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3 messages

Chi-Wang Li <onbehalfof@manuscriptcentral.com> Tue, Aug 3, 2021 at 1:40 PM
Reply-To: chiwangli@gmail.com
To: muh.sarkowi@eng.unila.ac.id, sarkov323@yahoo.com

03-Aug-2021

Dear Mr. Sarkowi:

It is a pleasure to accept your manuscript entitled "Reservoir Identification of Bac-Man Geothermal Field Based on Gravity Anomaly Analysis and Modeling" in its current form for publication in the Journal of Applied Science and Engineering. The comments of the reviewer(s) who reviewed your manuscript are included at the foot of this letter.

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Sincerely,
Prof. Chi-Wang Li
Editor-in-Chief, Journal of Applied Science and Engineering

Reviewer(s)' Comments to Author:

Reviewer: 1

Comments to the Author
I congratulate the authors for their decision to improve their manuscript carefully and resubmit the revised version. The manuscript has been noticeably improved. I recommend the authors to choose stronger visualization style in their future works. Adding complementary information of any kind (in your study is e.g. thermal data) to the concluding plots (your cross sections), always, helps readers to understand and believe on the accuracy of the results.

Reviewer: 2

Comments to the Author
The revised paper has answered the reviewer's questions. It is accetable for publication in JASE.

Muh Sarkowi <muh.sarkowi@eng.unila.ac.id> Wed, Aug 4, 2021 at 7:18 AM
To: chiwangli@gmail.com

Dear Prof. Chi-Wang Li,

Thanks for your email and I already send the manuscript materials to the editorial board.

Best regards
Muh Sarkowi

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Chi-Wang Li <chiwangli@gmail.com> Wed, Aug 4, 2021 at 7:24 AM
To: Muh Sarkowi <muh.sarkowi@eng.unila.ac.id>

Rahmat,

Great.

Best regards,

Professor Chi-Wang Li, Ph.D.
Department of Water Resources & Environmental Engineering

Tamkang University, Taiwan
Editor-in-Chief
Journal of Applied Science and Engineering
http://jase.tku.edu.tw/

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Reservoir Identification of Bac-Man Geothermal Field Based on Gravity Anomaly Analysis and Modeling

Muh Sarkowi[1]*, Rahmat Catur Wibowo[2]

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Abstract

The Bac-Man geothermal field is located between the provinces of Albay and Sorsogon on the Bicol Peninsula. Several geophysical modeling methods have been carried out to identify the Bac-Man field geothermal system. This research focuses on 3D modeling and analysis of gravity data which aims to identify the geothermal reservoir in the Bac-Man field. This research includes several things, such as: spectrum analysis and the separation of Bouger's anomalies; gradient analysis; and anomaly modeling. Based on the modeling results, there are 3 low anomaly closures in the middle which are separated by high anomalies which can be interpreted that the geothermal reservoir in the Bac-Man field may be divided into 3 reservoirs, namely the southern part (Cawayan and Tanawon sector), the eastern part (Boton sector). and the northern part (Palayan - Inang Maharang sector) where each reservoir area is separated by the presence of a fault or intrusion structure.

Keywords: Bac-Man field, Gravity, Modeling, Reservoir, Geothermal

1. Introduction

The Bacon - Manito (Bac-Man) geothermal field is located in the Podcol mountains on the island of Luzon, about 350 km southeast of Manila. The exploration of the Bac-Man geothermal field has been carried out since 1977. The reservoir model has an area of 23 km^2, a depth of 1500 m and a temperature of 240°C to 320°C. Based on geological, geochemical and geophysical data, a conceptual model of the Bac-Man geothermal system has been made (Austria, 2008).

Tugawin *et al.* (2015), carried out 2D Magnetotellurics inversion modeling in the Bac-Man field which shows the existence of 3 (three) geothermal reservoir areas, namely Palayan Bayan, Tikolob, and Malobago areas. These results are in accordance with the results of data interpretation of resisitivity vertical electric sounding (VES) and Schlumberger Resistivity Traversing (SRT). The Reservoir in the Palayan Bayan area has been in production since 1993, while the Tikolob prospect is on the west side of the Bac-Man field, separate from the Palayan Bayan system (Tugawin *et al.*, 2015).

Espartinez and See (2005) have conducted geochemical research in the Bac-Man Geothermal field to determine changes in reservoirs from their chemical properties. This is done to maintain the continuity of steam production in the Bac-Man field considering that of the 3 geothermal reservoir sectors, the Palayan Bayan and Cawayan sectors are still producing while the Boton sector has not been producing since 2009 (See, Fragata and Solis, 2005).

In this research, gravity data processing and modeling will be carried out to determine the geothermal reservoir in the Bac-Man field (Palayan Bayan, Cawayan and Boton). The results of the subsurface model derived from anomaly gravity analysis and the density distribution model resulting from compilation/correlation modeling with MT and temperature model data.

2. Bac-Man Geothermal System

The exploration of the Bac-Man geothermal field has been carried out since 1977. Several studies have been carried out ranging from geology, geochemistry, geophysics (gravity, magnetic, micro earthquake, magneto-telluric, temperature, etc.) with the aim of determining the geothermal reservoir, caprocks, heat-source, the geothermal system model and geothermal potential in the area. The total capacity of the power plant in the Bac-Man area is 150 MWe generated from 4 generating units, namely: Unit I began operating in 1993 and unit II in 1995 which was named Palayang Bayan (2 x 55 Mwe), in 1996 the Cawayan geothermal plant began operating (20 Mwe), and in 1998 the Unit III power plant in the Botong area began operating (20 Mwe). The Bac-Man geothermal field is located in the Podcol mountains 350 km southeast of Manila. The local fault system is known as the Bac-Man Fault Zone (BFZ) (Dimabayao, Rowe and Barker, 2019). The fault zone is indicated by a series of volcanoes that are mostly NW-SE (Figure 1). Structurally controlled by a fault system which is believed to be an extension of the San Vicente Linao Fault (SVLF) which is a stretch of the Philippine fault. The most prominent regional geological structure in the area is the San Vicente-Linao Fault in the Northwest - Southeast (NW-SE) which slopes across the Bico Peninsula (Resyes, Delfin and Bueza, 1995).

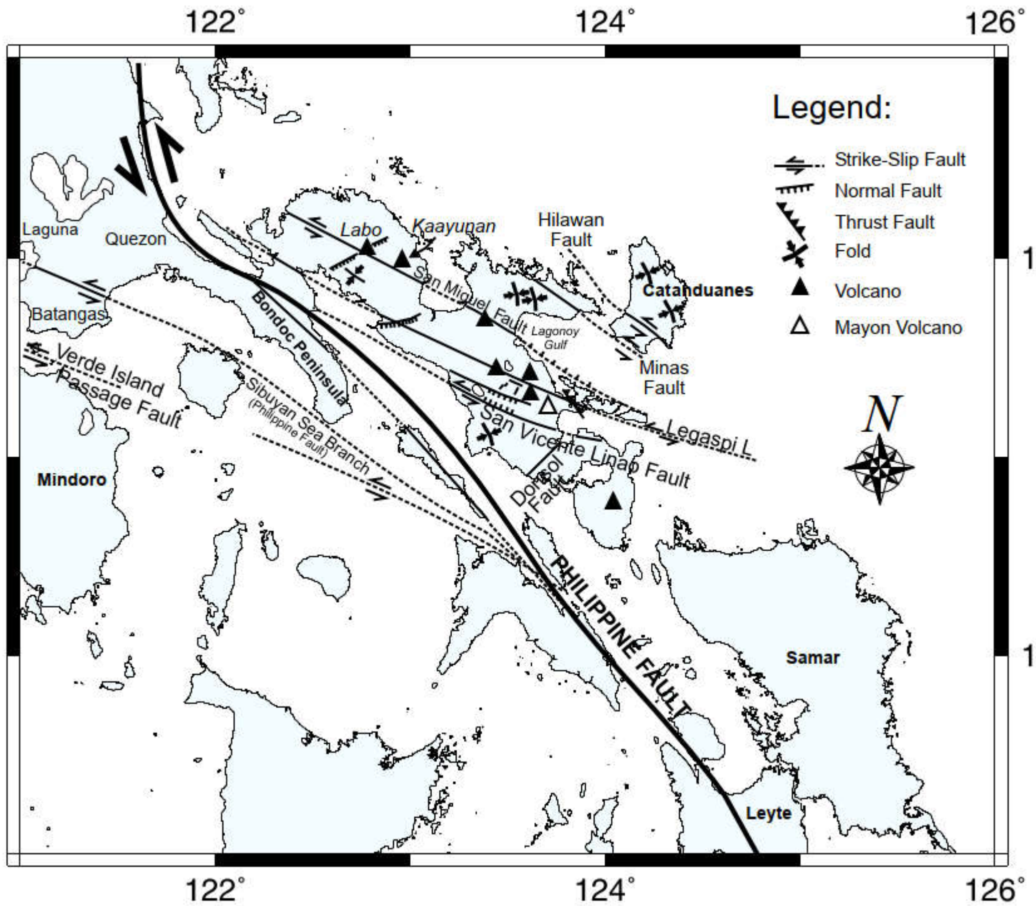

Figure 1. Bicol Peninsula Fault Area, San Vicente-Linao Fault (SVLF) (Lagmay, Tengonciang and Uy, 2005).

The Bac-Man geothermal system is divided into two regions, namely the western and eastern parts of Bac-Man. The eastern part of Bac-Man is further divided into the North Namito lowlands and the Podcol highlands, where the Podcol plateau can be divided into eight geographic sectors, namely: Inang Maharang, Putting Bato, Palayan Bayan, Cawayan, Tanawon, Osiao, Bangas and Botong (Resyes, Delfin and Bueza, 1995). Neutral chloride hot springs with a temperature of 89 ° C - 96 ° C are found in the lowlands of Manito. Solfatara is found in Cawayan and Pangas, while in West BacMan, cold to warm and cold SO4 springs are found.

The most recent volcanic event in the Pocdol highlands occurred more than 40 thousand years ago. This is related to the formation of the Tanawon and Cawayan craters, as well as the extrusion of the Botong and Pangas domes. The youngest volcanoes generally occur in subsurface areas with high temperatures, permeable formations, and active thermal manifestations (Figure 2) (Resyes, Delfin and Bueza, 1995).

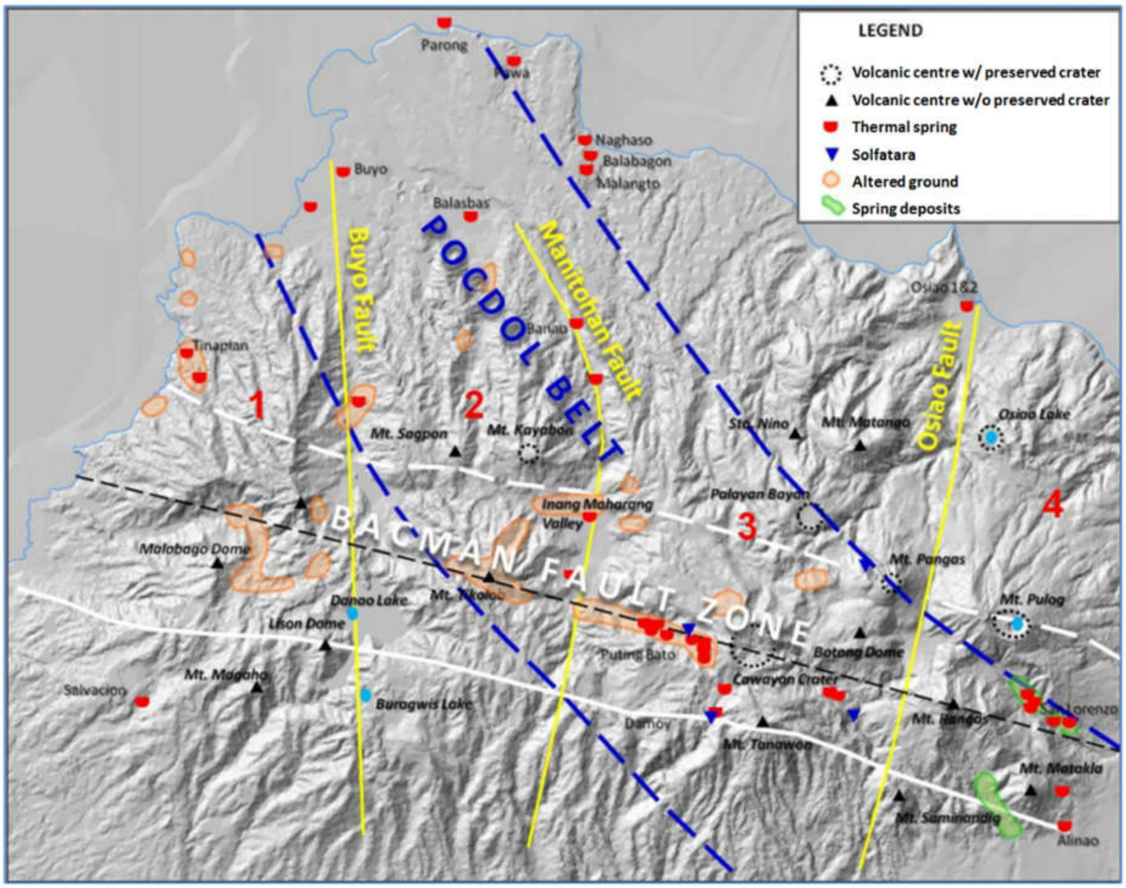

Figure 2. Structure and manifestations at the Bac-Man geothermal field (Africa, 2013).

Layugan *et al.* (2005), analyzed and interpreted magneto-telluric data based on data from 1999 and 2001 which obtained the contour boundaries of the anomaly resistivity of the conductive zone as a reservoir area.

An iso-resistivity map at a depth of -1100 m from MSL which is correlated with the geological structure in the area shows that the central part of the Bac-Man fault zone has a low resistivity value (Tugawin *et al.*, 2015). The Bac-Man reservoir area covers an area of 26 - 36 km2, while the Kayabon reservoir located to the northwest of Bac-Man covers an area of 12 - 18 km2 (Figure 3).

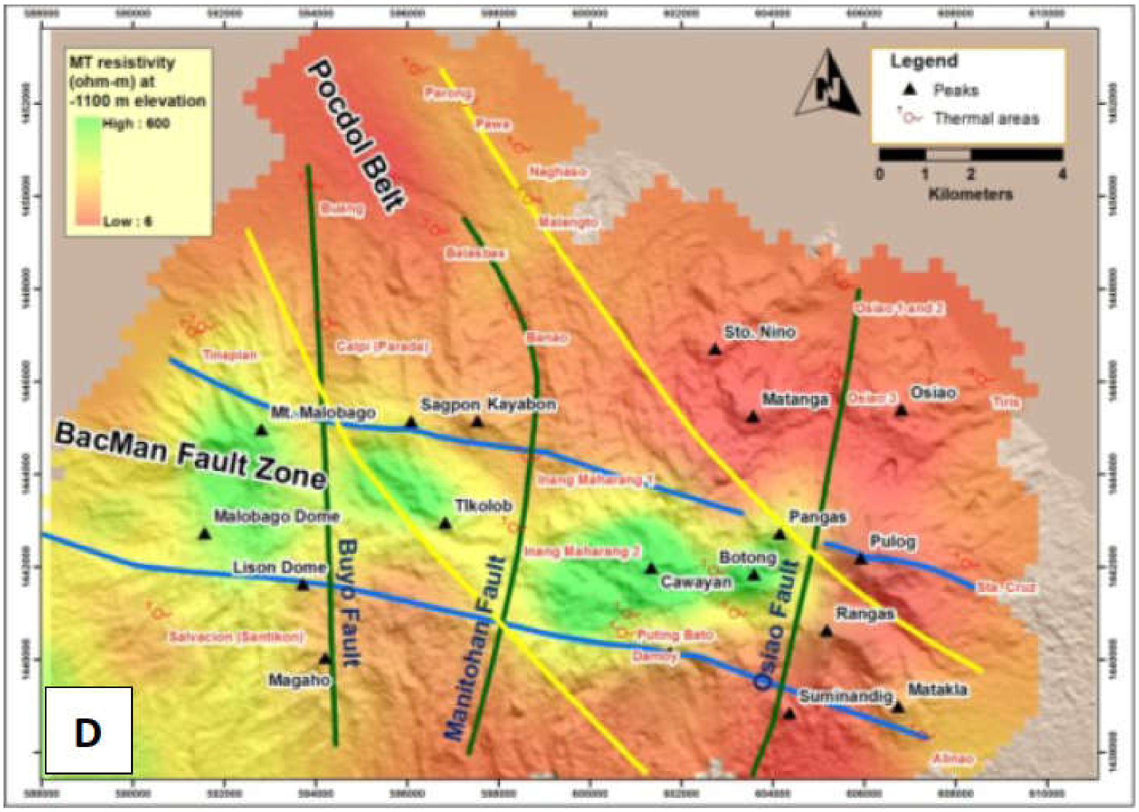

Figure 3. An isoresistivity map at a depth of -1100 m from MSL which is correlated with the geological structure in the area shows that the central part of the Bac-Man fault zone has a low resistivity value (Tugawin *et al.*, 2015).

The results of this MT study support the results of previous MT research conducted by Layugan *et al.* (2005), which found that the prospect area for the Bac-Man geothermal reservoir is in Botong, Cawayan and Tikolob although the results show a larger area than the results of previous MT studies.

Research related to reservoir temperature was carried out by Austria, 2008, in which the eastern part of Palayan - Bayan has a high temperature of 326 ° C (Austria, 2008). The temperature contour map at a depth of -1000 meters from MSL is shown in Figure 4.

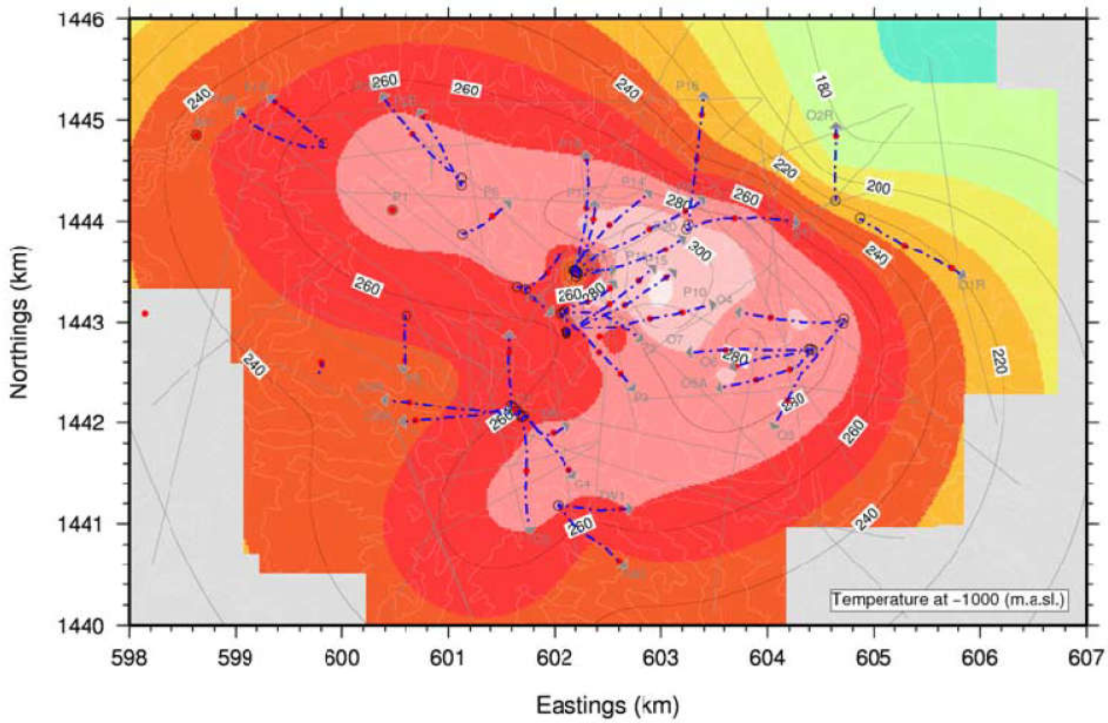

Figure 4. Temperature contour map at a depth of -1000 meters from MSL (Austria, 2008)

3. Methods

The gravity data used in this study were 125 points which were the results of measurements from 2009 to 2010 (Monasterial, 2015). Processing of gravity data includes: determination of surface density using the Parasnis and Nettleton method, determination of Bouguer anomaly, Bouguer anomaly filtering, Bouguer anomaly separation, horizontal and vertical gradient analysis of Bouguer anomaly, and Bouguer anomaly modeling. Analysis and interpretation were carried out to verify the Bac-Man geothermal reservoir area and structures in the area. The analysis and interpretation are carried out by correlating the gravity model with geological data, well data and other geophysical data. The research flow carried out is shown in Figure 5.

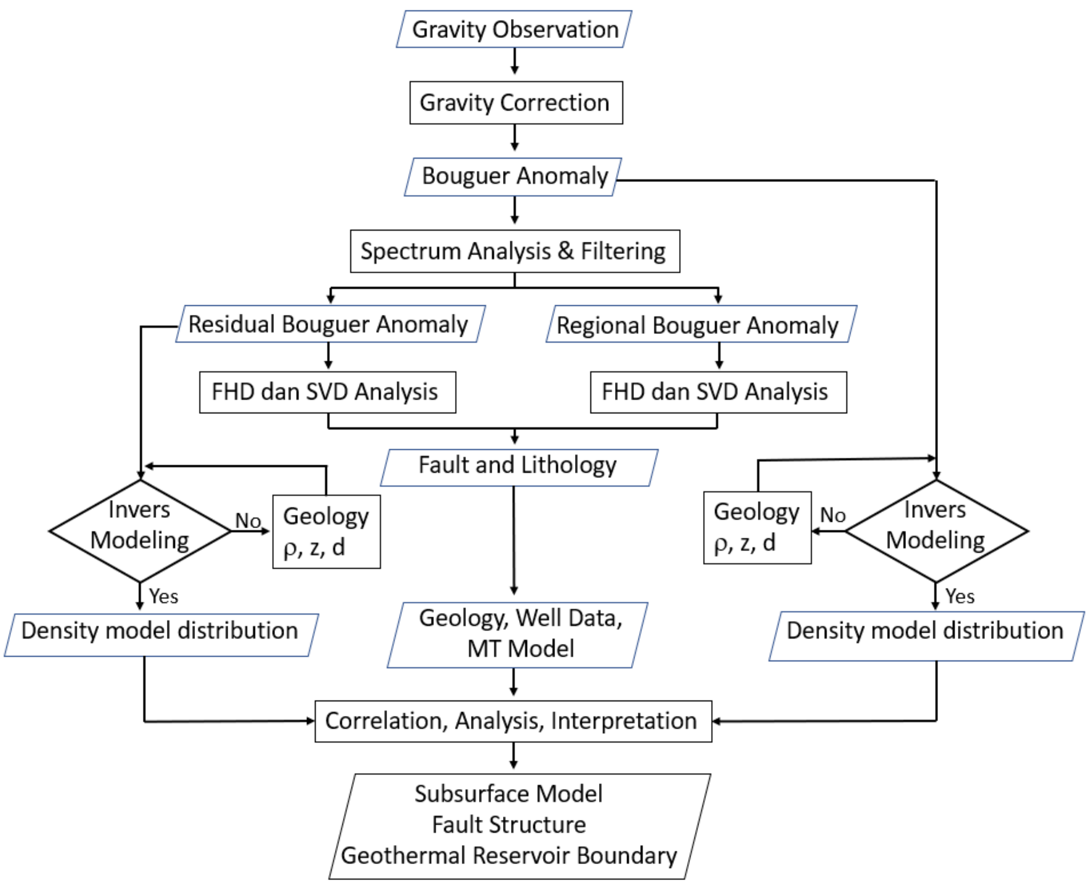

Figure 5. Flowchart of research in determining the boundary of a geothermal reservoir

Density determination was carried out using the Parasnis method and the Nettleton method. The results of calculations using the Parasnis method get a value of 2.24 g/cc, while calculations using the Nettleton method for 2 (two) cross sections get a value of 2.35 g/cc and 2.38 g/cc. This density value when compared with geological conditions in the field has an appropriate value, so that in research for the calculation of Bouguer correction and modeling using a density of 2.35 g/cc.

To obtain Bouguer anomaly, gravity observation data is performed by gravity theoretic correction at latitude φ, free air correction (free air correction), Bouguer correction and terrain correction. The calculation of the gravity theorical correction at latitude φ uses the International Gravity Formula 1980 equation (Wellenhof and Moritz, 2005):

$$g_{\varphi} = 978.032{,}7(1 + 5.3024\ 10^{-3}\ Sin^2\varphi - 5{,}8\ 10^{-6}\ Sin^2\ 2\phi \qquad (1)$$

Meanwhile, for free air correction, the FAA equation = -0.308 h (mGall/m) is used which is obtained from the derivative of the Earth's normal gravity equation in the form of an ellipsoid, namely:

$$g_{\phi,h} = g_{\phi} + \frac{\partial g_{\phi}}{\partial h} h \qquad (2)$$

$$\frac{\partial g_{\phi}}{\partial h} = -\frac{2g_{\phi}}{a}(1 + f + m - 2f\ sin^2\ \phi) = -0{,}308\ mGall/m \qquad (3)$$

The Bouguer correction value is calculated using the approach model for the slab model, namely:

$$Bc = 2\pi G\rho h\ = 0.04193\rho h \qquad (4)$$

Where ρ is rock density (g/cc), h is height (m), and Bc is Bouguer correction (mGall).

Terrain corrections were calculated using a combination of the equations given by Nagy (1966) and Kane (1962). In the calculation of terrain correction, the topographic model is approached with a prism-shaped arrangement of objects measuring 1 km x 1 km with a height in accordance with the topography of the area up to a radius of 50 km. The topographical data used is DEM data taken from INA Geoportal.

4. Result and Discussions

The Bouguer anomaly in the Bac-Man geothermal field has a value of 18 - 41 mGall, with a high anomaly in the West to the Northwest and a little in the middle, while the anomaly is low in the middle. The high anomaly in the Northwest part is probably related to the heat-source of the geothermal system in the Bac-Man field, while the low anomaly in the middle part flanking the high anomaly is probably related to the presence of a reservoir in the area (Figure 6).

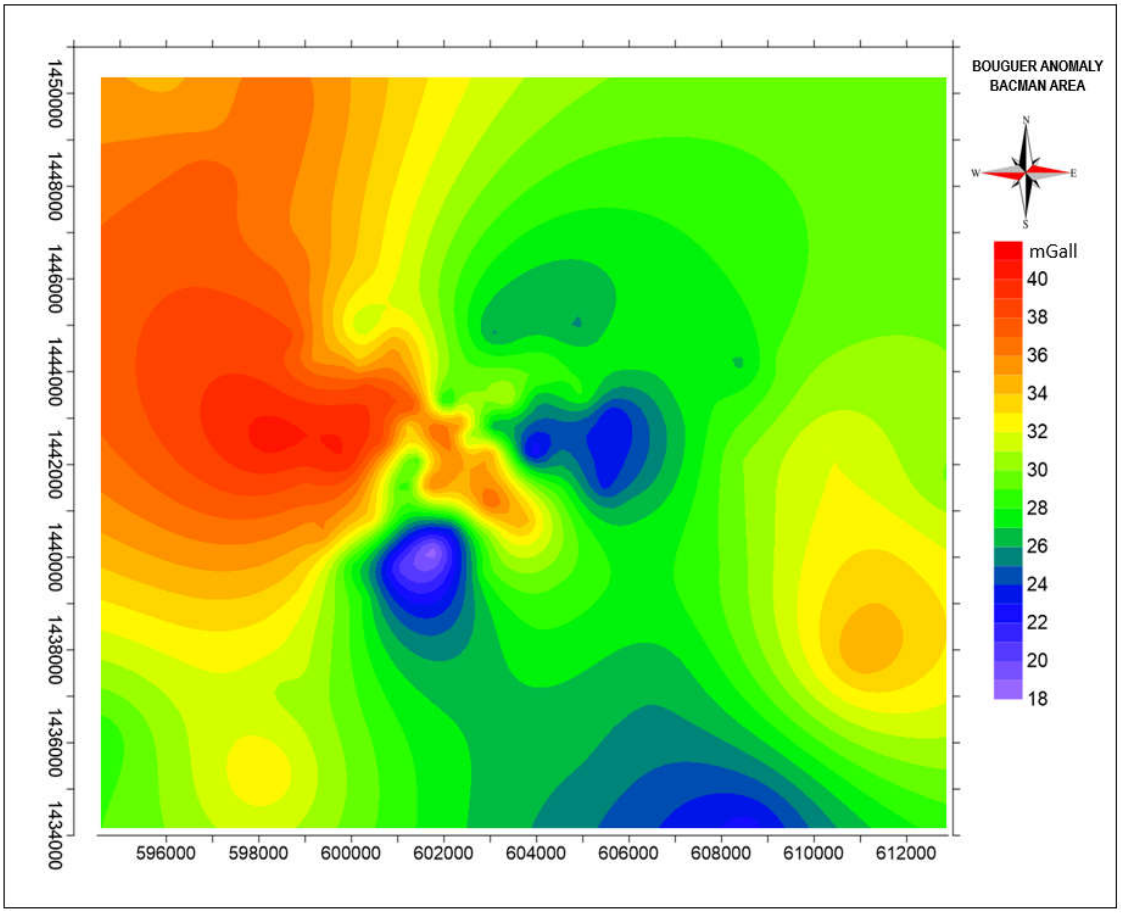

Figure 6. Map of the Bouguer anomaly of the Bac-Man geothermal field area

Spectral analysis was carried out to determine the boundary of the regional bouguer anomaly and the residual area of the study. The results of this spectral analysis are then used to estimate the window width for gravity anomaly filtering. In general, a Fourier transformation is to reconstruct/unravel an arbitrary wave into a sine wave with a variable frequency where the sum of the sine waves is the original waveform (Bhattacharyya and Leu (1977); Ghosh and Singh (2014)). Spectrum analysis is used to determine the depth of the structure of the anomaly. In this study, the analysis of the spectrum analysis used Fourier transform, where the results are used to estimate the width of the filtering window. The spectrum analysis was carried out by making a cross section of the Bouguer anomaly as many as 5 trajectories with a point interval of 250 m. The result of spectrum analysis from 5 lines of Bouguer anomaly shows that the average regional Bouguer anomaly depth is 2500 meters. Based on these results, the separation of regional Bouguer anomalies and residual Bouguer anomalies is used a moving average filter with a window width of 5 km x 5 km.

The residual Bouguer anomaly map from the Bouguer anomaly filtering using the moving average method with windows 5 km x 5 km is shown in Figure 7. Residual Bouguer anomaly maps have values from -12 mGall to 9 mGall with high anomalies occupying the eastern and central parts of the study area surrounded by low anomalies in the north, south and east. This area which occupies a low anomaly is probably the geothermal reservoir area of the Bac-Man field and this is in accordance with the magnetoteluric geophysical data as well as well data. There are 3 low anomaly closures in the middle which are separated by high anomalies. It can be interpreted that the geothermal reservoir in the Bac-Man field may be divided into 3 reservoirs, namely the North, South and East. Reservoirs may be separated from one another by fault structures or the presence of intrusion in the area.

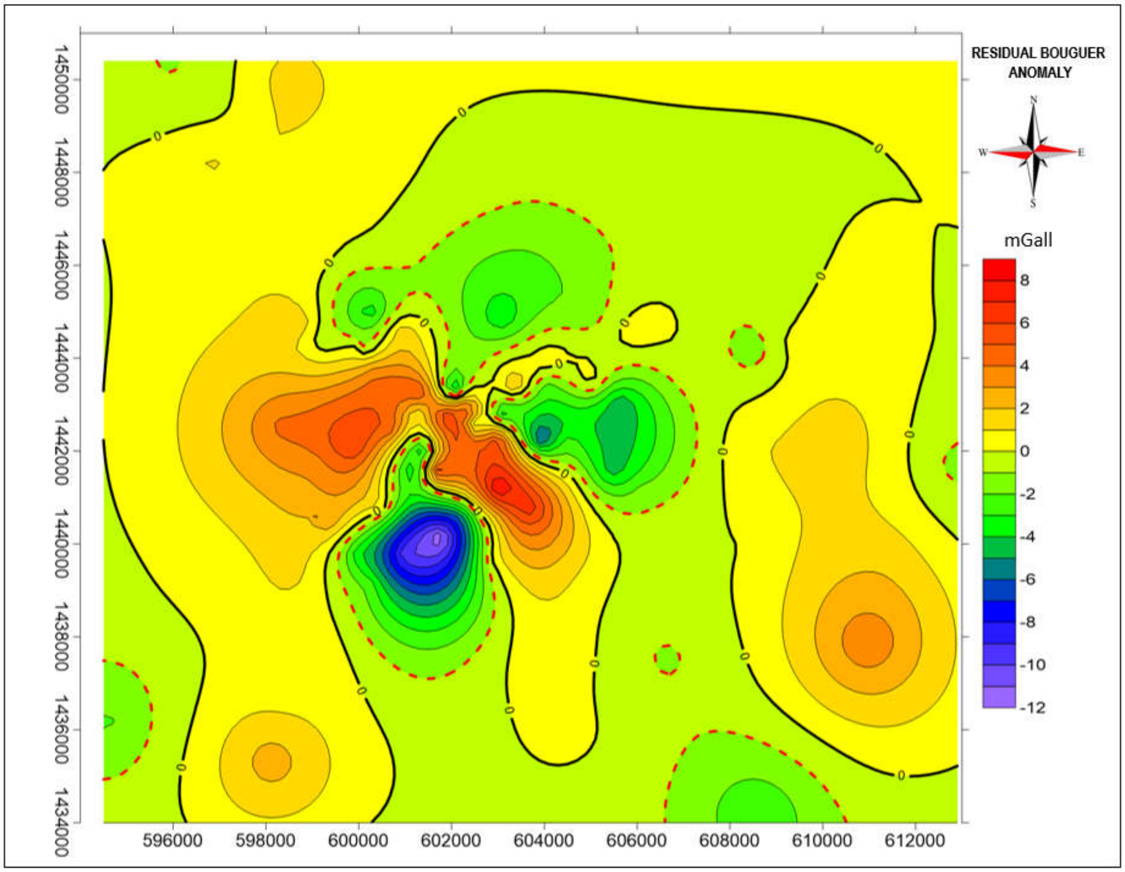

Figure 7. Map of the Bouguer Residual anomaly of the Bac-Man geothermal field

To support the analysis of the Bouguer Residual anomaly in identifying: the existence of the fault structure, the lithological boundary and to generate the shallow effect anomaly, a vertical gradient analysis of the Bouguer Residual anomaly was carried out. Theoretically, this method is derived from Laplace's equation for surface gravity anomalies:

$$\nabla^2 \Delta g = 0 \text{ atau } \frac{\partial^2 \Delta g}{\partial x^2} + \frac{\partial^2 \Delta g}{\partial y^2} + \frac{\partial^2 \Delta g}{\partial z^2} = 0 \quad (5)$$

$$\frac{\partial^2 \Delta g}{\partial z^2} = -\frac{\partial^2 \Delta g}{\partial x^2} + \frac{\partial^2 \Delta g}{\partial y^2} \quad (6)$$

In this study, the SVD anomaly gravity value is calculated using a filtering process, namely through convolution between anomaly gravity and a second vertical derivative filter.

$$\Delta Gsvd(\Delta x, \Delta y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \Delta g(x, y) F(x - \Delta x, v - \Delta y)\, dxdy \qquad (7)$$

Where F is the second vertical derivative filter according to the above equation and ΔG is the gravity anomaly.

The second vertical derivative filter used in this study is the Elkins (1951) type. The SVD map compiled Bouguer Residual anomaly with low residual Bouguer anomaly contours and the boundaries of the Bac-Man field geothermal prospects from the MT data is shown in Figure 8.

Data compilation of low Bouguer Residual anomaly, Bouguer Residual anomaly SVD, and reservoir prospect boundaries derived from magneto-telluric data were carried out to identify the presence of a reservoir in the area. In general, geothermal reservoirs will have a low Bouguer anomaly, because a good geothermal reservoir will have a high porosity value, high permeability so that the reservoir rock will have a low density. The SVD map of Bouguer Residual anomaly compiled with: Low Residual Bouguer anomaly, reservoir area boundary derived from magneto-telluric data, and reservoir prospect area derived from Bouguer Residual anomaly data is shown in Figure 8.

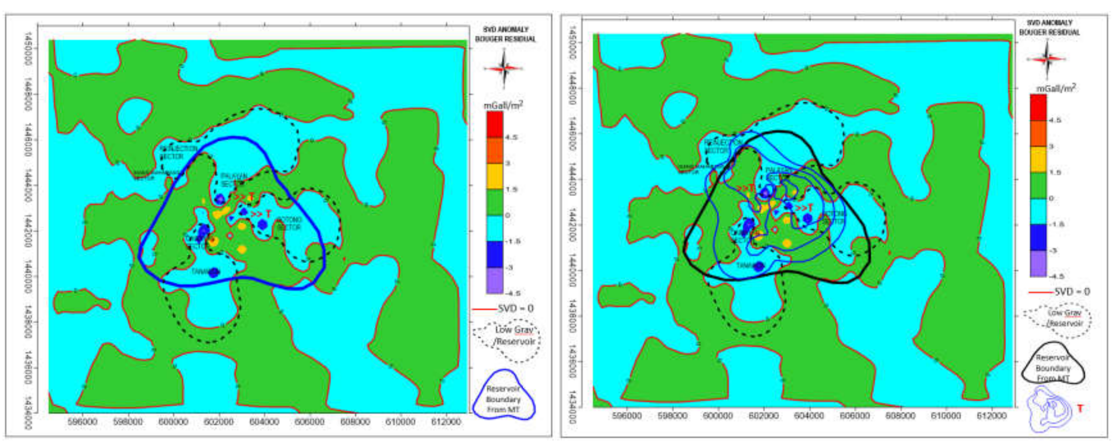

Figure 8. SVD map of the residual Bouguer anomaly overlaid with the reservoir area derived

from magnetotelluric data, and the reservoir prospect area derived from the Bouguer Residual anomaly data.

The figure shows that the reservoir locations of the four data provide the same results. The reservoir areas identified from the Bouguer Residual anomaly data and the Bouguer Residual SVD anomaly provide more detailed results, namely the Bac-Man geothermal reservoir is separated into 3 areas, namely: the Cawayan and Tanawon sectors in the South, the Boton sector which is located in the East, and the East sector. Palayang. This result is also supported by the high temperature in the area, where the highest temperature is in the Palayan sector.

The temperature distribution map at a depth of 1200 m from MSL shows that the center has a high temperature which is probably due to intrusion in the area. The existence of this intrusion is in accordance with the high residual gravity anomaly pattern in the area, where the intrusion is also a barrier from 3 reservoir locations in the area.

To obtain a model of the subsurface structure of the Bac-Man Geothermal Field in this study, a 3D inversion modeling of Bouguer Residual anomaly was carried out. The equation used and the calculation of 3D inversion modeling is the subsurface model approach which is composed of prisms with the amount according to: measurement area, data grid, thickness and depth of objects. The calculation of the gravity response for each prism block uses the Plouff (1976) equation:

$$g = G\Delta\rho \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2} \mu_{ijk}\left[z_k\, arctan\frac{x_i y_i}{z_k R_{ijk}} - x_i\, log\left(R_{ijk} + y_i\right) - y_i\, log\left(R_{ijk} + x_i\right)\right]$$

Where: $R_{ijk} = \sqrt{x_i^2 + y_j^2 + z_k^2}$; $\mu_{ijk} = (-1)^i (-1)^j (-1)^k$

The results of Bouguer Residual anomaly 3D inversion modeling using the Grav3D program are shown in Figure 9. The density distribution model of the 3D inversion modeling results shows the distribution of high and low density in the middle of the study area with a value of 2 g/cc to 2.9 g/cc. To obtain a subsurface structure model, the model is then carried out by slicing the selected paths which will be compared and correlated with models such as: temperature data models, magneto-telluric cross-sectional models, structural models and others.

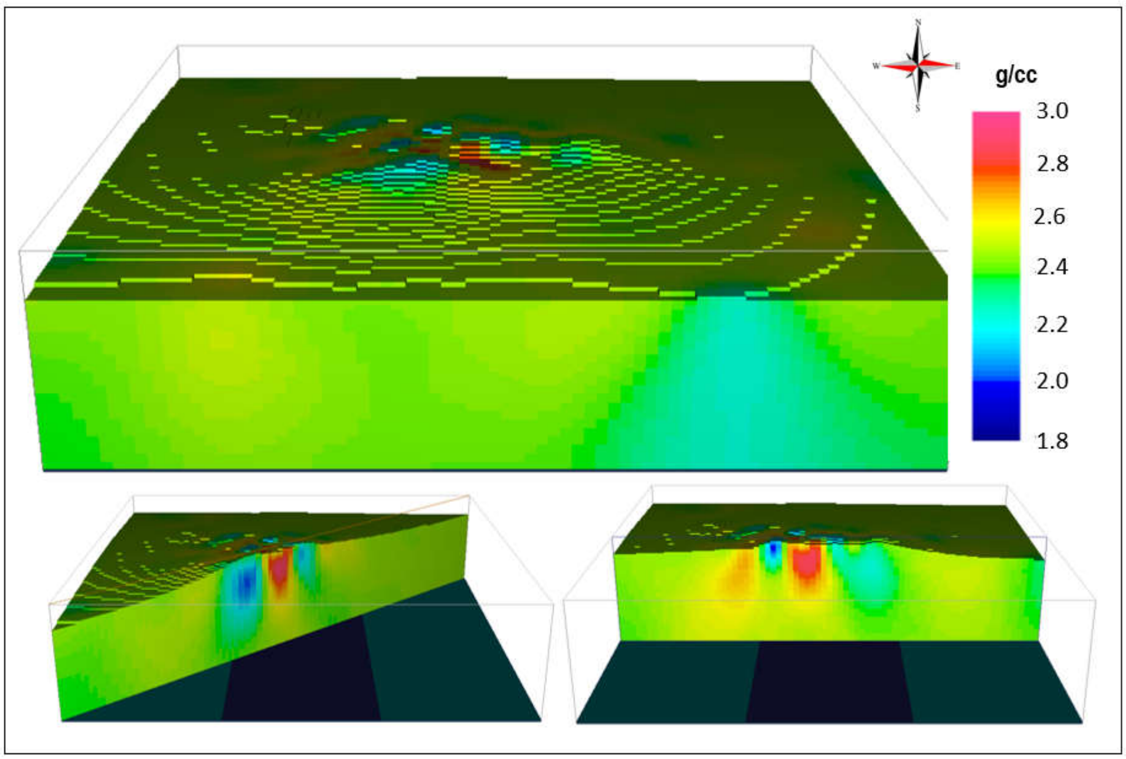

Figure 9. The subsurface density distribution model from the 3D inversion modeling result of Bouguer Residual anomaly in Bac-Man geothermal field

The density distribution model resulting from the 3D Bouguer anomaly residual inversion which is correlated with the temperature cross-sectional model and the intrusion structure on the NW-SE trajectory is shown in Figure 10. The results of the 3D Bouguer anomaly residual inversion result which are correlated with the temperature section model

(Ramos, 2002) and the intrusion structure shows a good correlation, the presence of intrusion is correlated with high density in the area. Likewise, the SVD section indicates that the intrusion is no single but separated into three parts according to the model derived from well data and temperature data.

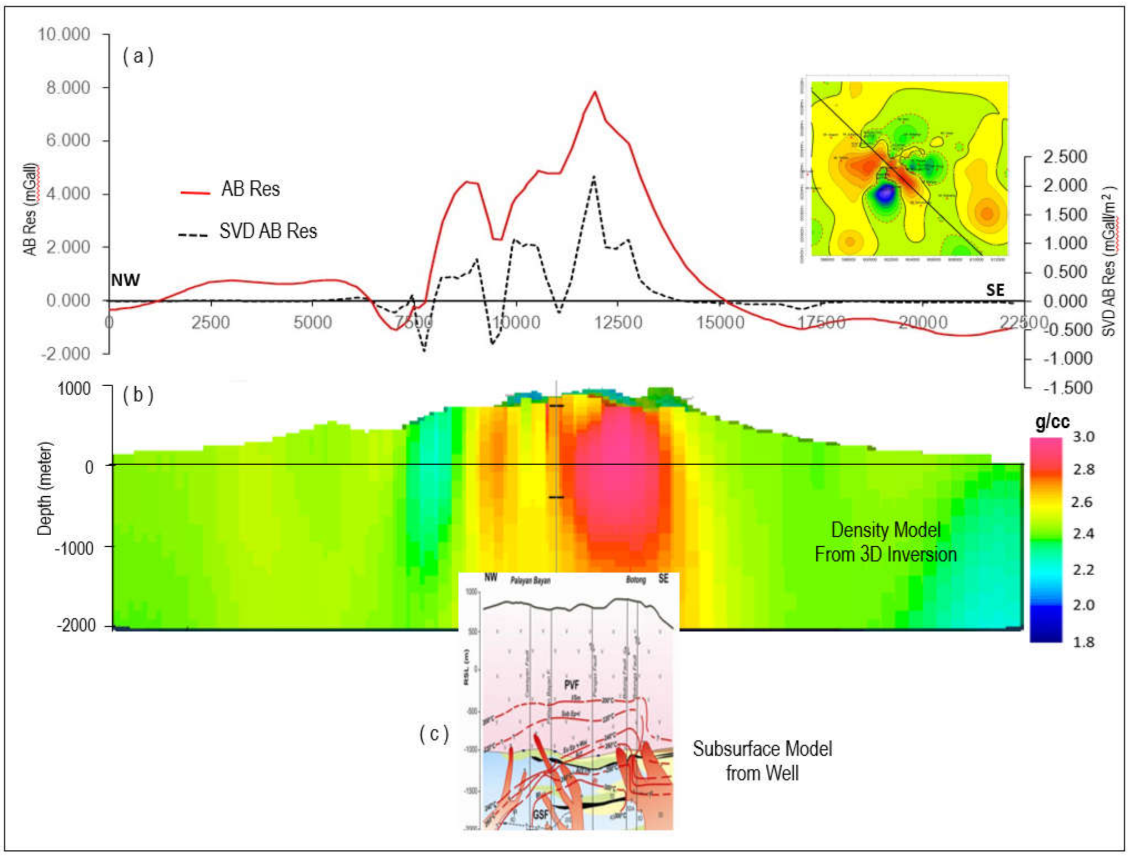

Figure 10. The cross section of the density distribution model resulting from the 3D Bouguer Residual anomaly inversion correlated with the temperature and intrusion structure cross-sectional model for the NW-SE trajectory.

The density distribution model resulting from the 3D Bouguer anomaly residual inversion which is correlated with the temperature cross-section model and the intrusion structure on the NE-SW trajectory is shown in Figure 11. The results of the 3D Bouguer anomaly residual inversion result which correlated the temperature cross-section model and the intrusion structure show the existence of good correlation, the presence of intrusion correlates with high density in the area. Likewise, the SVD section indicates that the intrusion is no single but separated into two parts according to the model derived from well data and temperature data.

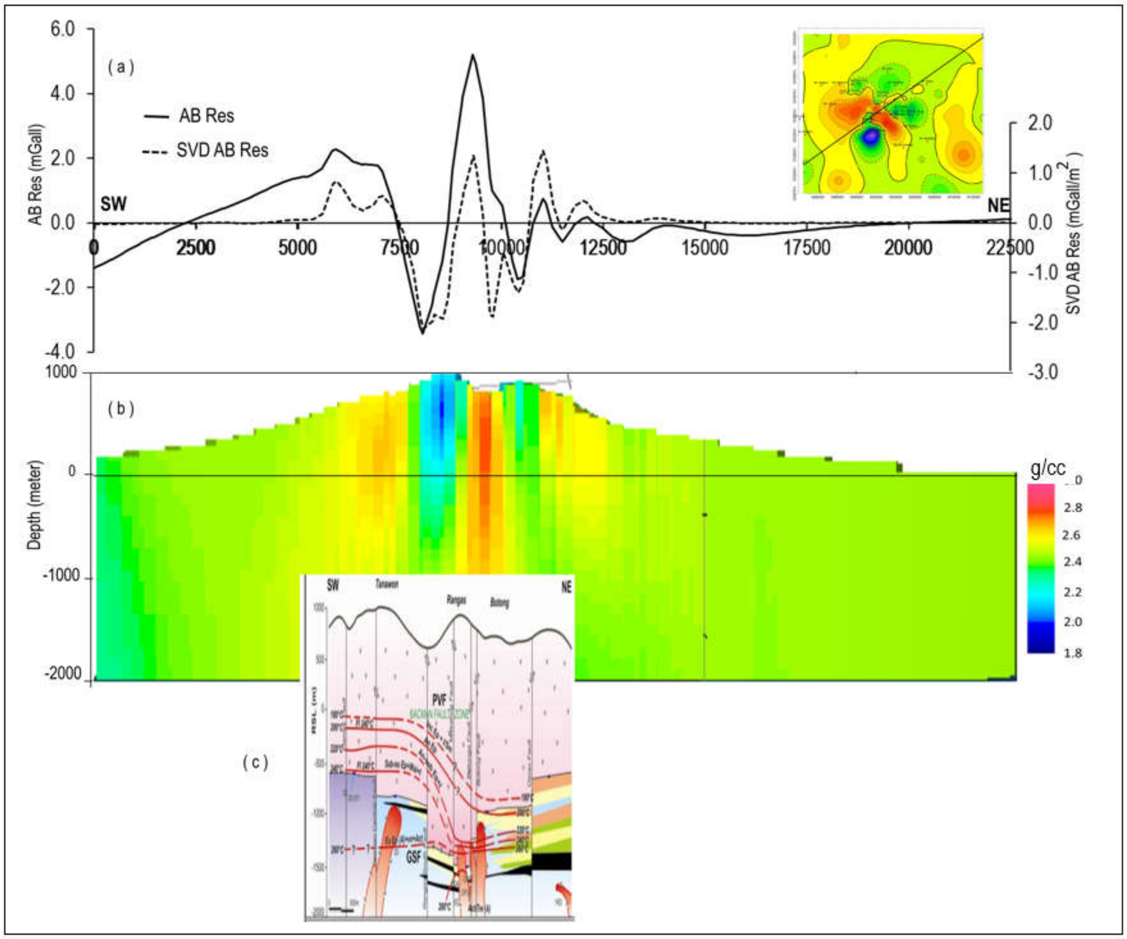

Figure 11. The cross section of the density distribution model resulted from the Bouguer Residual anomaly 3D inversion which is correlated with the temperature and intrusion structure cross-sectional model for the NE-SW trajectory.

The model is correlated with: the boundary of the geothermal reservoir area delineated from the MT results, the division of the geothermal sector, and the presence of volcanoes that control the geothermal system in the Bac-Man field.

The results of the correlation analysis between the cut density distribution models for density 2.1 g/cc - 2.4 g/cc (interpreted as a geothermal reservoir) and the reservoir prospect boundary derived from MT indicate that the reservoir locations have similarities, but the reservoir area derived from the gravity model is more broad and in more detail. From the gravity modeling shows that the geothermal reservoir in the Bac-Man field is divided into 3 areas, namely: the southern part (Cawayan and Tanawon sector), the eastern part (Boton sector) and the northern part (Palayan -Inang Maharang sector) where each reservoir area is. separated by the presence of fault structures or intrusions in the area. The division of the 3 reservoir areas is in accordance with the well data and the results of reservoir modeling research in the area, where the geothermal reservoir area of the Bac-Man field is divided into 3 sectors, namely the south (Cawayan and Tanawon sectors), the east (Boton sector) and the north (the North sector). Palayan-Inang Maharang) (Figure 12). The reservoir sectors are separated by intrusion in the area, this is supported by the temperature of the reservoir in the area which has a higher temperature than the surrounding area.

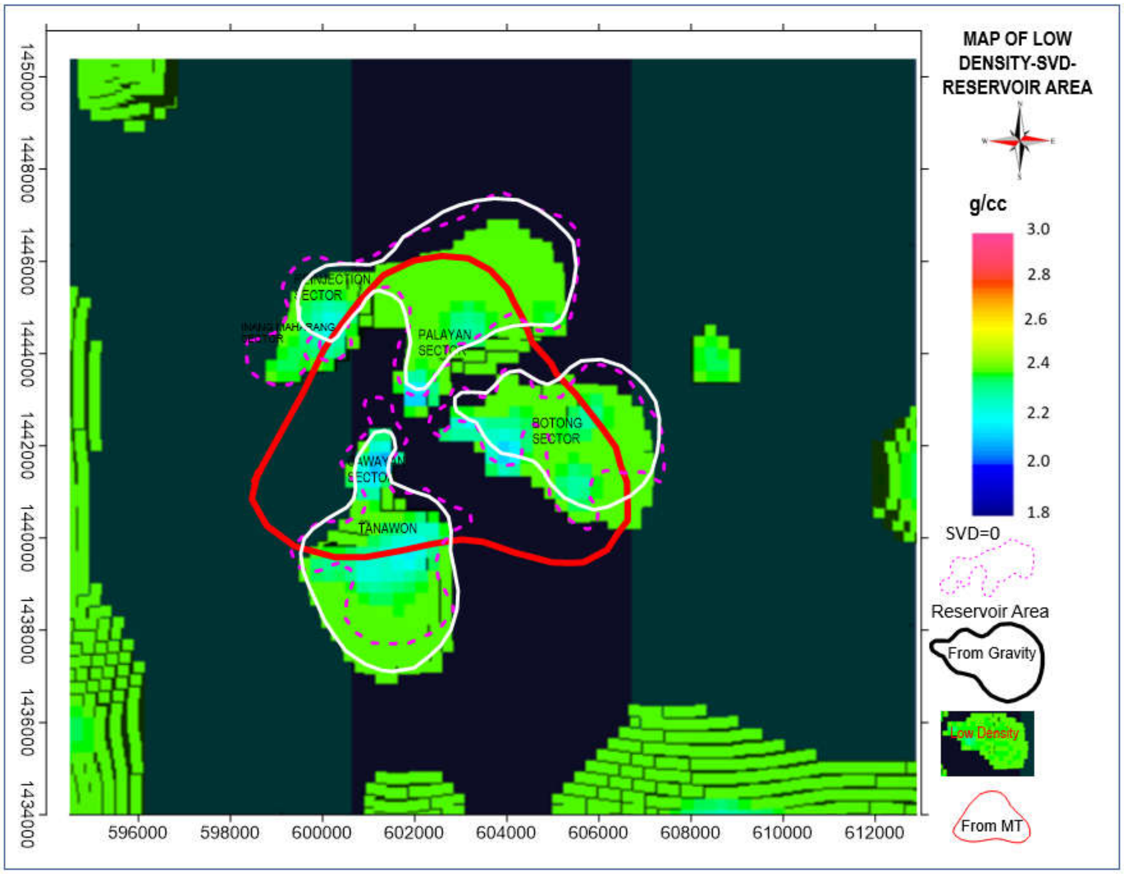

Figure 12. Density distribution model of Bouguer Residual anomaly 3D inversion modeling results shown for densities 2.1 g/cc - 2.4 g/cc. The model is correlated with: geothermal reservoir area boundaries delineated from the MT results, SVD = 0 maps, the division of geothermal areas, and the presence of volcanoes that control the geothermal system in the Bac-Man field.

5. Conclusions

Based on the results of gravity research on the Bac-Man geothermal field supported by geological data, well data, magneto-telluric data, and temperature data, several conclusions can be drawn regarding the Bac-Man geothermal field, namely:

1. Bouguer anomaly in the study area has a value of 18 - 41 mGall, with a high anomaly in the West to the Northwest and a little in the middle, while the anomaly is low in the middle. From the analysis of the Bouguer anomaly spectrum, it is found that the Bouguer Regional and Residual anomaly limits are at a depth of 2500 m.

2. Residual Bouguer anomaly calculated using a moving average filter with windows 5 km x 5 km shows that the residual Bouguer anomaly has a value of -12 mGall to 9 mGall with high anomalies occupying the eastern and central parts. There are 3 low anomaly closures in the middle which are separated by high anomalies, which can be interpreted that the geothermal reservoir in the Bac-Man field may be divided into 3 reservoirs, namely the North, South and East.

3. The density distribution model from the 3D inversion modeling shows that the density distribution model cut for density 2.1 g/cc - 2.4 g/cc has a correlation with the reservoir boundary derived from MT, but the reservoir area derived from the gravity model is wider and more detailed. The results of gravity modeling show that the geothermal reservoir in the Bac-Man field is divided into 3 areas, namely: the southern part (Cawayan and Tanawon sector), the eastern part (Boton sector) and the northern part (Palayan - Inang Maharang sector) where each reservoir area is. separated by the presence of fault structures or intrusions in the area. The division of the 3 reservoir areas is in accordance with the well data and the results of reservoir modeling research in the area. The reservoir sectors are separated by intrusion in the

area. This is also supported by temperature data which shows that the area has a higher temperature than the surrounding area.

4. In order to obtain more detailed reservoir boundaries, especially the outer reservoir boundaries, it is suggested to add more detailed gravity measurement points in the North, East and South.

Acknowledgements

We would like to thank all those who have helped in the implementation of this research, especially the Geophysical Engineering Department, Faculty of Engineering, University of Lampung.

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Reservoir Identification of Bac-Man Geothermal Field Based on Gravity Anomaly Analysis and Modeling

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Abstract

The Bac-Man geothermal field is located between the provinces of Albay and Sorsogon on the Bicol Peninsula. Several geophysical modeling methods have been carried out to identify the Bac-Man field geothermal system. This research focuses on 3D modeling and analysis of gravity data which aims to identify the geothermal reservoir in the Bac-Man field. This research includes several things, such as spectrum analysis and the separation of Bouger's anomalies, gradient analysis, and anomaly modeling. Based on the modeling results, there are 3 low anomaly closures in the middle which are separated by high anomalies, which can be interpreted that the geothermal reservoir in the Bac-Man field may be divided into 3 reservoirs, namely the southern part (Cawayan and Tanawon sector), the eastern part (Boton sector) and the northern part (Palayan - Inang Maharang sector) where each reservoir area is separated by the presence of a fault or intrusion structure.

Keywords: Bac-Man field, Gravity, Modeling, Reservoir, Geothermal

1. Introduction

The Bacon - Manito (Bac-Man) geothermal field is located in the Podcol mountains on the island of Luzon, about 350 km southeast of Manila. The exploration of the Bac-Man geothermal field has been carried out since 1977. The reservoir model has 23 km^2, 1500 m depth, and a temperature of 240ºC to 320ºC. Based on geological, geochemical, and geophysical data, a conceptual model of the Bac-Man geothermal system has been made [1].

Tugawin *et al.* (2015) [2] carried out 2D magneto-telluric (MT) inversion modeling in the Bac-Man field, which shows the existence of 3 (three) geothermal reservoir areas, namely Palayan Bayan, Tikolob, and Malobago areas. These results follow the results of data interpretation of resistivity vertical electric sounding (VES) and Schlumberger Resistivity Traversing (SRT) [2]. The reservoir in the Palayan Bayan area has been in production since 1993, while the Tikolob prospect is on the west side of the Bac-Man field, separate from the Palayan Bayan system [2].

Espartinez and See (2005) [3] have conducted geochemical research in the Bac-Man Geothermal field to determine changes in reservoirs from their chemical properties. It is done to maintain the continuity of steam production in the Bac-Man field considering that of the 3 geothermal reservoir sectors, the Palayan Bayan and Cawayan sectors are still producing while the Boton sector has not been producing since 2009 [4].

In this research, gravity data processing and modeling will be carried out to determine the geothermal reservoir in the Bac-Man field (Palayan Bayan, Cawayan, and Boton). The results of the subsurface model derived from anomaly gravity analysis and the density distribution model resulting from compilation/correlation modeling with MT and temperature model data.

2. Bac-Man Geothermal System

The exploration of the Bac-Man geothermal field has been carried out since 1977. Several studies have been carried out, ranging from geology, geochemistry, geophysics (gravity, magnetic, micro earthquake, MT, temperature, etc.) to determine the geothermal reservoir, caprocks, heat-source, the geothermal system model, and geothermal potential in the area. The total capacity of the power plant in the Bac-Man area is 150 MWe generated from 4 generating units, namely: Unit I began operating in 1993 and unit II in 1995 which was named Palayang Bayan (2 x 55 Mwe), in 1996 the Cawayan geothermal plant began operating (20 Mwe), and in 1998 the Unit III power plant in the Botong area began operating (20 Mwe). The Bac-Man geothermal field is located in the Podcol mountains 350 km southeast of Manila. The local fault system is known as the Bac-Man Fault Zone (BFZ) [5] . The fault zone is indicated by a series of volcanoes that are mostly NW-SE (Figure 1). Structurally controlled by a fault system, which is believed to be an extension of the San Vicente Linao Fault (SVLF), is a stretch of the Philippine fault. The most prominent regional geological structure in the area is the San Vicente-Linao Fault in the Northwest - Southeast (NW-SE), which slopes across the Bico Peninsula [6].

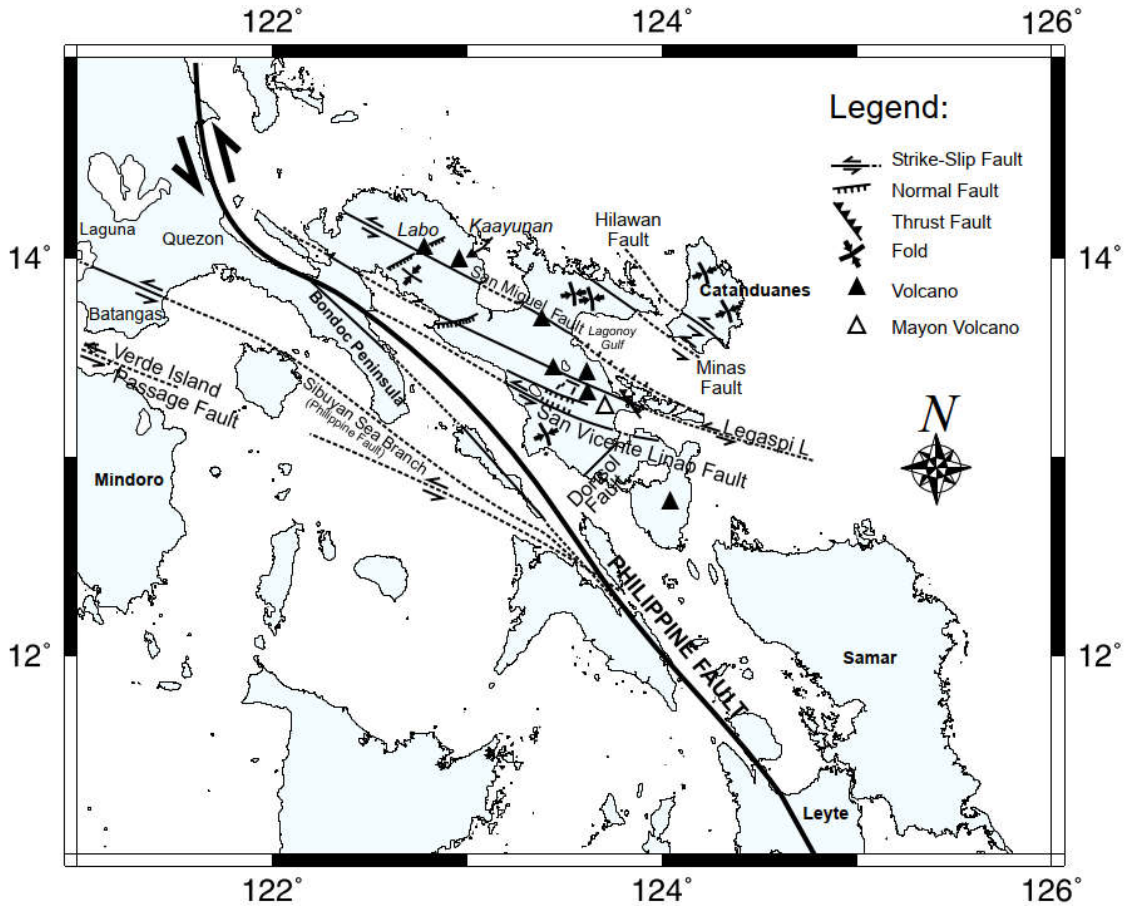

Figure 1. Bicol Peninsula fault area, San Vicente-Linao fault (SVLF) [7].

The Bac-Man geothermal system is divided into two regions, namely the western and eastern parts of Bac-Man. The eastern part of Bac-Man is further divided into the North Namito lowlands and the Podcol highlands. The Podcol plateau can be divided into eight geographic sectors: Inang Maharang, Putting Bato, Palayan Bayan, Cawayan, Tanawon, Osiao, Bangas, and Botong [6]. Neutral chloride hot springs with a temperature of 89 °C - 96 °C are found in the lowlands of Manito. In Cawayan and Pangas, Solfatara is found in West Bac-Man, cold to warm and cold SO_4 springs are found.

The most recent volcanic event in the Pocdol highlands occurred more than 40 thousand years ago. That is related to the formation of the Tanawon and Cawayan craters and the

Botong and Pangas domes extrusion. The youngest volcanoes generally occur in subsurface areas with high temperatures, permeable formations, and active thermal manifestations (Figure 2) [6].

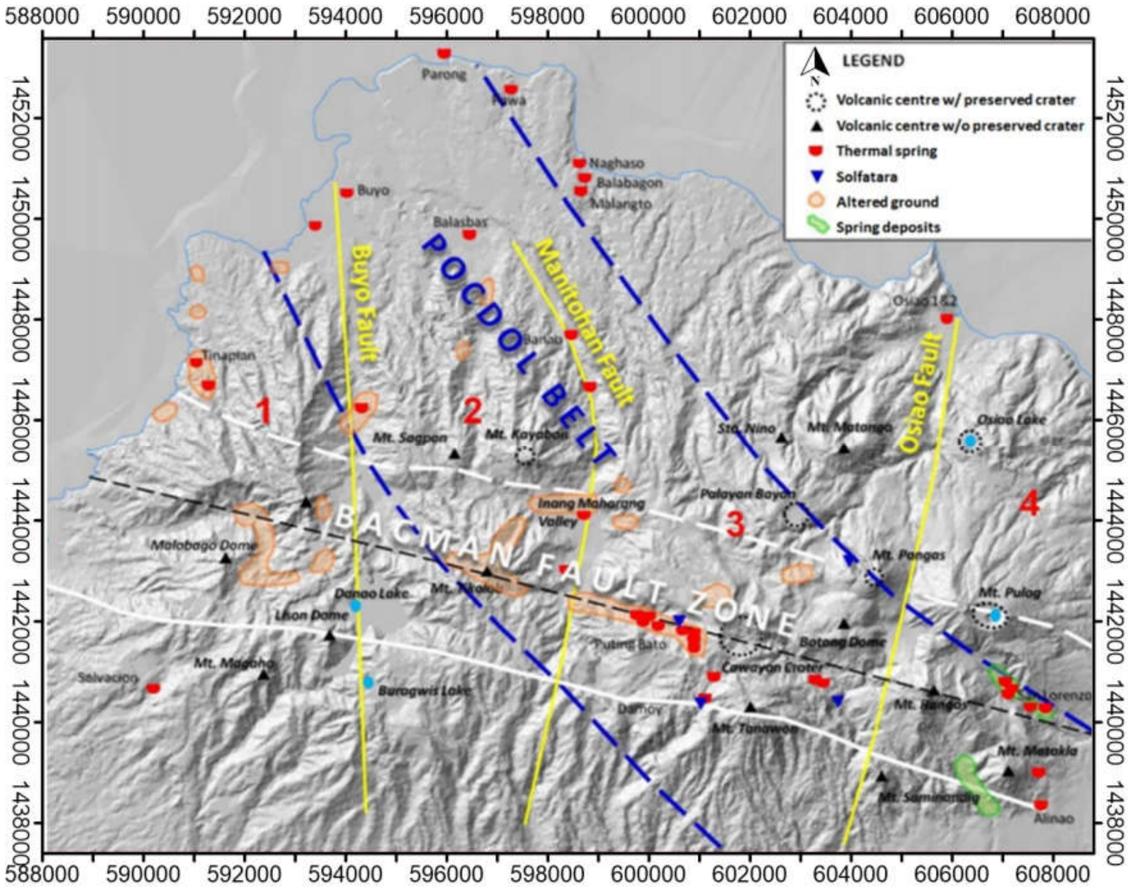

Figure 2. Structure and manifestations at the Bac-Man geothermal field [8].

Layugan *et al.* (2005) [9] analyzed and interpreted MT data based on data from 1999 and 2001, which obtained the contour boundaries of the conductive zone's anomaly resistivity as a reservoir area.

An iso-resistivity map at a depth of -1100 m from MSL, which is correlated with the geological structure in the area, shows that the central part of the Bac-Man fault zone has a low resistivity value [2]. The Bac-Man reservoir area covers 26 - 36 km2, while the Kayabon reservoir located to the northwest of Bac-Man covers an area of 12 - 18 km2 (Figure 3).

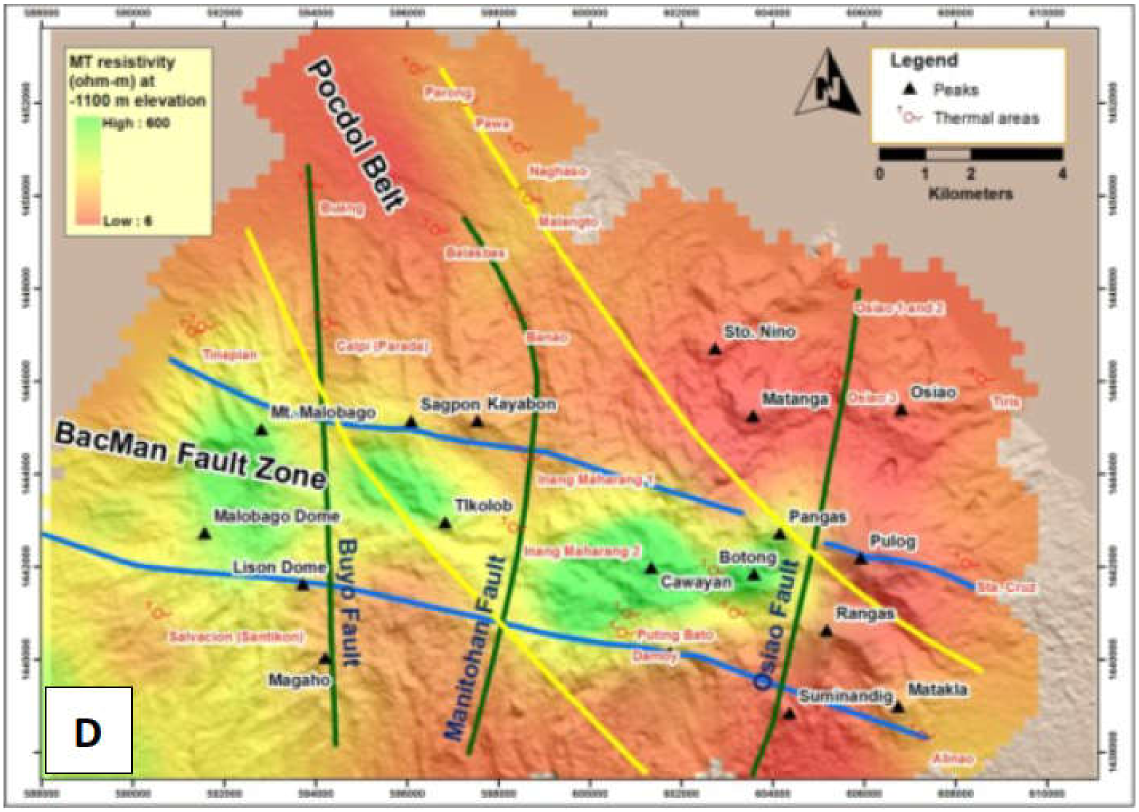

Figure 3. An isoresistivity map at a depth of -1100 m from MSL which is correlated with the geological structure in the area, shows that the central part of the Bac-Man fault zone has a low resistivity value [2].

The results of this MT study support the results of previous MT research conducted by Layugan *et al.* (2005) [9], which found that the prospect area for the Bac-Man geothermal reservoir is in Botong, Cawayan, and Tikolob. However, the results show a larger area than the results of previous MT studies.

Research related to reservoir temperature was carried out by Austria (2008) [1], in which the eastern part of Palayan - Bayan has a high temperature of 326 ° C. The temperature contour map at a depth of -1000 meters from MSL is shown in Figure 4.

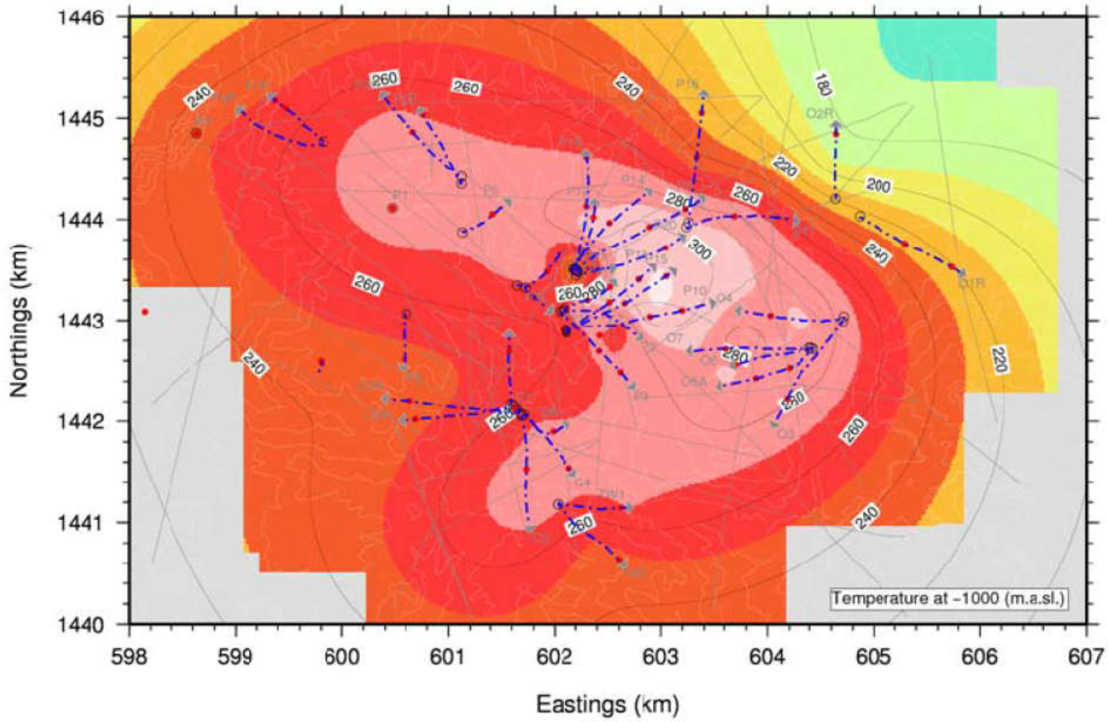

Figure 4. Temperature contour map at a depth of -1000 meters from MSL [1].

3. Methods

The gravity data used in this study were 125 points: the results of measurements from 2009 to 2010 [10]. Processing gravity data includes determination of surface density using the Parasnis and Nettleton method, the determination of Bouguer anomaly, Bouguer anomaly filtering, Bouguer anomaly separation, and horizontal and vertical gradient analysis Bouguer anomaly, and Bouguer anomaly modeling. Analysis and interpretation were carried out to verify the Bac-Man geothermal reservoir area and structures in the area. The analysis and interpretation are carried out by correlating the gravity model with geological data, well data, and other geophysical data. The research flow carried out is shown in Figure 5.

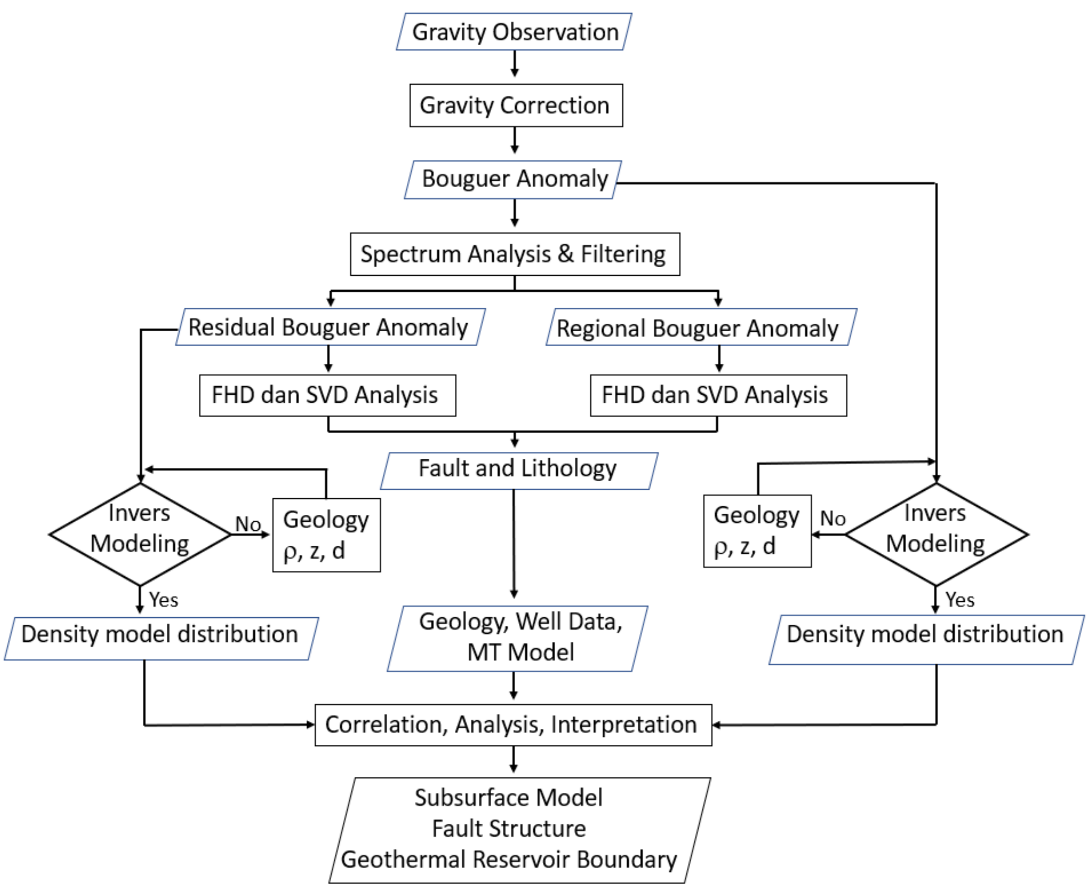

Figure 5. Flowchart of research in determining the boundary of a geothermal reservoir

Density determination was carried out using the Parasnis method and the Nettleton method. The calculations using the Parasnis method get a value of 2.24 g/cc, while calculations using the Nettleton method for 2 (two) cross-sections get a value of 2.35 g/cc and 2.38 g/cc. When compared with geological conditions in the field, this density value has an appropriate value, so that in research for the calculation of Bouguer correction and modeling using a density of 2.35 g/cc.

Bouguer anomaly obtained, gravity observation data is performed by gravity theoretic correction at latitude φ, free air correction (free air correction), Bouguer correction and terrain correction. The calculation of the theoretical gravity correction at latitude φ uses the International Gravity Formula 1980 equation (equation 1) [11]:

$$g_{\varphi} = 978.032,7(1 + 5.3024\ 10^{-3}\ Sin^2\varphi - 5,8\ 10^{-6}\ Sin^2\ 2\phi \qquad (1)$$

Meanwhile, for free air correction, the FAA equation = -0.308 h (mGal/m) is used, which is obtained from the derivative of the Earth's normal gravity equation in the form of an ellipsoid, namely:

$$g_{\phi,h} = g_{\phi} + \frac{\partial g_{\phi}}{\partial h} h \qquad (2)$$

$$\frac{\partial g_{\phi}}{\partial h} = -\frac{2g_{\phi}}{a}(1 + f + m - 2f\ sin^2\ \phi) = -0,308\ mGall/m \qquad (3)$$

The Bouguer correction value is calculated using the approaching model for the slab model, namely:

$$Bc = 2\pi G\rho h\ = 0.04193\rho h \qquad (4)$$

Where ρ is rock density (g/cc), h is the height (m), and Bc is Bouguer correction (mGal).

Terrain corrections were calculated using a combination of the equations given by Nagy

(1966) [12] and Kane (1962) [13]. In the calculation of terrain correction, the topographic model is approached with a prism-shaped arrangement of objects measuring 1 km x 1 km with a height following the topography of the area up to a radius of 50 km. The topographical data used is DEM data taken from INA Geoportal.

4. Result and Discussions

The Bouguer anomaly in the Bac-Man geothermal field has a value of 18 - 41 mGal, with a high anomaly in the west to the northwest and a little in the middle, while the anomaly is low in the middle. The high anomaly in the Northwest part is probably related to the geothermal system's heat source in the Bac-Man field. The low anomaly in the middle part flanking the high anomaly is probably related to a reservoir in the area (Figure 6).

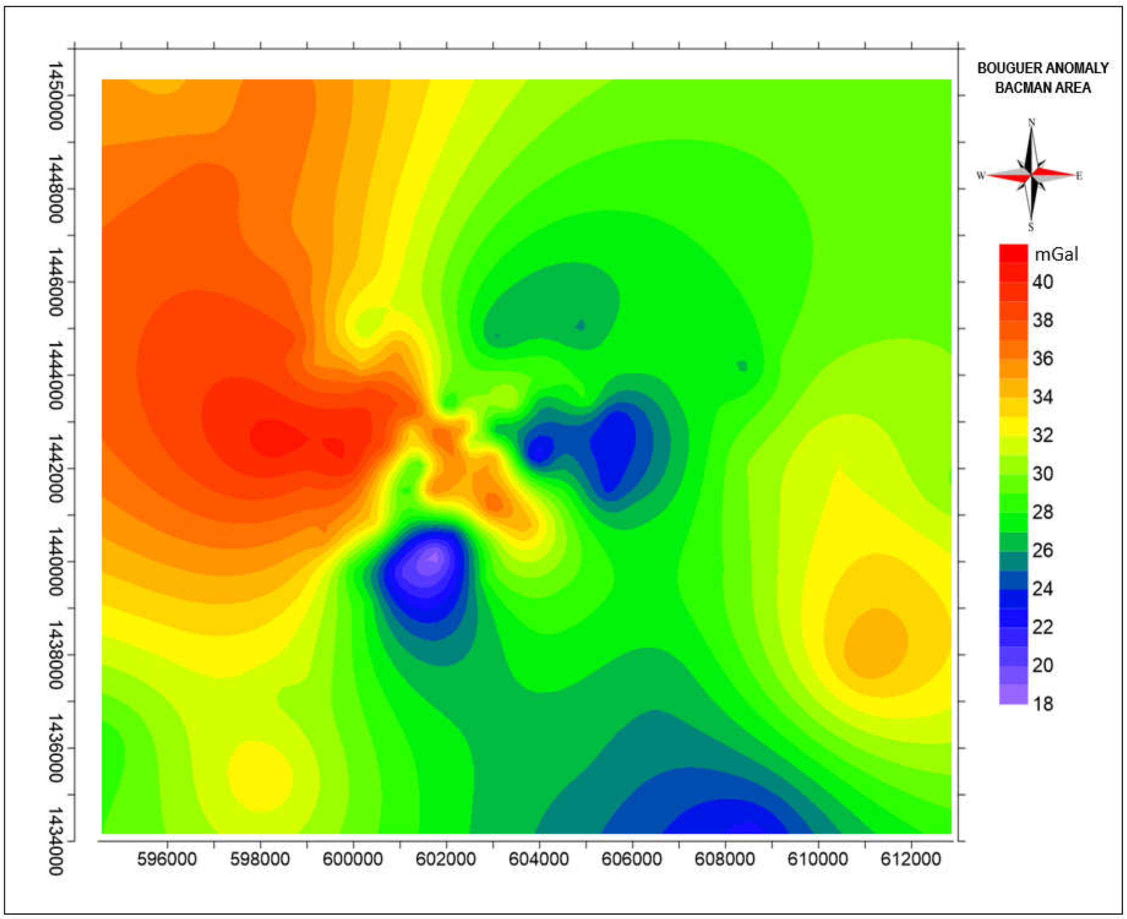

Figure 6. Map of the Bouguer anomaly of the Bac-Man geothermal field area

Spectral analysis was carried out to determine the boundary of the regional Bouguer anomaly and the residual area of the study. The results of this spectral analysis are then used to estimate the window width for gravity anomaly filtering. In general, a Fourier transformation is to reconstruct/unravel an arbitrary wave into a sine wave with a variable frequency where the sum of the sine waves is the original waveform [14-15]. Spectrum analysis is used to determine the depth of the structure of the anomaly. In this study, the analysis of the spectrum analysis used Fourier transform, where the results are used to estimate the width of the filtering window. The spectrum analysis was carried out by making a cross-section of the Bouguer anomaly as many as 5 trajectories with a point interval of 250 m. The result of spectrum analysis from 5 lines of Bouguer anomaly shows that the average regional Bouguer anomaly depth is 2500 meters. Based on these results, the separation of regional Bouguer anomalies and residual Bouguer anomalies is a moving average filter with a window width of 5 km x 5 km.

The residual Bouguer anomaly map from the Bouguer anomaly filtering using the moving average method with windows 5 km x 5 km is shown in Figure 7. Residual Bouguer anomaly maps have values from -12 mGal to 9 mGal, with high anomalies occupying the eastern and central parts of the study area surrounded by low anomalies in the north, south, and east. This area that occupies a low anomaly is probably the geothermal reservoir area of the Bac-Man field. This is following the MT geophysical data and well data. There are 3 low anomaly closures in the middle, which are separated by high anomalies. It can be interpreted that the geothermal reservoir in the Bac-Man field may be divided into 3 reservoirs, namely the north, south, and east. Reservoirs may be separated from one another by fault structures or the presence of intrusion in the area.

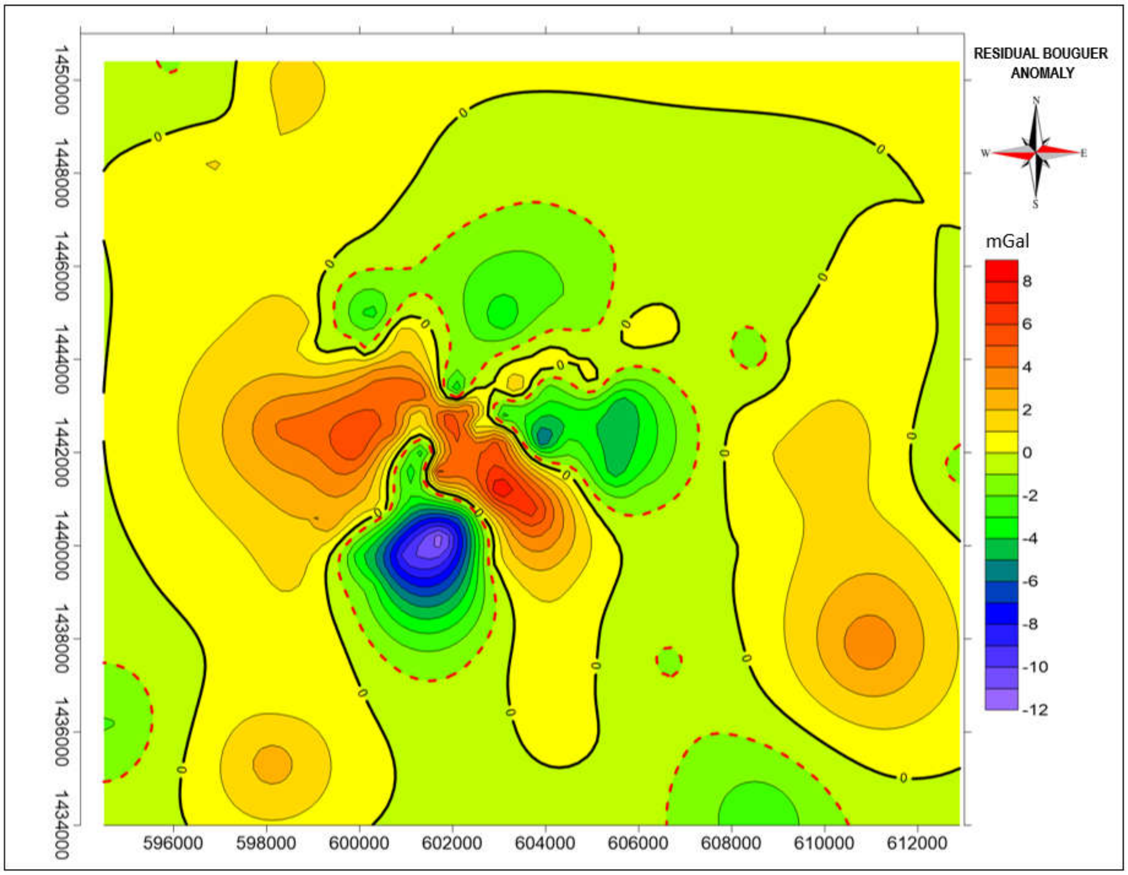

Figure 7. Map of the Bouguer Residual anomaly of the Bac-Man geothermal field

To support the Bouguer Residual anomaly analysis to generate the existence of the fault structure, the lithological boundary, and the shallow effect anomaly, a vertical gradient analysis of the Bouguer Residual anomaly was carried out. Theoretically, this method is derived from Laplace's equation for surface gravity anomalies:

$$\nabla^2 \Delta g - 0 \text{ atau } \frac{\partial^2 \Delta g}{\partial x^2} + \frac{\partial^2 \Delta g}{\partial y^2} + \frac{\partial^2 \Delta g}{\partial z^2} = 0 \quad (5)$$

$$\frac{\partial^2 \Delta g}{\partial z^2} = -\frac{\partial^2 \Delta g}{\partial x^2} + \frac{\partial^2 \Delta g}{\partial y^2} \quad (6)$$

In this study, the SVD anomaly gravity value is calculated using a filtering process, namely through convolution between anomaly gravity and a second vertical derivative filter.

$$\Delta Gsvd(\Delta x, \Delta y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \Delta g(x,y) F(x-\Delta x, v-\Delta y)\,dxdy \quad (7)$$

Where F is the second vertical derivative filter according to the above equation and ΔG is the gravity anomaly.

This study's second vertical derivative filter is the Elkins (1951) [16] type. The SVD map compiled Bouguer Residual anomaly with low residual Bouguer anomaly contours. The boundaries of the Bac-Man field geothermal prospects from the MT data are shown in Figure 8.

Data compilation of low Bouguer Residual anomaly, Bouguer Residual anomaly SVD, and reservoir prospect boundaries derived from MT data were carried out to identify a reservoir in the area. In general, geothermal reservoirs will have a low Bouguer anomaly because a good geothermal reservoir will have a high porosity value and high permeability. The reservoir rock will have a low density. The SVD map of Bouguer Residual anomaly compiled with: Low Residual Bouguer anomaly, reservoir area boundary derived from MT data, and reservoir prospect area derived from Bouguer Residual anomaly data is shown in Figure 8.

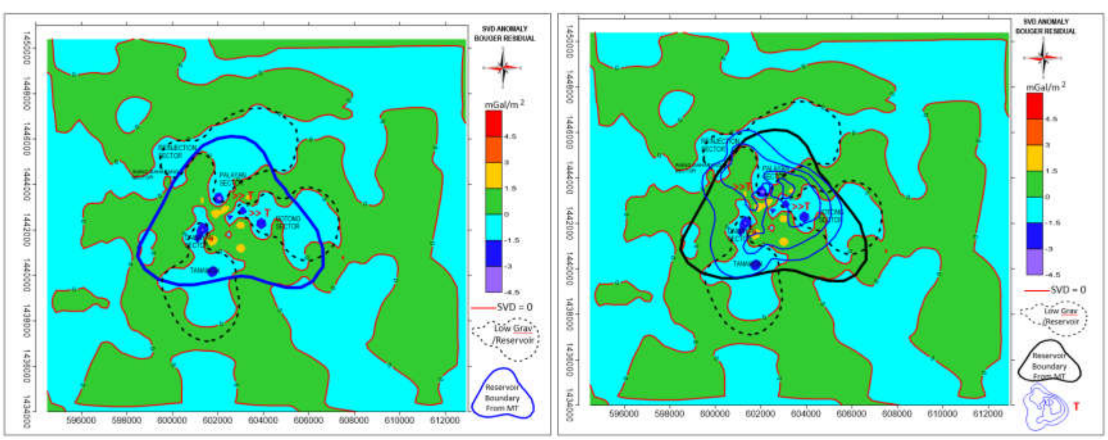

Figure 8. SVD map of the residual Bouguer anomaly overlaid with the reservoir area derived

from MT data and the reservoir prospect area derived from the Bouguer Residual anomaly data.

The figure shows that the reservoir locations of the four data provide the same results. The reservoir areas identified from the Bouguer Residual anomaly data and the Bouguer Residual SVD anomaly provide more detailed results, namely the Bac-Man geothermal reservoir is separated into 3 areas, namely: the Cawayan and Tanawon sectors in the south, the Boton sector, which is located in the east, and the East sector Palayang. This result is also supported by the high temperature in the area, where the highest temperature is in the Palayan sector.

The temperature distribution map at a 1200 m from MSL shows that the center has a high temperature which is probably due to intrusion in the area. This intrusion follows the high residual gravity anomaly pattern in the area, where the intrusion is also a barrier from 3 reservoir locations in the area.

A 3D inversion modeling of Bouguer Residual anomaly was carried out to obtain a structural model of the Bac-Man Geothermal Field. The equation used and the calculation of 3D inversion modeling is the subsurface model approach composed of prisms with the amount according to measurement area, data grid, thickness, and depth of objects. The calculation of the gravity response for each prism block uses the Plouff (1976) equation [17]:

$$g = G\Delta\rho \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2} \mu_{ijk}\left[z_k \arctan\frac{x_i y_i}{z_k R_{ijk}} - x_i \log\left(R_{ijk}+y_i\right) - y_i \log\left(R_{ijk}+x_i\right)\right] \quad (8)$$

Where: $R_{ijk} = \sqrt{x_i^2 + y_j^2 + z_k^2}$; $\mu_{ijk} = (-1)^i(-1)^j(-1)^k$

The results of Bouguer Residual anomaly 3D inversion modeling using the Grav3D program are shown in Figure 9. The 3D inversion modeling results' density distribution model shows the distribution of high and low density in the middle of the study area with a value of 2 g/cc to 2.9 g/cc. The model is then carried out by slicing the selected paths, which will be compared and correlated with models such as temperature data models, MT cross-sectional models, structural models, and others to obtain a structural model.

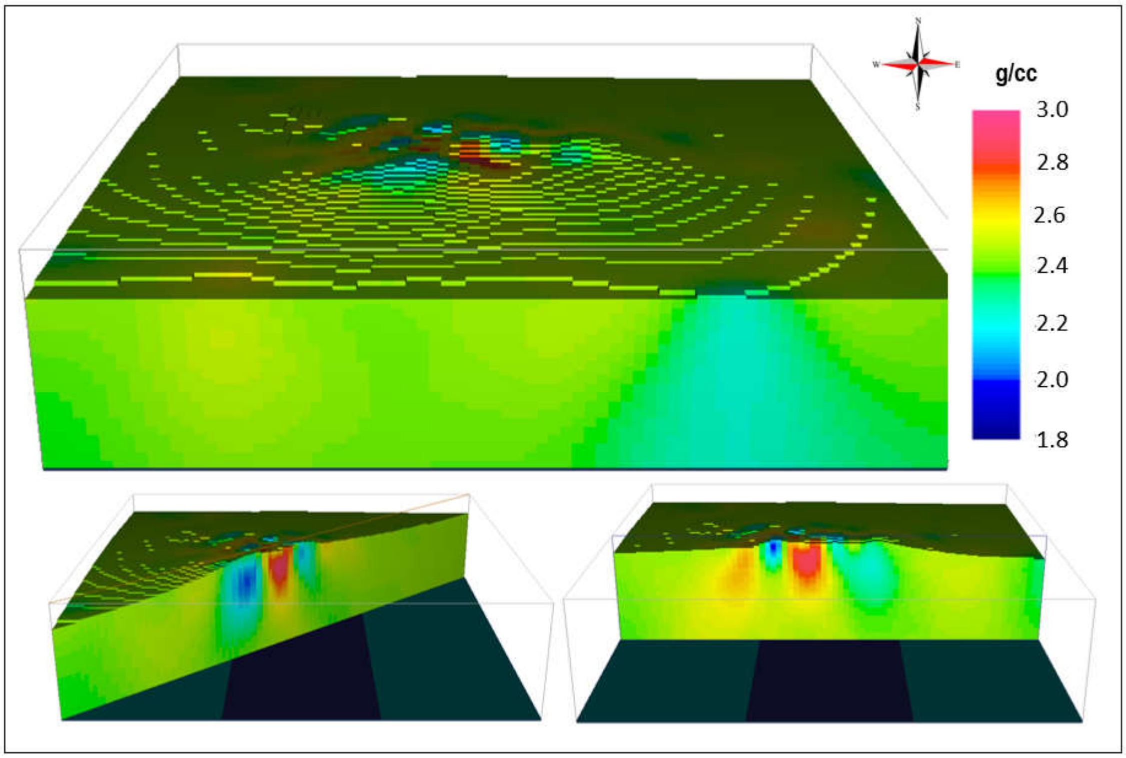

Figure 9. The subsurface density distribution model from the 3D inversion modeling result of Bouguer residual anomaly in Bac-Man geothermal field

The density distribution model resulting from the 3D Bouguer anomaly residual inversion which is correlated with the cross-sectional temperature model and the intrusion structure on the NW-SE trajectory, is shown in Figure 10. The 3D Bouguer anomaly residual inversion result correlated with the temperature section model [18], and the intrusion structure shows a good correlation. The presence of intrusion is correlated with high density in the area. Likewise, the SVD section indicates that the intrusion is no single but separated into three parts according to the model derived from well data and temperature data.

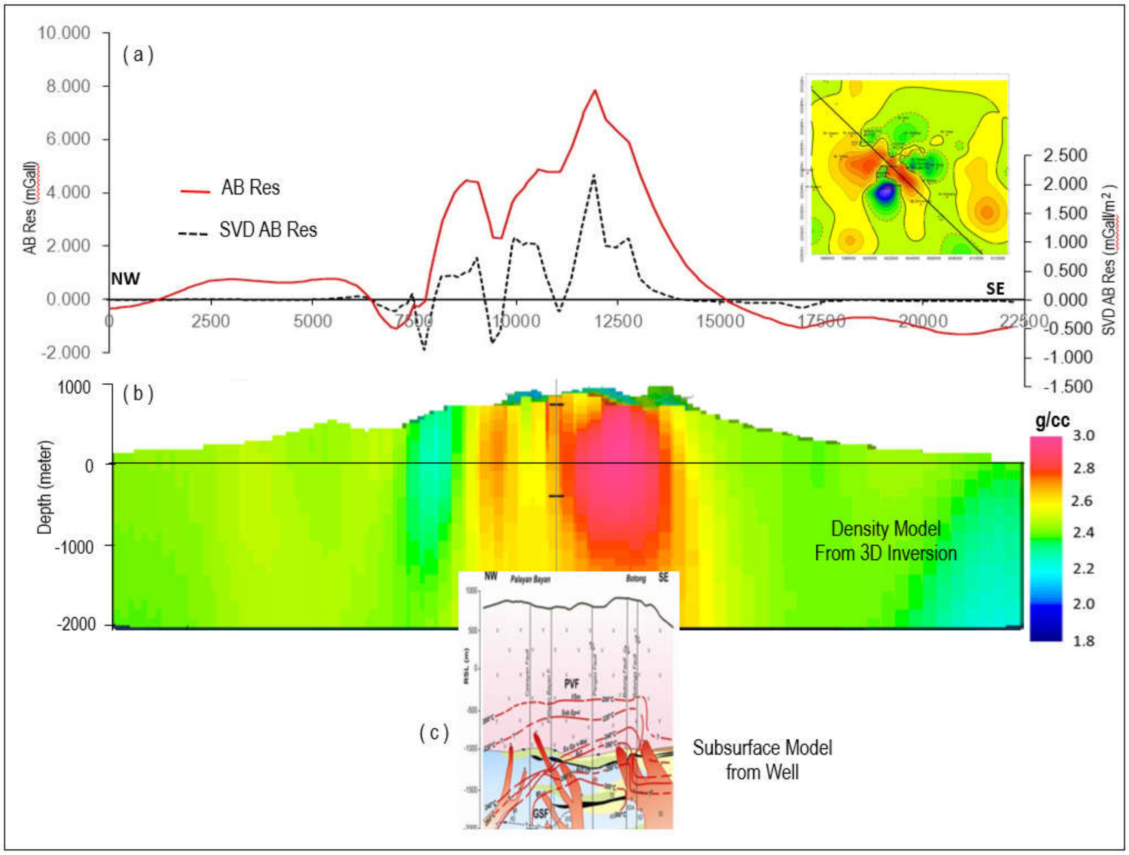

Figure 10. The cross-section of the density distribution model resulting from the 3D Bouguer residual anomaly inversion correlated with the temperature and intrusion structure cross-sectional model for the NW-SE trajectory [18].

The density distribution model resulting from the 3D Bouguer anomaly residual inversion which is correlated with the temperature cross-section model and the intrusion structure on the NE-SW trajectory, is shown in Figure 11. The 3D Bouguer anomaly residual inversion result, which correlated the temperature cross-section model and the intrusion structure, shows a good correlation. The presence of intrusion correlates with high density in the area. Likewise, the SVD section indicates that the intrusion is no single but separated into two parts according to the model derived from well data and temperature data.

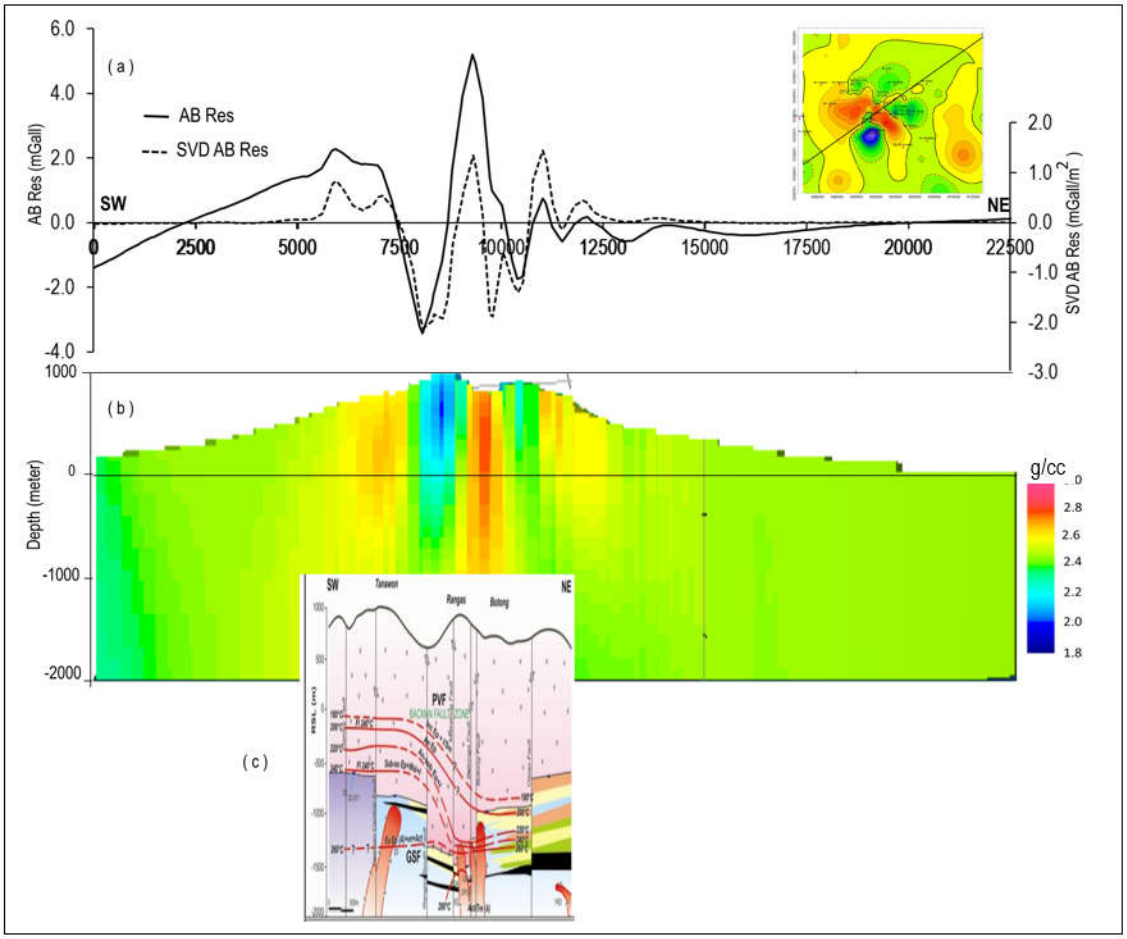

Figure 11. The cross-section of the density distribution model resulted from the Bouguer Residual anomaly 3D inversion which is correlated with the temperature and intrusion structure cross-sectional model for the NE-SW trajectory [18].

The model is correlated with: the boundary of the geothermal reservoir area delineated from the MT results, the division of the geothermal sector, and volcanoes that control the geothermal system in the Bac-Man field.

The results of the correlation analysis between the cut density distribution models for density 2.1 g/cc - 2.4 g/cc (interpreted as a geothermal reservoir) and the reservoir prospect boundary derived from MT indicate that the reservoir locations have similarities. However, the reservoir area derived from the gravity model is broader and in more detail. The gravity modeling shows that the geothermal reservoir in the Bac-Man field is divided into 3 areas: the southern part (Cawayan and Tanawon sector), the eastern part (Boton sector), and the northern part (Palayan-Inang Maharang sector). Each reservoir area is separated by the presence of fault structures or intrusions in the area. The division of the 3 reservoir areas follows the well data and the results of reservoir modeling research in the area. That the geothermal reservoir area of the Bac-Man field is divided into 3 sectors, namely the south (Cawayan and Tanawon sectors), the east (Boton sector), and the north (the North sector). Palayan-Inang Maharang) (Figure 12). The reservoir sectors are separated by intrusion in the area. This is supported by the reservoir temperature in the area with a higher temperature than the surrounding area.

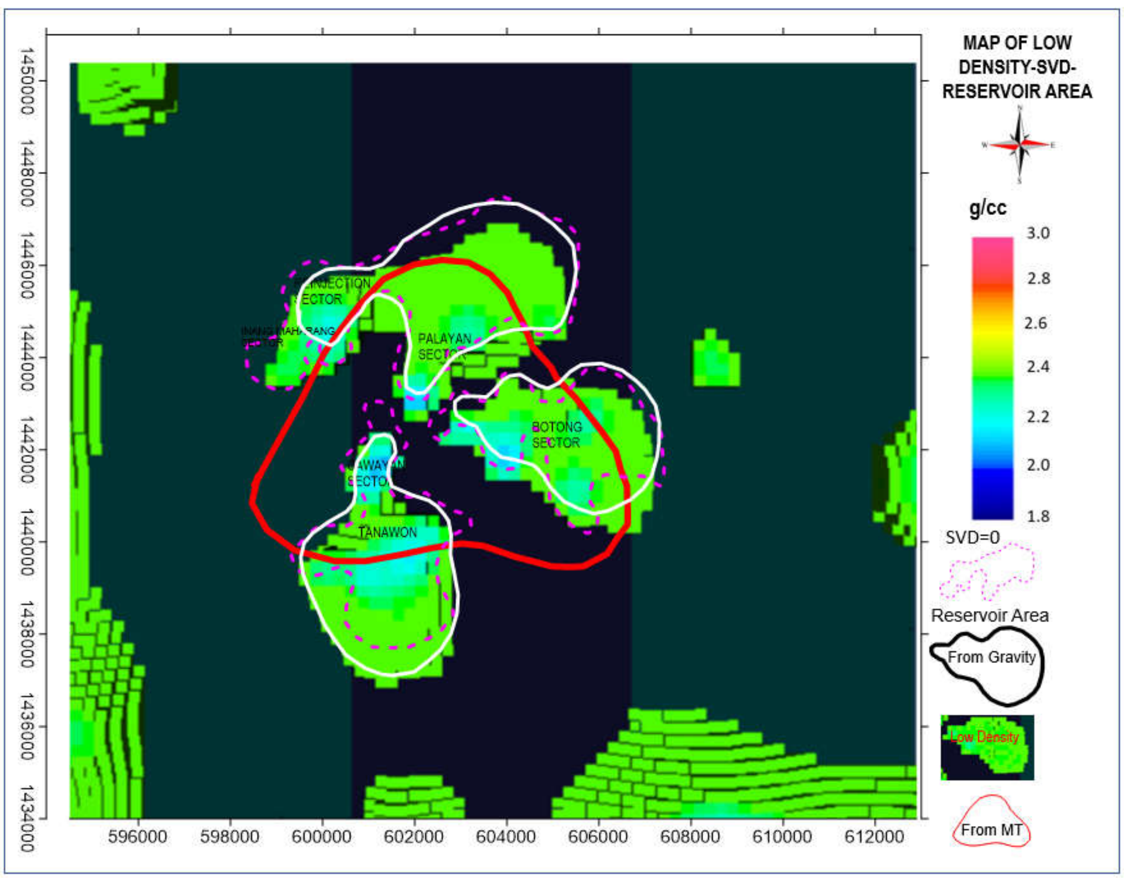

Figure 12. The density distribution model of Bouguer Residual anomaly 3D inversion

modeling results shown for densities 2.1 g/cc - 2.4 g/cc. The model is correlated with: geothermal reservoir area boundaries delineated from the MT results, SVD = 0 maps, the division of geothermal areas, and volcanoes that control the geothermal system in the Bac-Man field.

5. Conclusions

Based on the results of gravity research on the Bac-Man geothermal field supported by geological data, well data, MT data, and temperature data, several conclusions can be drawn regarding the Bac-Man geothermal field, namely:

1. Bouguer anomaly in the study area has a value of 18 - 41 mGal, with a high anomaly in the west to the northwest and a little in the middle, while the anomaly is low in the middle. From the Bouguer anomaly spectrum analysis, it is found that the Bouguer Regional and Residual anomaly limits are at a depth of 2500 m.

2. Residual Bouguer anomaly calculated using a moving average filter with windows 5 km x 5 km shows that the residual Bouguer anomaly has a value of -12 mGal to 9 mGal with high anomalies occupying the eastern and central parts. There are 3 low anomaly closures in the middle that are separated by high anomalies. The geothermal reservoir in the Bac-Man field may be divided into 3 reservoirs: the North, South, and East.

3. The density distribution model from the 3D inversion modeling shows that the density distribution model cut for density 2.1 g/cc - 2.4 g/cc correlates with MT reservoir boundary. However, the reservoir area derived from the gravity model is broader and more detailed. The results of gravity modeling show that the geothermal reservoir in the Bac-Man field is divided into 3 areas: the southern part (Cawayan and Tanawon sector), the eastern part (Boton sector), and the northern part (Palayan - Inang Maharang sector) where each reservoir area is separated by the presence of fault structures or intrusions in the area. The division of the 3 reservoir areas follows the well data and the results of reservoir modeling research in the area. The reservoir sectors are separated by intrusion in the area. Temperature data also support this,

showing that the area has a higher temperature than the surrounding area.

4. Detailed reservoir boundaries, especially the outer reservoir boundaries, it is suggested to add more detailed gravity measurement points in the north, east, and south.

Acknowledgments

We want to thank all those who have helped implement this research, especially the Geophysical Engineering Department, Faculty of Engineering, University of Lampung.

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Reservoir Identification of Bac-Man Geothermal Field Based on Gravity Anomaly Analysis and Modeling

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Abstract

The Bac-Man gravity modeling was carried out to describe the geological structures that control the geothermal system and estimate the area of the geothermal reservoir. A total of 125 data points were used to produce a complete Bouguer anomaly map of the area. The gravity data are separated into regional and residual components to enhance the structural features of the sedimentary and basement rocks in the study area. Gravity data were analyzed using gradient interpretation techniques for edge detection, such as vertical descent. To perform three-dimensional (3-D) modeling, a 5 × 5 km volume and a depth of 2.5 km were selected. This study presents the interpretation of various gravity anomaly maps and 3-D inversion models. The interpretation of the vertical derivative of the gravity data indicates the presence of a low gradient anomaly. The anomaly map is used to identify several faults or intrusions compared to the faults or intrusions that are mapped. The 3-D model reveals that there are 3 geothermal reservoirs, and the average block density value is 2.25 g/cc. These reservoirs are spread over the Southern area (Cawayan and Tanawon Sector), East area (Boton Sector), and Palayan-Inang Maharang area. Faults or rock intrusions are the limiting factors for the three existing reservoirs. The results obtained from this study will lead to a better understanding of the geothermal system in the study area, in particular, reservoir

boundaries, and assist in future geothermal exploration.

Keywords: Bac-Man field, Gravity, Modeling, Reservoir, Geothermal

1. Introduction

Geothermal energy is a natural source of heat contained within the Earth, and it can be extracted and used to generate electricity or for heating applications. A geothermal system consists of three elements: a heat source, reservoir rock, and caprock [1]. The Bacon - Manito (Bac-Man) geothermal field is located in the Podcol mountains on Luzon, about 350 km southeast of Manila. The exploration of the Bac-Man geothermal field has been carried out since 1977. The reservoir model has 23 km^2, 1500 m depth, and a temperature of 240ºC to 320ºC. Based on geological and geophysical data, a conceptual model of the Bac-Man geothermal system has been made [2]. Tugawin et al. (2015) [3] carried out 2D magneto-telluric (MT) inversion modeling in the Bac-Man field, which shows the existence of 3 (three) geothermal reservoir areas, namely Palayan Bayan, Tikolob, and Malobago areas. These results follow the results of data interpretation of resistivity vertical electric sounding (VES) [4] and Schlumberger Resistivity Traversing (SRT). The reservoir in the Palayan Bayan area has been in production since 1993, while the Tikolob prospect is on the west side of the Bac-Man field, separate from the Palayan Bayan system [3].

The gravity method is applied to determine the geometry of the geothermal reservoir and describe the geological structures that control the system. The gravity method is generally used to describe the subsurface structures that control geothermal systems in geothermal exploration. Certain geothermal reservoirs and their fluid content cause density differences between the geothermal reservoir and the surrounding rock. The basis of the gravity method is the density contrast in the rock. Gravity studies in various regions of the world have yielded valuable results for geothermal exploration, such as the investigation of basement topography in geothermal fields [5]; magma chambers and intrusion bodies associated with heat source from the geothermal system; and faults delineation and fracture zones corresponding to geothermal system reservoirs [6]. Therefore, the gravity method is one of the most economical geophysical methods for modeling geothermal systems. The gravity anomaly interpretation procedure consists of many techniques depending on the quality of the data set and the purpose of the analysis [7]. Gravity anomaly maps are generally analyzed using multiple linear transformations, directional derivative-based techniques, and inverse modeling techniques. Gravity data in the form of a Bouguer anomaly map is used to describe the study area's geological characteristics and subsurface structures. Observations of gravity at the Earth's surface reflect the superimposed effects of broader and deeper mass variations as well as shallower and more localized changes near the point of observation. This research focuses on the 3D modeling of gravity data to estimate the geothermal reservoir extent and understand the subsurface structure of the geothermal system.

2. Bac-Man Geothermal System

The exploration of the Bac-Man geothermal field has been carried out since 1977. Several studies have been carried out, ranging from geology and geophysics (gravity, magnetic, microearthquake, MT, temperature) to determine the geothermal reservoir, caprocks, heat-source, the geothermal system model, and geothermal potential in the area. The total capacity of the power plant in the Bac-Man area is 150 MWe generated from 4 generating units, namely: Unit I began operating in 1993 and unit II in 1995 which was named Palayang Bayan (2 x 55 Mwe), in 1996 the Cawayan geothermal plant began operating (20 Mwe), and in 1998 the Unit III power plant in the Botong area began operating (20 Mwe). The Bac-Man geothermal field is located in the Podcol mountains 350 km southeast of Manila. The local fault system is known as the Bac-Man Fault Zone (BFZ) [8]. The fault zone is indicated by a series of volcanoes that are mostly NW-SE (Figure 1). Structurally controlled by a fault system, which is believed to be an extension of the San Vicente Linao Fault (SVLF), is a stretch of the Philippine fault. The most prominent regional geological structure in the area is the San Vicente-Linao Fault in the Northwest - Southeast (NW-SE), which slopes across the Bico Peninsula [9].

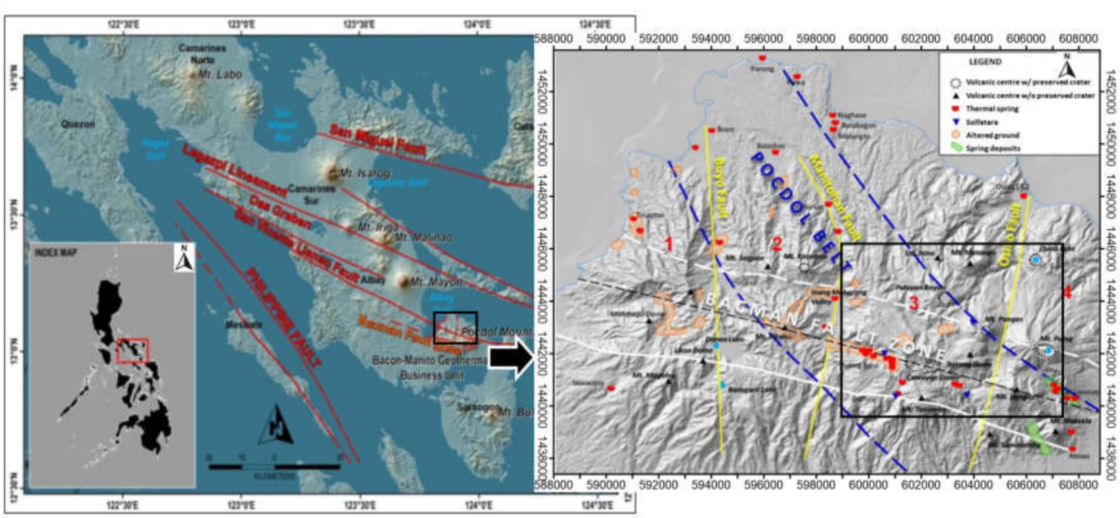

Figure 1. Map of the study area location and faults structure in the Bac-Man geothermal field [3][10].

The Bac-Man geothermal system is divided into two regions, namely the western and eastern parts of Bac-Man. The eastern part of Bac-Man is further divided into the North Namito lowlands and the Podcol highlands. The Podcol plateau can be divided into eight geographic sectors: Inang Maharang, Putting Bato, Palayan Bayan, Cawayan, Tanawon, Osiao, Bangas, and Botong [9]. Neutral chloride hot springs with a temperature of 89 °C - 96 °C are found in the lowlands of Manito. In Cawayan and Pangas, Solfatara is found in West Bac-Man, cold to warm, and cold SO_4 springs are found.

The most recent volcanic event in the Pocdol highlands occurred more than 40 thousand years ago. That is related to the formation of the Tanawon and Cawayan craters and the Botong and Pangas domes extrusion. The youngest volcanoes generally occur in subsurface areas with high temperatures, permeable formations, and active thermal manifestations (Figure 2) [9].

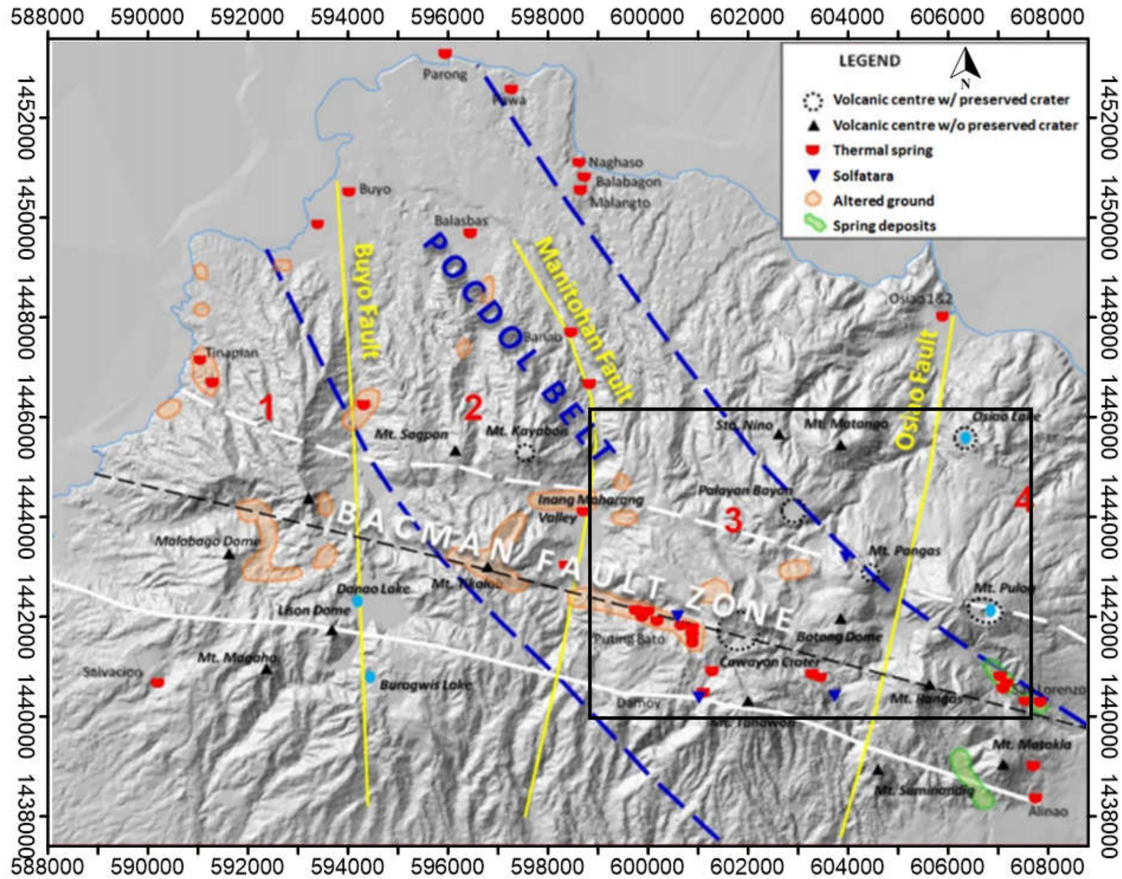

Figure 2. Structure and manifestations at the Bac-Man geothermal field [10].

Layugan et al. (2005) [11] analyzed and interpreted MT data based on 1999 and 2001, which obtained the contour boundaries of the conductive zone's anomaly resistivity as a reservoir area.

An iso-resistivity map at a depth of -1100 m from MSL, which is correlated with the geological structure in the area, shows that the central part of the Bac-Man fault zone has a low resistivity value [3]. The Bac-Man reservoir area covers 26 - 36 km2, while the Kayabon reservoir located to the northwest of Bac-Man covers an area of 12 - 18 km2 (Figure 3).

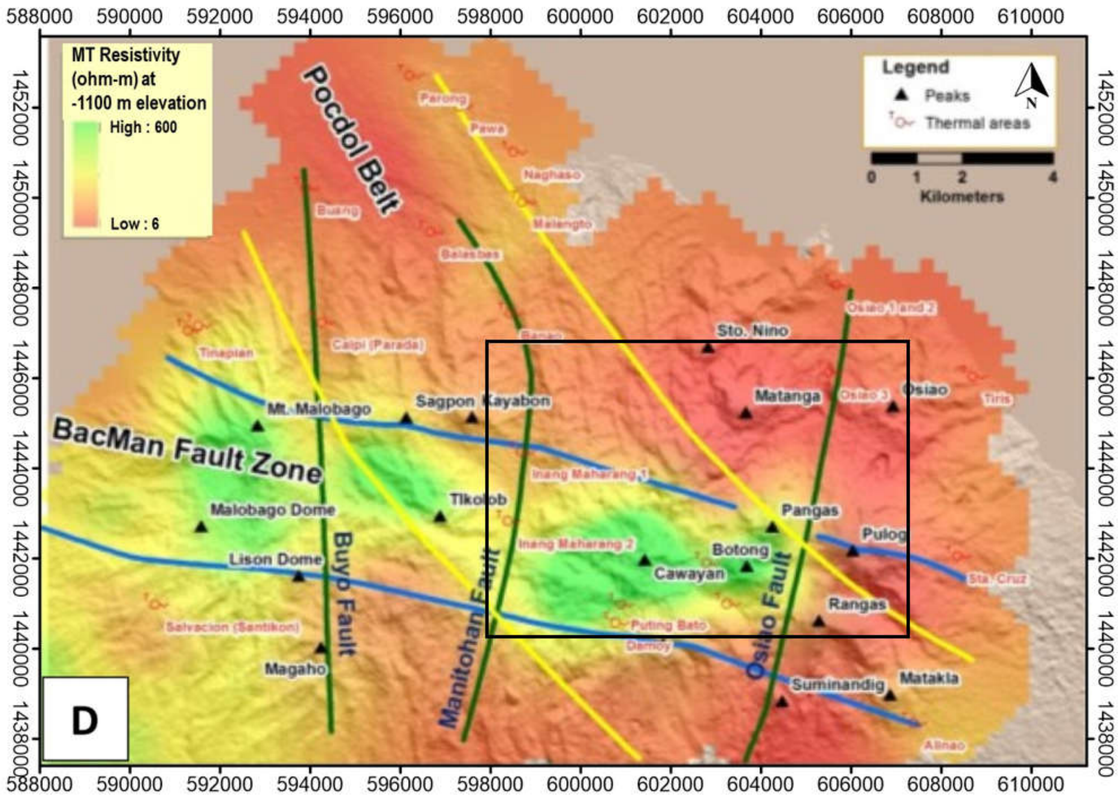

Figure 3. An isoresistivity map at a depth of -1100 m from MSL which is correlated with the geological structure in the area, shows that the central part of the Bac-Man fault zone has a low resistivity value [3].

The results of this MT study support the results of previous MT research conducted by Layugan et al. (2005) [11], which found that the prospect area for the Bac-Man geothermal reservoir is in Botong, Cawayan, and Tikolob. However, the results show a larger area than the results of previous MT studies.

Research related to reservoir temperature was carried out by Austria (2008) [2], in which the eastern part of Palayan - Bayan has a high temperature of 326 ° C. The temperature contour map at a depth of -1000 meters from MSL is shown in Figure 4.

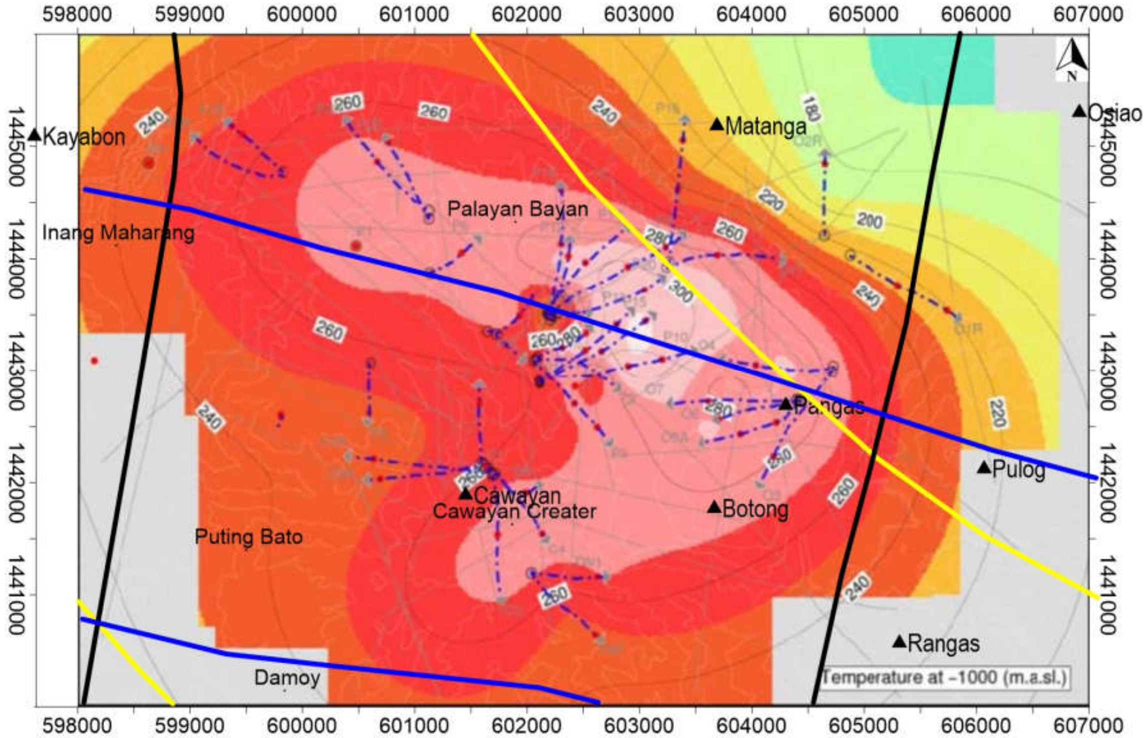

Figure 4. Temperature contour map at a depth of -1000 meters from MSL [2].

3. Methods

The gravity data used in this study were 125 points: measurements from 2009 to 2010 [12]. Processing gravity data includes determination of surface density using the Parasnis and Nettleton method, Bouguer anomaly, Bouguer anomaly filtering, Bouguer anomaly separation, vertical gradient analysis Bouguer anomaly, and Bouguer anomaly modeling. Analysis and interpretation were carried out to verify the Bac-Man geothermal reservoir area and structures in the area. The analysis and interpretation are carried out by correlating the gravity model with geological data, well data, and other geophysical data. The research flow carried out is shown in Figure 5.

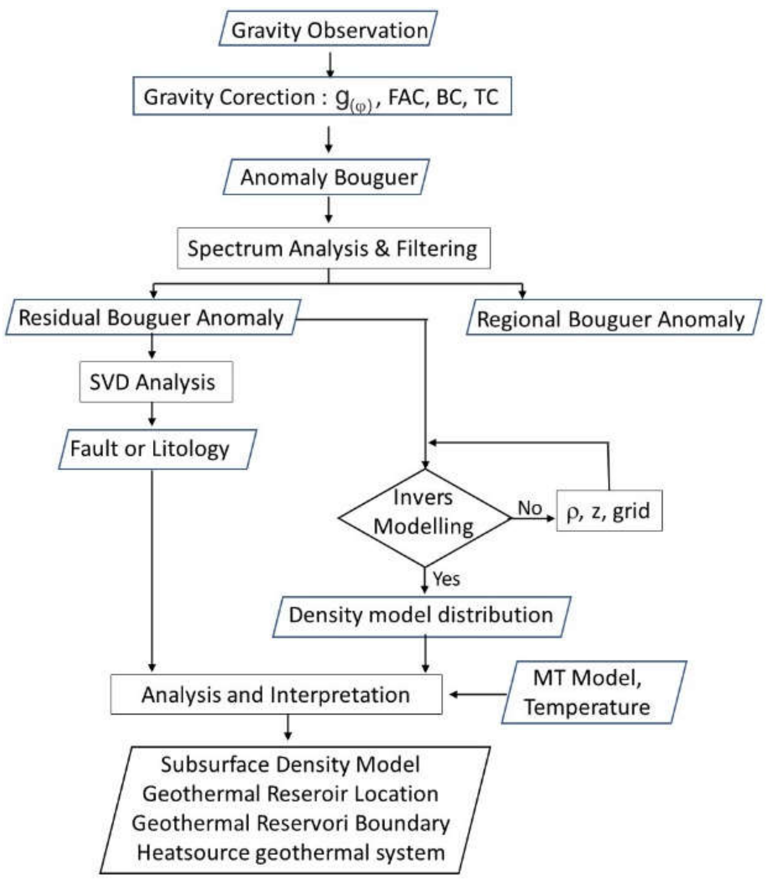

Figure 5. Flowchart of research in determining the boundary of a geothermal reservoir

Density determination was carried out using the Parasnis method and the Nettleton method. The Parasnis method calculations get a value of 2.24 g/cc, while calculations using the Nettleton method for 2 (two) cross-sections get a value of 2.35 g/cc and 2.38 g/cc. When compared with geological conditions in the field, this density value has an appropriate value in research for calculating Bouguer correction and modeling using a density of 2.35 g/cc.

Bouguer anomaly obtained, gravity observation data is performed by gravity theoretic correction at latitude φ, free air correction (free air correction), Bouguer correction, and terrain correction. The calculation of the theoretical gravity correction at latitude φ uses the International Gravity Formula 1980 equation (equation 1) [13]:

$$g_{\varphi} = 978.032{,}7(1 + 5.3024\ 10^{-3}\ Sin^2 \varphi - 5{,}8\ 10^{-6}\ Sin^2\ 2\phi \quad (1)$$

Meanwhile, for free air correction, the FAA equation = -0.308 h (mGal/m) is used, which is obtained from the derivative of the Earth's normal gravity equation in the form of an ellipsoid, namely:

$$g_{\phi,h} = g_{\phi} + \frac{\partial g_{\phi}}{\partial h} h \quad (2)$$

$$\frac{\partial g_{\phi}}{\partial h} = -\frac{2 g_{\phi}}{a}(1 + f + m - 2f\ sin^2\ \phi) = -0.308\ mGall/m \quad (3)$$

The Bouguer correction value is calculated using the approaching model for the slab model, namely:

$$Bc = 2\pi G \rho h\ =\ 0.04193 \rho h \quad (4)$$

Where ρ is rock density (g/cc), h is the height (m), and Bc is Bouguer correction (mGal).

Terrain corrections were calculated using a combination of the equations given by Nagy (1966) [14] and Kane (1962) [15]. In the calculation of terrain correction, the topographic model is approached with a prism-shaped arrangement of objects measuring 1 km x 1 km with a height following the area's topography up to a radius of 50 km. The topographical data used is DEM data taken from INA Geoportal [16].

The Bouguer anomaly contains contributions from regional trends resulting from the presence of deep and large structures. The effect of this structure on the gravitational field appears as a large wavelength anomaly, which masks the smaller and shallower effects. To highlight the gravitational anomaly associated with the source of interest for this work, a regional-remaining split of the Bouguer anomaly was performed using the open-source Generic Mapping Tools (GMT) software to map and plot geographic data. This tool adjusts the trend surface with the grid and calculates the residuals. The regional trend is removed by using the trend-matched grid and removing the polynomial trend in the grid file.

Spectral analysis was carried out to determine the boundary of the regional Bouguer anomaly and the residual area of the study. The results of this spectral analysis are then used to estimate the window width for gravity anomaly filtering. In general, a Fourier transformation is to reconstruct/unravel an arbitrary wave into a sine wave with a variable frequency where the sum of the sine waves is the original waveform [17-18]. Spectrum analysis is used to determine the depth of the structure of the anomaly. In this study, the analysis of the spectrum analysis used Fourier transform [19], where the results are used to estimate the width of the filtering window.

$$F(g) = 2\pi\gamma m \frac{e^{|k|(z_0 - z_1)}}{|k|} \tag{5}$$

The energy spectrum of the equation is:

$$E(k) = \frac{4\pi^2\gamma^2\rho^2}{|k|^2} e^{-2|k|z} \tag{6}$$

$$\log E(k) = \log(4\pi^2\gamma^2\rho^2) - 2|k|z - 2\log|k| \tag{7}$$

$$\log E(k) = \log A - 2|k|z \quad (8)$$

where Z_0 (depth point), Z_1 (depth mass) $Z_1 > Z_0$, $k = 2\pi/\lambda$ ((wave number), λ (wavelength), g (gravity anomaly), ρ (density).

The separation of regional Bouguer anomalies and residual Bouguer anomalies is a moving average filter with a 5 km x 5 km window width. The calculation of the moving average is done by averaging the anomaly values for several points of gravity, as shown by the equation:

$$\Delta g_{Reg}(i,j) = \frac{(\Delta g(i-n, j-n) + \cdots + \Delta g(i,j) + \cdots + \Delta g(i+n, j+n))}{N} \quad (9)$$

where $n = \frac{N-1}{2}$, and N must be an odd number.

This average is the regional anomaly, and the residual anomaly is obtained by subtracting the data from the gravity measurement with the regional anomaly [20].

There are several methods for detecting the edges caused by fault structures or geological boundaries. Most of these methods are high-pass filters based on the horizontal and vertical derivatives of the gravity anomaly. One of these methods is the vertical gradient method, which has been used intensively to delineate contacts of density change from gravity data or pseudo gravity data. Theoretically, this method is derived from Laplace's equation for surface gravity anomalies [19][21]:

$$\nabla^2 \Delta g = 0 \text{ atau } \frac{\partial^2 \Delta g}{\partial x^2} + \frac{\partial^2 \Delta g}{\partial y^2} + \frac{\partial^2 \Delta g}{\partial z^2} = 0 \quad (10)$$

$$\frac{\partial^2 \Delta g}{\partial z^2} = -\frac{\partial^2 \Delta g}{\partial x^2} + \frac{\partial^2 \Delta g}{\partial y^2} \tag{11}$$

In this study, the Second Vertical Derivative (SVD) anomaly gravity value is calculated using a filtering process, namely through convolution between anomaly gravity and an SVD filter [19].

$$\Delta Gsvd(\Delta x, \Delta y) - \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \Delta g(x, y) F(x - \Delta x, v - \Delta y) dxdy \tag{12}$$

Where F is the SVD filter according to the above equation and ΔG is the gravity anomaly.

Gravity inversion aims to determine the density distribution that would explain the measurements or the shape and dimensions of density variation. However, the inversion of the field gravity data is one of the most ambiguous problems in exploration geophysics studies [22]. Due to data noise and inhomogeneity of geological bodies, inversion of gravity data is usually fraught with difficulties even with reasonably accurate gravity measurements and data reduction.

A 3D inversion modeling of Bouguer Residual anomaly was carried out to obtain a structural model of the Bac-Man Geothermal Field with open source GRAV3D software [23][24]. The equation used and the calculation of 3D inversion modeling is the subsurface model approach composed of prisms with the amount according to measurement area, data grid, thickness, and depth of objects. The calculation of the gravity response for each prism block uses the Plouff (1976) equation [25]:

$$g = G\Delta\rho \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2} \mu_{ijk} \left[z_k \, arctan \frac{x_i y_i}{z_k R_{ijk}} - x_i \, log\left(R_{ijk} + y_i\right) - y_i \, log\left(R_{ijk} + x_i\right) \right] \quad (8)$$

Where: $R_{ijk} = \sqrt{x_i^2 + y_j^2 + z_k^2}$; $\mu_{ijk} = \left(-1\right)^i \left(-1\right)^j \left(-1\right)^k$

4. Result and Discussions

The Bouguer anomaly in the Bac-Man geothermal field has a value of 18 - 41 mGal, with a high anomaly in the west to the northwest and a little in the middle, while the anomaly is low in the middle. The high anomaly in the Northwest part is probably related to the geothermal system's heat source in the Bac-Man field. The low anomaly in the middle part flanking the high anomaly is probably related to a reservoir in the area (Figure 6).

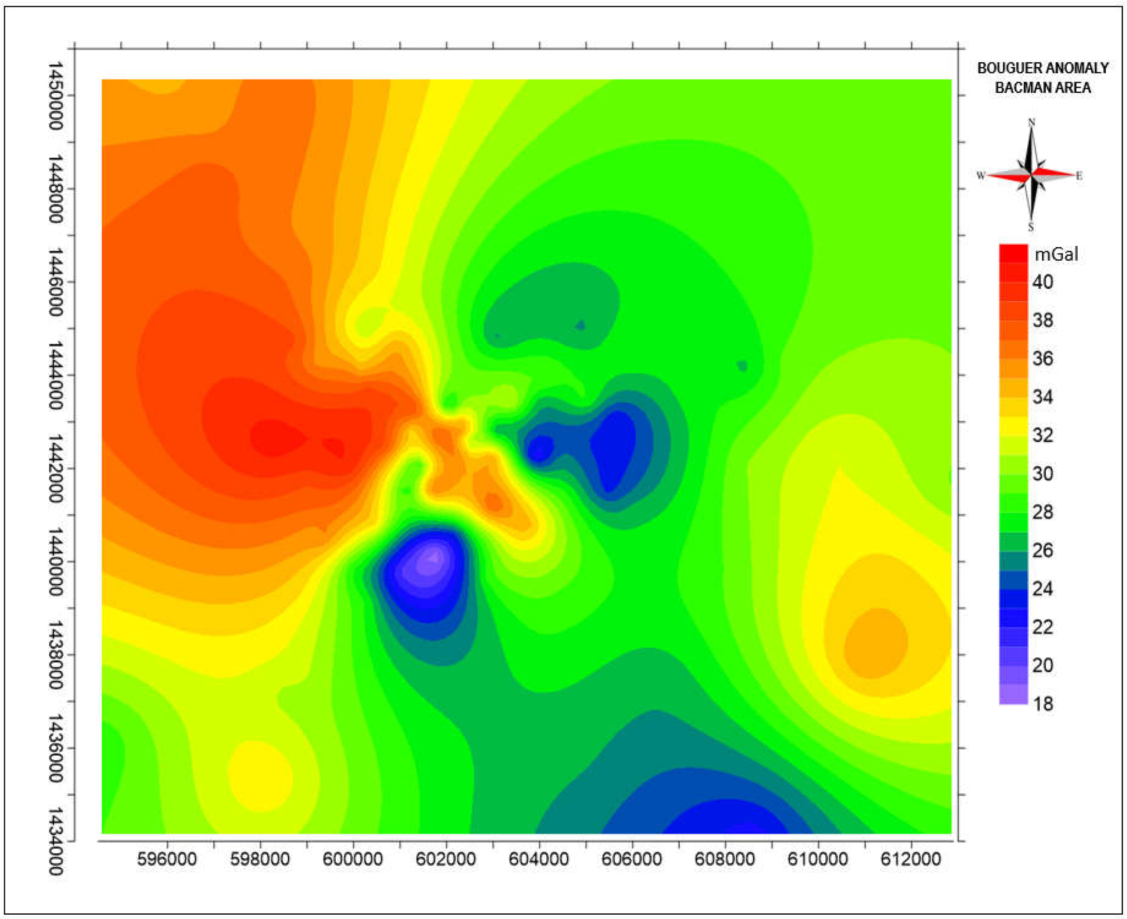

Figure 6. Map of the Bouguer anomaly of the Bac-Man geothermal field area

The spectrum analysis was carried out by cross-sectioning the Bouguer anomaly as many as 5 trajectories with a point interval of 250 m (Figure 7). The spectrum analysis result from 5 lines of Bouguer anomaly shows that the average regional Bouguer anomaly depth is

2500 meters (Figure 8). Based on these results, the separation of regional Bouguer anomalies and residual Bouguer anomalies is a moving average filter with a 5 km x 5 km window width.

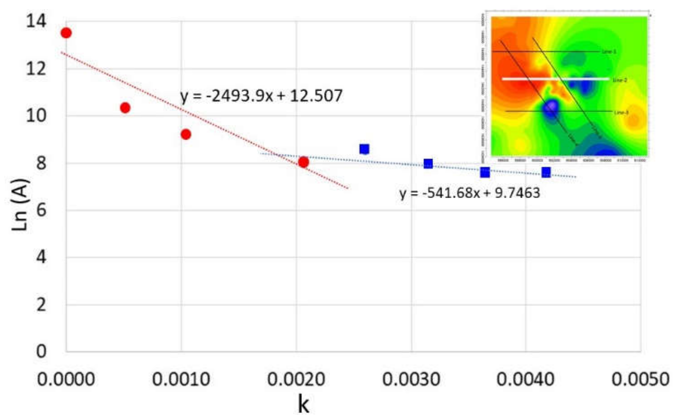

Figure 7. Bouguer anomaly spectrum analysis to determine the depth limits of regional and residual anomalies. The spectrum analysis results for line 2 get the depth limit value of the residual regional Bouguer anomaly of 2483.9 = 2500 m.

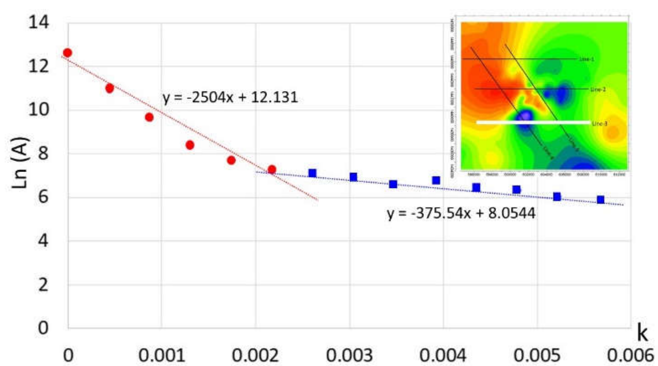

Figure 8. Bouguer anomaly spectrum analysis to determine the depth limits of regional and residual anomalies. The spectrum analysis results for line 2 get the depth limit value of the residual regional Bouguer anomaly of 2504 = 2500 m.

The residual Bouguer anomaly map from the Bouguer anomaly filtering using the moving average method with windows 5 km x 5 km is shown in Figure 9. Residual Bouguer anomaly maps have values from -12 mGal to 9 mGal. High anomalies occupy the eastern and central parts of the study area, surrounded by low anomalies in the north, south, and east.

This area that occupies a low anomaly is probably the geothermal reservoir area of the Bac-Man field. This is following the MT geophysical data and well data. There are 3 low anomaly closures in the middle, which are separated by high anomalies. It can be interpreted that the geothermal reservoir in the Bac-Man field may be divided into 3 reservoirs, namely the north, south, and east. Reservoirs may be separated from one another by fault structures or the presence of intrusion in the area.

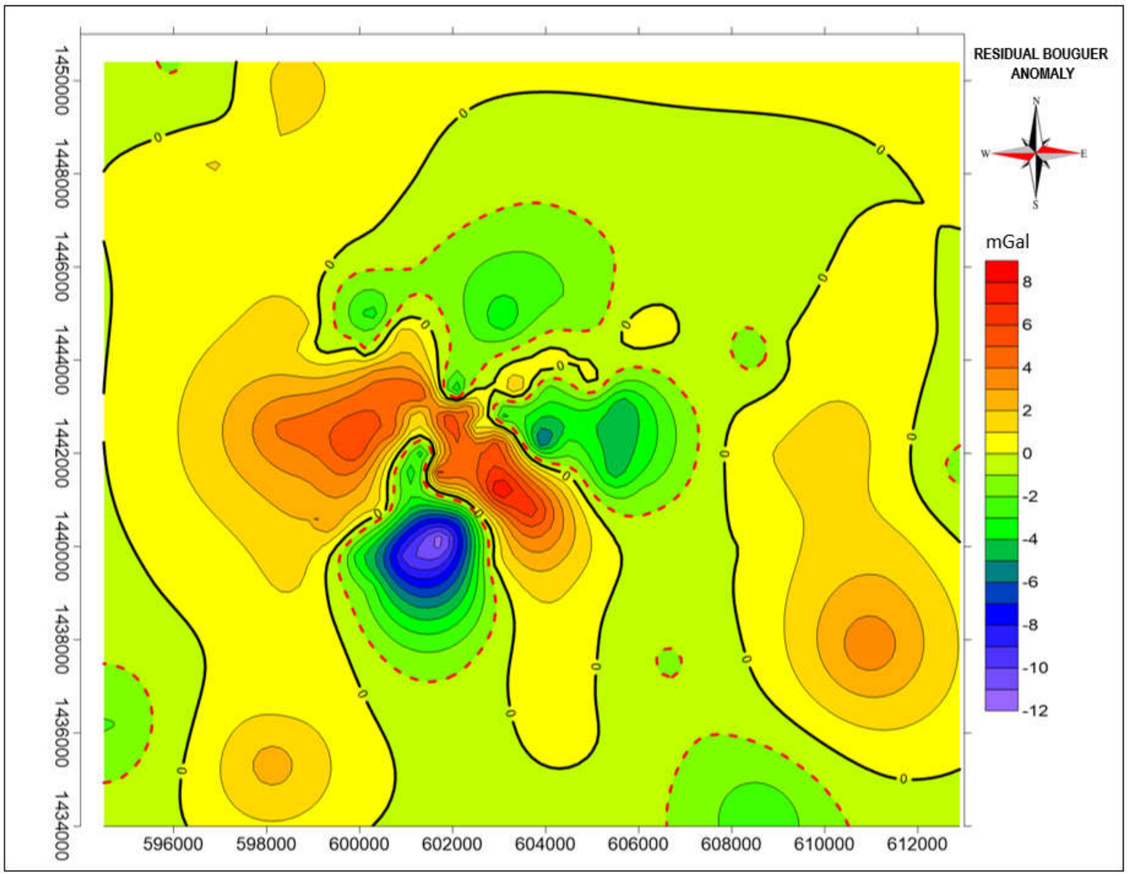

Figure 9. Map of the Bouguer Residual anomaly of the Bac-Man geothermal field

This study's SVD filter is the Elkins (1951) [21] type. The SVD map compiled Bouguer Residual anomaly with low residual Bouguer anomaly contours. The boundaries of the Bac-Man field geothermal prospects from the MT data are shown in Figure 10.

Data compilation of low Bouguer Residual anomaly, Bouguer Residual anomaly SVD, and reservoir prospect boundaries derived from MT data were carried out to identify a reservoir in the area. In general, geothermal reservoirs will have a low Bouguer anomaly because a good geothermal reservoir will have a high porosity value and high permeability. The reservoir rock will have a low density. The SVD map of Bouguer Residual anomaly compiled with: Low Residual Bouguer anomaly, reservoir area boundary derived from MT data, and reservoir prospect area derived from Bouguer Residual anomaly data is shown in Figure 10.

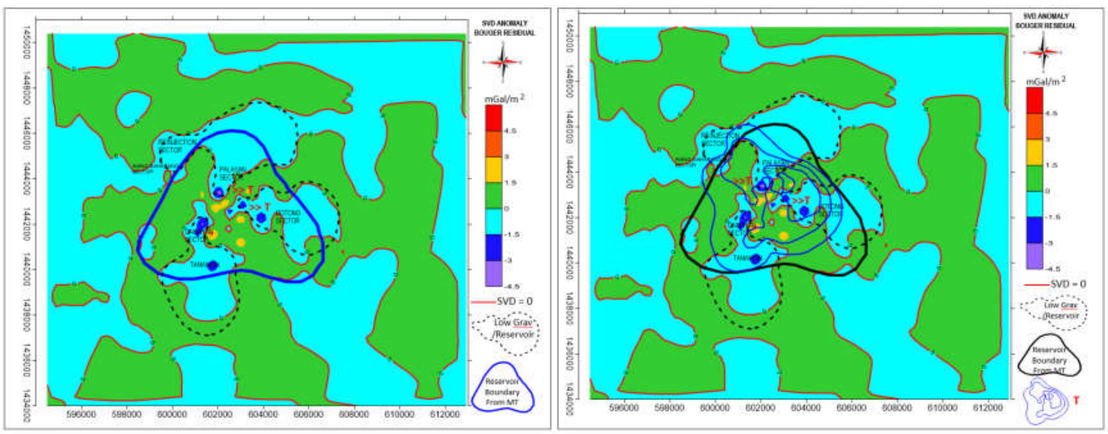

Figure 10. SVD map of the residual Bouguer anomaly overlaid with the reservoir area derived from MT data and the reservoir prospect area derived from the Bouguer Residual anomaly data.

The figure shows that the reservoir locations of the four data provide the same results. The reservoir areas identified from the Bouguer Residual anomaly data and the Bouguer Residual SVD anomaly provide more detailed results, namely the Bac-Man geothermal reservoir is separated into 3 areas, namely: the Cawayan and Tanawon sectors in the south, the Boton sector, which is located in the east, and the East sector Palayang. This result is also supported by the high temperature in the area, where the highest temperature is in the Palayan sector.

The temperature distribution map at 1200 m from MSL shows that the center has a high temperature, probably due to intrusion. This intrusion follows the high residual gravity anomaly pattern in the area, where the intrusion is also a barrier from 3 reservoir locations in the area. Based on drilling data in the Bac-Man geothermal area, dike and intrusive rocks such as monzogabbro, monzodiorite, and epidote have high-density characteristics (gabbro = 3.03 g/cc; amphibolite = 2.96 g/cc) [26]. These dike and intrusion zones have high temperatures interpreted as heat sources of the Bac-Man geothermal system [27]. The high gravity anomaly is associated with the presence of high density below the surface.

The results of Bouguer Residual anomaly 3D inversion modeling using the Grav3D program are shown in Figure 11. The 3D inversion modeling result, density distribution model, shows high and low density in the middle of the study area with a value of 2 g/cc to 2.9 g/cc. The model is then carried out by slicing the selected paths, which will be compared and correlated with temperature data models, MT cross-sectional models, structural models, and others to obtain a structural model.

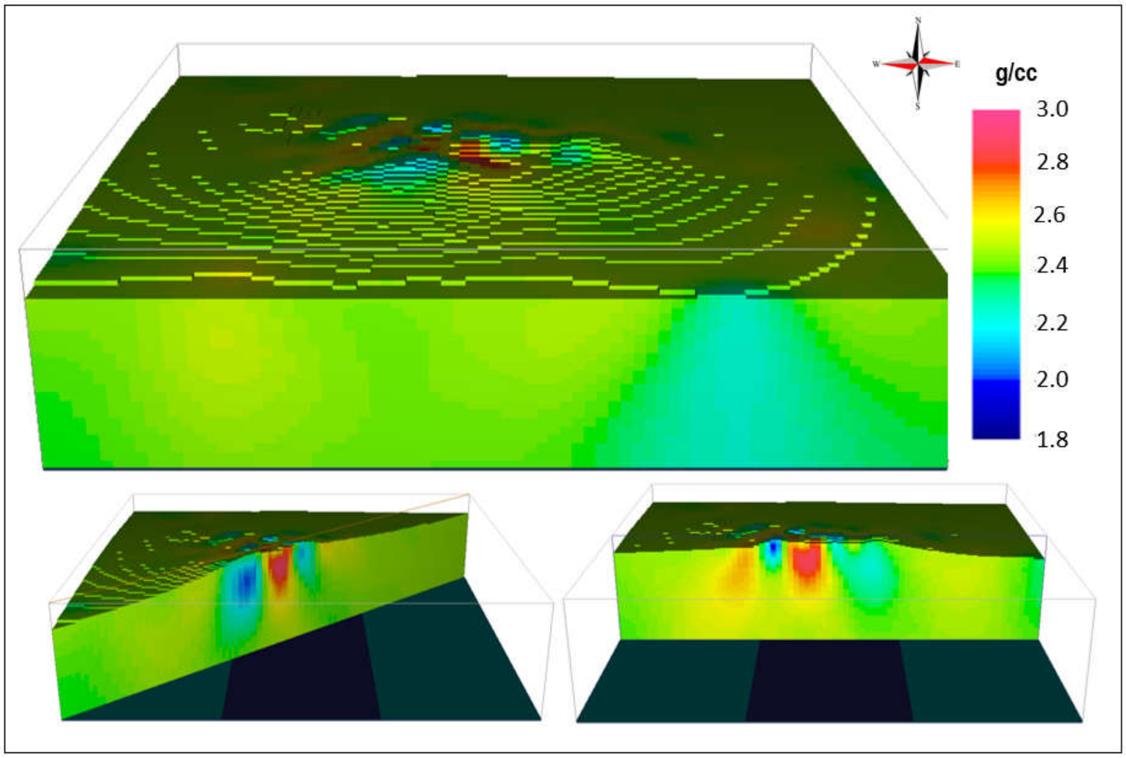

Figure 11. The subsurface density distribution model from the 3D inversion modeling result of Bouguer residual anomaly in Bac-Man geothermal field

The density distribution model resulting from the 3D Bouguer anomaly residual inversion which is correlated with the cross-sectional temperature model and the intrusion structure on the NW-SE trajectory is shown in Figure 12. The 3D Bouguer anomaly residual inversion result correlated with the temperature section model [27], and the intrusion structure shows a good correlation. The presence of intrusion is correlated with high density in the area. Likewise, the SVD section indicates that the intrusion is no single but separated into three parts according to the model derived from well data and temperature data.

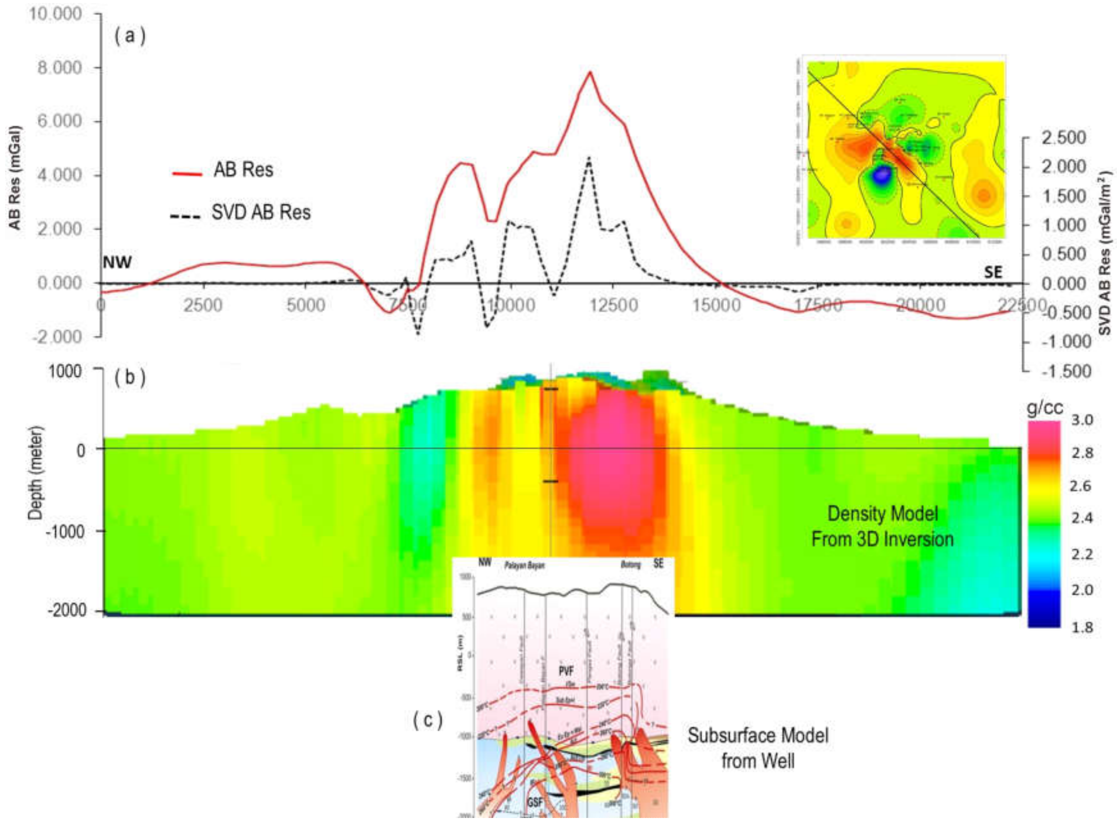

Figure 12. The cross-section of the density distribution model resulting from the 3D Bouguer residual anomaly inversion correlated with the temperature and intrusion structure cross-sectional model for the NW-SE trajectory [27].

The density distribution model resulting from the 3D Bouguer anomaly residual inversion which is correlated with the temperature cross-section model and the intrusion structure on the NE-SW trajectory is shown in Figure 13. The 3D Bouguer anomaly residual inversion result, which correlated the temperature cross-section model and the intrusion structure, shows a good correlation. The presence of intrusion correlates with high density in the area. Likewise, the SVD section indicates that the intrusion is no single but separated into two parts according to the model derived from well data and temperature data.

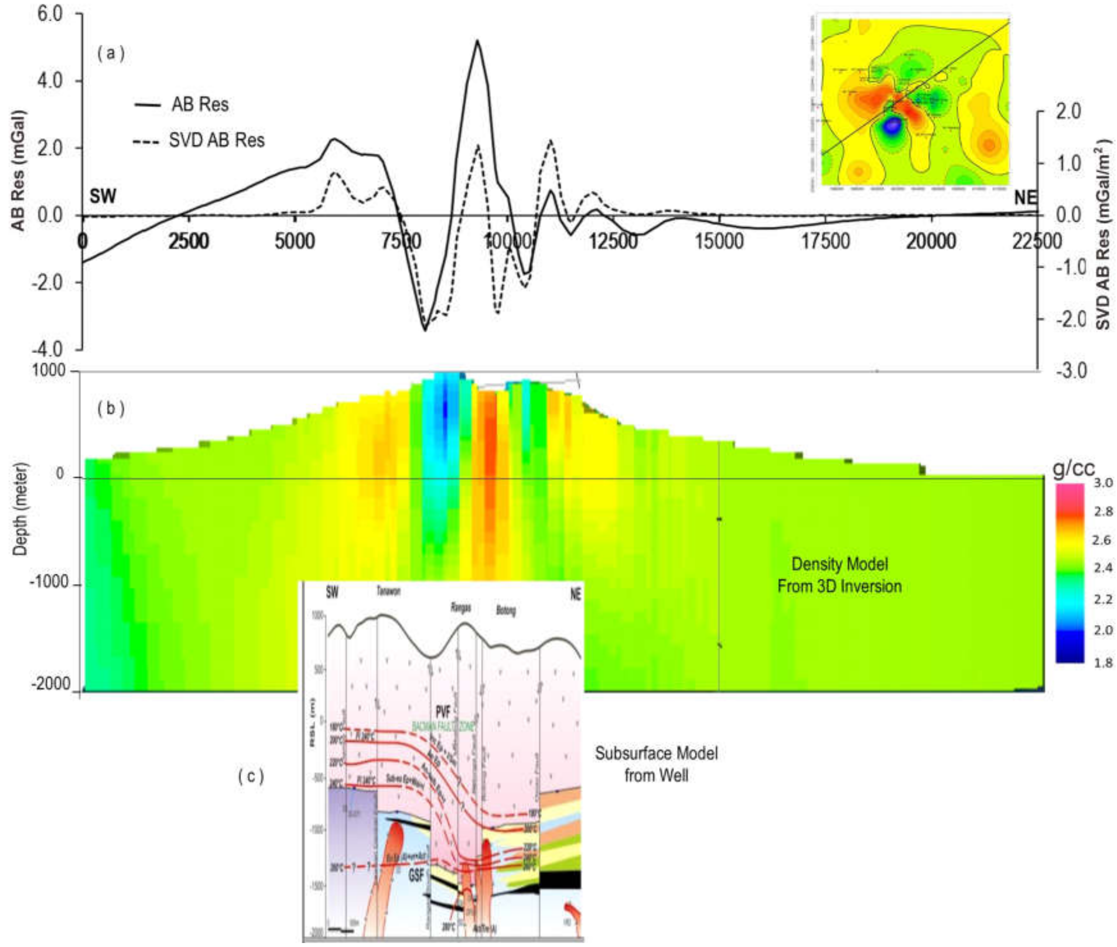

Figure 13. The cross-section of the density distribution model resulted from the Bouguer Residual anomaly 3D inversion which is correlated with the temperature and intrusion structure cross-sectional model for the NE-SW trajectory [27].

The model is correlated with: the boundary of the geothermal reservoir area delineated from the MT results, the division of the geothermal sector, and volcanoes that control the geothermal system in the Bac-Man field.

The results of the correlation analysis between the cut density distribution models for density 2.1 g/cc - 2.4 g/cc (interpreted as a geothermal reservoir) and the reservoir prospect boundary derived from MT indicate that the reservoir locations have similarities. However, the reservoir area derived from the gravity model is broader and in more detail. The gravity modeling shows that the geothermal reservoir in the Bac-Man field is divided into 3 areas: the southern part (Cawayan and Tanawon sector), the eastern part (Boton sector), and the northern part (Palayan-Inang Maharang sector). Each reservoir area is separated by the presence of fault structures or intrusions in the area. The division of the 3 reservoir areas follows the well data and the results of reservoir modeling research in the area. That the geothermal reservoir area of the Bac-Man field is divided into 3 sectors, namely the south (Cawayan and Tanawon sectors), the east (Boton sector), and the north (the North sector). Palayan-Inang Maharang) (Figure 14). The reservoir sectors are separated by intrusion in the study area and supported by the reservoir temperature in the area with a higher temperature than the surrounding area.

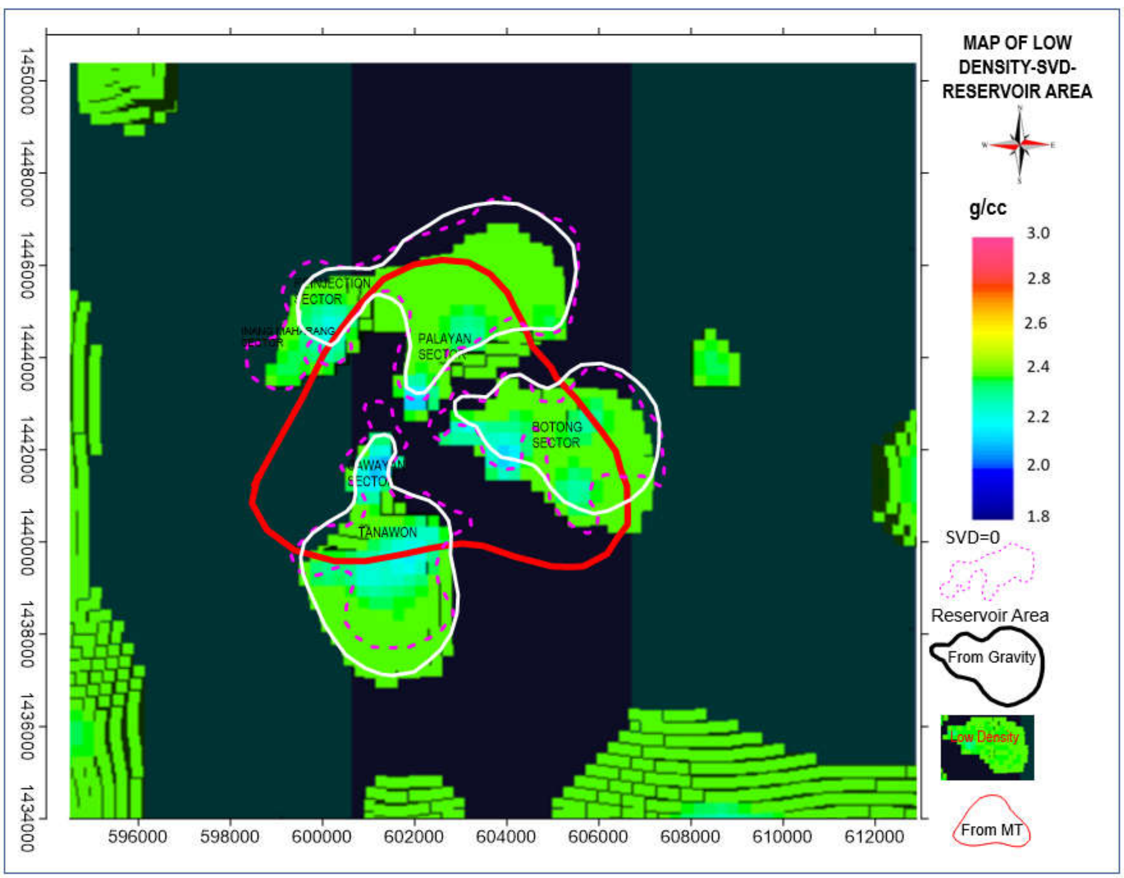

Figure 14. The density distribution model of Bouguer Residual anomaly 3D inversion

modeling shows densities 2.1 g/cc - 2.4 g/cc. The model is correlated with: geothermal reservoir area boundaries delineated from the MT results, SVD = 0 maps, the division of geothermal areas, and volcanoes that control the geothermal system in the Bac-Man field.

5. Conclusions

Based on the results of gravity research on the Bac-Man geothermal field supported by geological data, well data, MT data, and temperature data, several conclusions can be drawn regarding the Bac-Man geothermal field, namely:

1. Bouguer anomaly in the study area has a value of 18 - 41 mGal, with a high anomaly in the west to the northwest and a little in the middle, while the anomaly is low in the middle. From the Bouguer anomaly spectrum analysis, it is found that the Bouguer Regional and Residual anomaly limits are at a depth of 2500 m.

2. Residual Bouguer anomaly calculated using a moving average filter with windows 5 km x 5 km shows that the residual Bouguer anomaly has a value of -12 mGal to 9 mGal with high anomalies occupying the eastern and central parts. There are 3 low anomaly closures in the middle that are separated by high anomalies. The geothermal reservoir in the Bac-Man field may be divided into 3 reservoirs: the North, South, and East.

3. The density distribution model from the 3D inversion modeling shows that the density distribution model cut for density 2.1 g/cc - 2.4 g/cc correlates with the MT reservoir boundary. However, the reservoir area derived from the gravity model is broader and more detailed. The results of gravity modeling show that the geothermal reservoir in the Bac-Man field is divided into 3 areas: the southern part (Cawayan and Tanawon sector), the eastern part (Boton sector), and the northern part (Palayan - Inang Maharang sector) where each reservoir area is separated by the presence of fault structures or intrusions in the area. The division of the 3 reservoir areas follows the well data and the results of reservoir modeling research in the area. The reservoir sectors are separated by intrusion in the area. Temperature data also support this,

showing that the area has a higher temperature than the surrounding area.

4. Detailed reservoir boundaries, especially the outer reservoir boundaries, suggest adding more detailed gravity measurement points in the north, east, and south.

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