existence of a fault that separates the Pakuli Formation sedimentary rock (Qp) consisting of sandstones, conglomerates, breccia, carbonate claystone and gneiss rocks of the Gumbasa Complex (TRjgg) and directed directed peridotite (Ultrabasa) Wana (TRw) complexes northeast to southwest and northwest to southeast.

Subterranean modeling results on B-B incisions' have rock density values from low to high. High density results have a range of values from 2.9 to 3.25 g/cm³ of gneiss rocks, Schist rocks, amphibolite rocks of Gumbasa Complex (TRjgg) and peridotite rocks (Ultrabasa) Complex Wana (TRw). The results of the low to medium density values have a range of values of 2.2 to 2.85 g/cm³ which is breakthrough granite-granitoid rocks (Tmpt), Alluvium deposits (Ql) and Pakuli Formation sedimentary rocks (Qp) consisting of sandstones, conglomerates, breccia and carbonate claystone. B-B incision shows the existence of sedimentary basins that dominate below the surface. This is possible which results in a low Bouguer anomaly value and it is suspected that there is a fault that is trending northwest to southeast and northeast to southwest.

Subterranean modeling results in C-C incisions have rock density values from low to high. High density results have a range of values from 2.9 to 3.25 g/cm³ of gneiss rocks, Schist rocks, amphibolite rocks of Gumbasa Complex (TRjgg) and peridotite rocks (Ultrabasa) Complex Wana (TRw). The results of the low to medium density values have a range of values of 2.2 to 2.85 g/cm³ which are breakthrough granite-granitoid rocks (Tmpt), Alluvium deposits (Ql) and Pakuli Formation sedimentary rocks (Qp) consisting of sandstones, conglomerates, breccia, carbonate claystone. C-C incision shows the suspicion of the existence of a fault that is directed northwest to southeast.

Subterranean modeling results on D-D incisions have rock density values from low to high. High density results have a range of values from 2.9 to 3.25 g/cm³ of gneiss rocks, Schist rocks, amphibolite rocks of Gumbasa Complex (TRjgg) and peridotite rocks (Ultrabasa) Complex Wana (TRw). The results of the low to medium density values have a range of values of 2.2 to 2.85 g/cm³ which are breakthrough granite-granitoid rocks (Tmpt), Alluvium deposits (Ql) and Pakuli Formation sedimentary rocks (Qp) consisting of sandstones, conglomerates, breccia, carbonate claystone. A D-D incision shows the suspicion of a fault that is trending northeast to southwest. It is possible that manifestations come out through the crack zone or rock gap so that the hot springs appear on the surface. The estimation of the existence of a reservoir in the study area is at a depth of 1 to 3.2 km which is dominated by sedimentary rocks with a density being close to the presence of faults.

The subsurface modeling results on E-E incisions' have rock density values from low to high. High density results have a range of values from 2.9 to 3.25 g/cm³ of gneiss rocks, Schist rocks, amphibolite
rocks of Gumbasa Complex (TRjgg) and peridotite rocks (Ultrabasa) Complex Wana (TRw). The results of the low to medium density values have a range of values of 2.2 to 2.85 g/cc are breakthrough granite-granitoid rocks (Tmpi), Alluvium deposits (Ql) and Pakuli Formation sedimentary rocks (Qp) consisting of sandstones, conglomerates, breccia, carbonate claystone. The E-E incision shows the alleged existence of three faults that trending northwest to southeast and northeast to southwest. E-E incision shows the existence of sedimentary basins that dominate below the surface. This is possible which results in a low Bouguer anomaly value.

4.5.2 X-axis incision
The F-F incision modeling results have rock density values from low to high. High density results have a range of values from 2.9 to 3.25 g/cc of gneiss rocks, Schist rocks, amphibolite rocks of Gumbasa Complex (TRjgg) and peridotite rocks (Ultrabasa) Complex Wana (TRw). The results of the low to medium density values have a range of values of 2.2 to 2.85 g/cc are breakthrough granite-granitoid rocks (Tmpi), Alluvium deposits (Ql) and Pakuli Formation sedimentary rocks (Qp) consisting of sandstones, conglomerates, breccia, carbonate claystone. The F-F incision shows that there are several suspected faults that separate high density and low density rock contrasts that have a northwest direction to the southeast and northeast to southwest.
The G-G incision modeling results have a value of rock density from low to high. High density results have a range of values from 2.9 to 3.25 g/cc of gneiss rock, Schist rock, amphibolite rocks of Gumbasa Complex (TRjgg) and peridotite rocks (Ultrabasa) Complex Wana (TRw). The results of low to medium density values have a range of values from 2.15 to 2.85 g/cc is breakthrough granite-granitoid rocks (Tmpi), Alluvium deposits (Ql) and Pakuli Formation sedimentary rocks (Qp) consisting of sandstones, conglomerates, breccia, carbonate claystone. G-G's incision shows the existence of a suspected fault which separates the contrast of high density and low density rock with a northwest direction to the southeast and northeast to southwest. The estimation of the existence of a reservoir in the study area is at a depth of 1 to 3.2 km which is dominated by sedimentary rocks with a density being close to the presence of faults.

(a)        (b)

Figure 12. Slicing map on Y-axis incision (a) Slice F-F’ (b) Slice G-G’

5. Conclusion
The subsurface geological structure of the study area consists of high density rocks with a range of values from 2.9 to 3.3 g/cc which are gneiss rocks, Schist rocks, amphibolite rocks of the Gumbasa Complex (TRjgg) and peridotite rocks (Ultrabasa) Complex Wana (TRw). The results of low to medium density values have a range of 2.2 to 2.9 g/cc is a breakthrough granite-granitoid (Tmpi) rock, Alluvium (Ql) sediment and Pakuli Formation sedimentary rock (Qp) consisting of sandstone, conglomerate, breccia, carbonate claystone. The 3D modeling based on gradient analysis (horizontal gradient and vertical gradient) in SDP geothermal areas can be interpreted as the existence of faults scattered at several points in the study area. The MAP 1 geothermal manifestation is located near the geological fault directed northwest to southeast and the lithological rock contact limit. It is possible that manifestations come out through the crack zone or rock gap so that the hot springs appear on the surface.

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