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Journal of Applied Science and Engineering - Decision on Manuscript ID JASE-2021-0255.R1

3 messages

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Tue, Aug 3, 2021 at 1:40 PM

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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Thank you for your fine contribution. On behalf of the Editors of the Journal of Applied Science and Engineering, we look forward to your continued contributions to the Journal.

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 acceptable for publication in JASE.

Muh Sarkowi <muh.sarkowi@eng.unila.ac.id>
To: chiwangli@gmail.com

Wed, Aug 4, 2021 at 7:18 AM

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Best regards
Muh Sarkowi

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Chi-Wang Li <chiwangli@gmail.com>
To: Muh Sarkowi <muh.sarkowi@eng.unila.ac.id>

Wed, Aug 4, 2021 at 7:24 AM

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

3 **Muh Sarkowi^{1*}, Rahmat Catur Wibowo²**

4 ¹**Geophysical Engineering, Universitas Lampung, Sumantri Brojonegoro Street No.1,**
5 **35145, Lampung, Indonesia, *email: muh.sarkowi@eng.unila.ac.id**

6 ²**Geophysical Engineering, Universitas Lampung, Sumantri Brojonegoro Street No.1**
7 **35145, Lampung, Indonesia, email: rahmat.caturwibowo@eng.unila.ac.id**

8 **Abstract**

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

20

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

22

23 **1. Introduction**

24 The Bacon - Manito (Bac-Man) geothermal field is located in the Podcol mountains on
25 the island of Luzon, about 350 km southeast of Manila. The exploration of the Bac-Man
26 geothermal field has been carried out since 1977. The reservoir model has an area of 23 km²,
27 a depth of 1500 m and a temperature of 240°C to 320°C. Based on geological, geochemical
28 and geophysical data, a conceptual model of the Bac-Man geothermal system has been made
29 (Austria, 2008).

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

37 Espartinez and See (2005) have conducted geochemical research in the Bac-Man
38 Geothermal field to determine changes in reservoirs from their chemical properties. This is
39 done to maintain the continuity of steam production in the Bac-Man field considering that of
40 the 3 geothermal reservoir sectors, the Palayan Bayan and Cawayan sectors are still
41 producing while the Boton sector has not been producing since 2009 (See, Fragata and Solis,
42 2005).

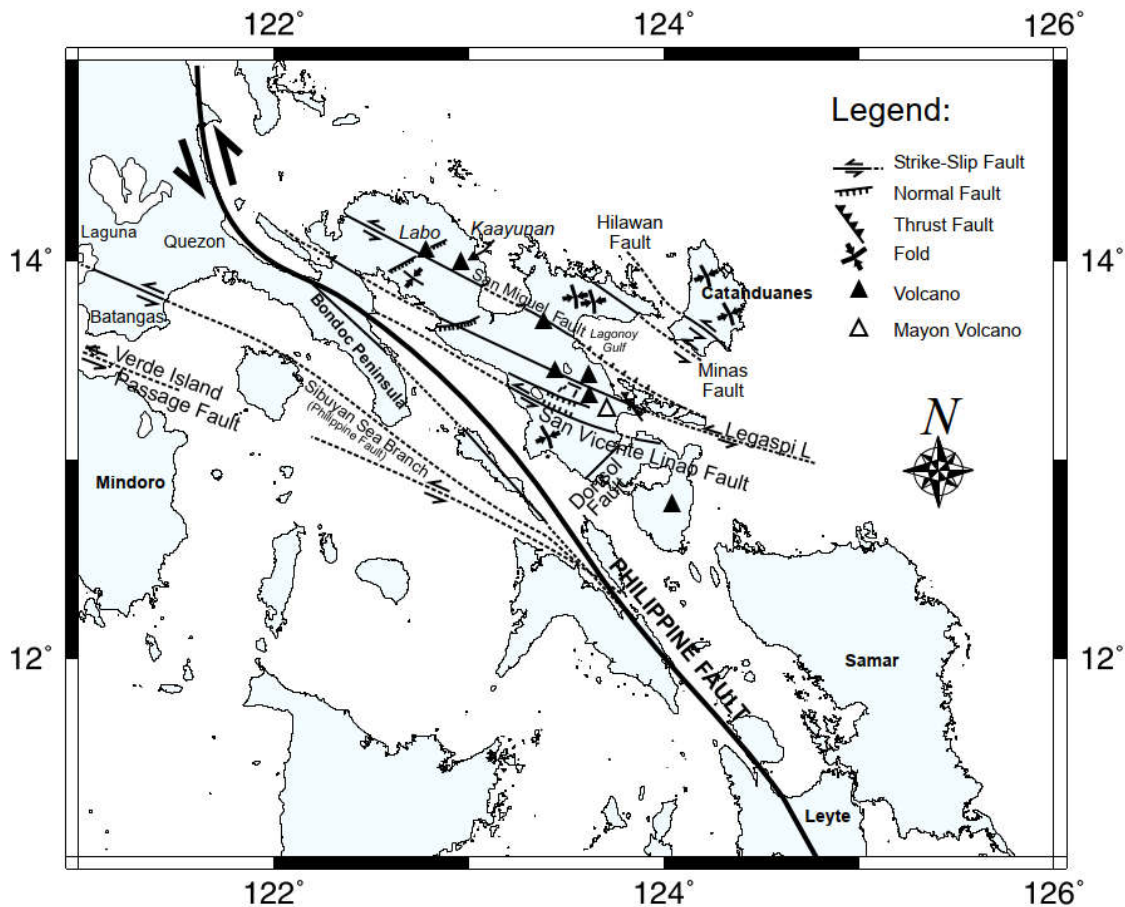
43 In this research, gravity data processing and modeling will be carried out to determine
44 the geothermal reservoir in the Bac-Man field (Palayan Bayan, Cawayan and Boton). The
45 results of the subsurface model derived from anomaly gravity analysis and the density
46 distribution model resulting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

47 model data.

48

49 **2. Bac-Man Geothermal System**

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

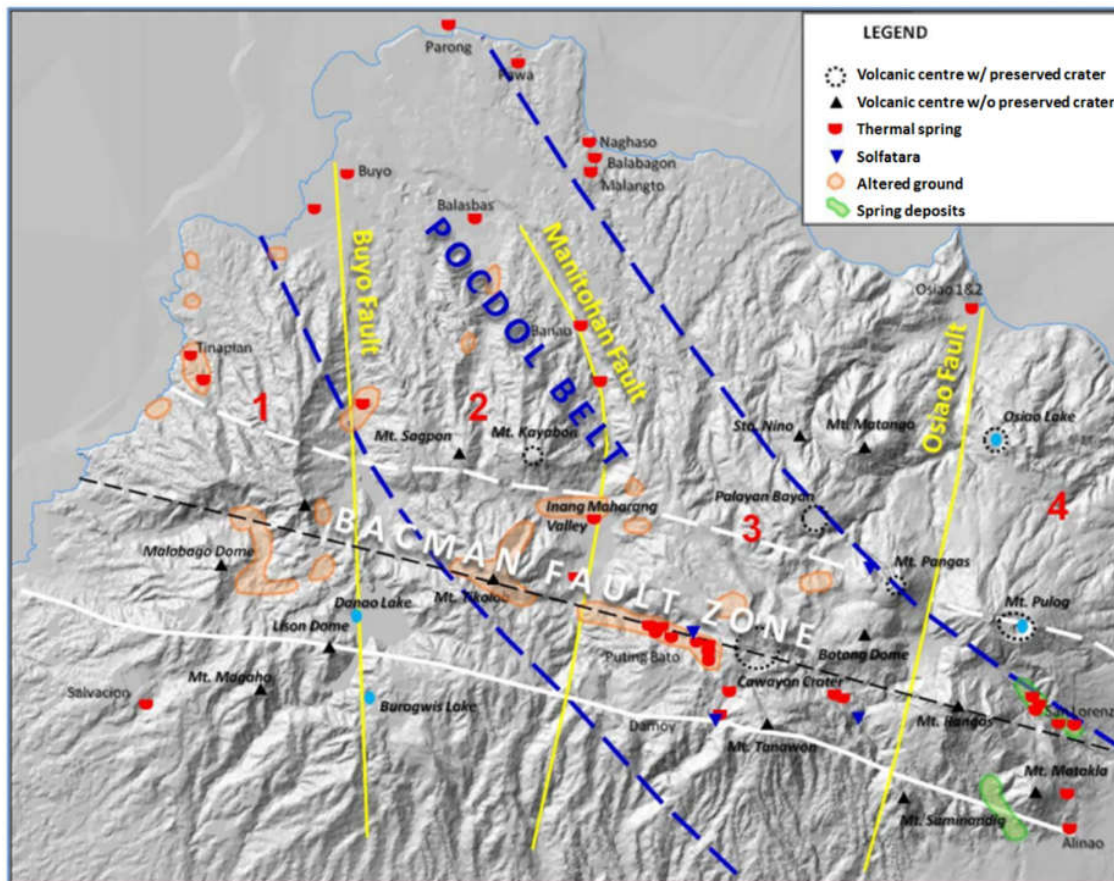


66

67 **Figure 1.** Bicol Peninsula Fault Area, San Vicente-Linao Fault (SVLF) (Lagmay, Tengonciang and Uy,
 68 2005).
 69

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

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



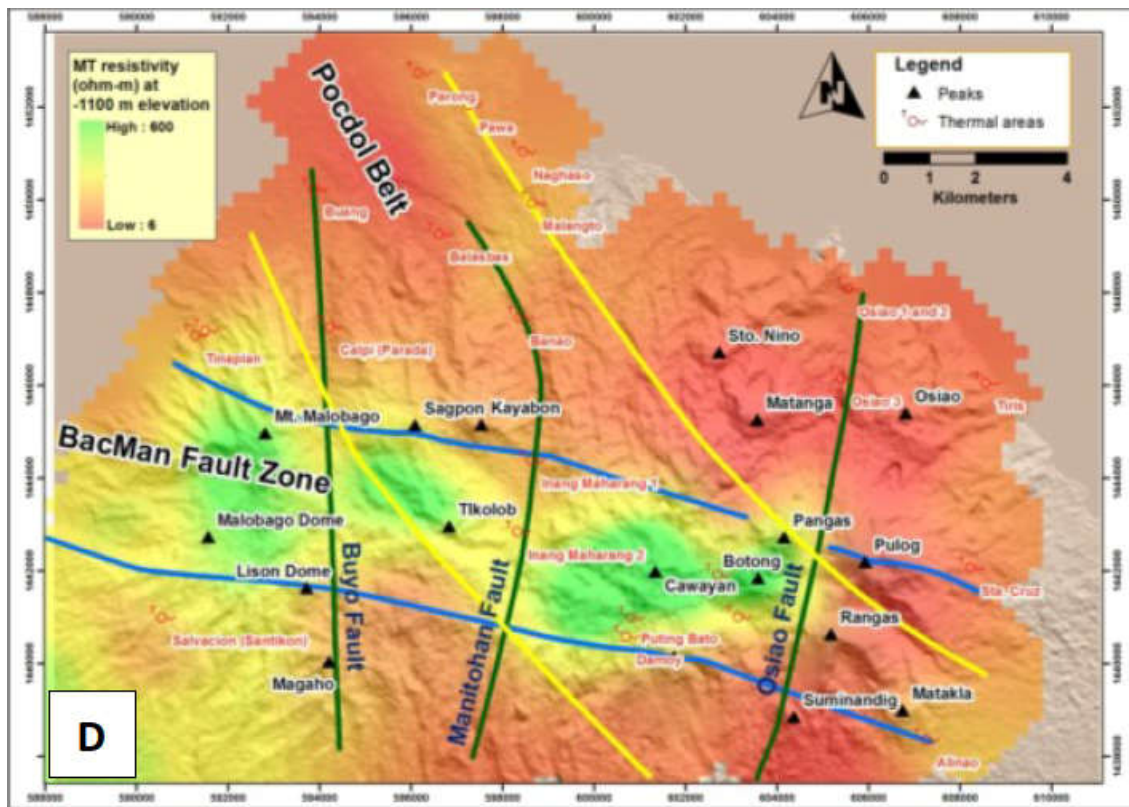
83

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

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

88 An iso-resistivity map at a depth of -1100 m from MSL which is correlated with the
89 geological structure in the area shows that the central part of the Bac-Man fault zone has a

90 low resistivity value (Tugawin *et al.*, 2015). The Bac-Man reservoir area covers an area of 26
91 - 36 km², while the Kayabon reservoir located to the northwest of Bac-Man covers an area of
92 12 - 18 km² (Figure 3).

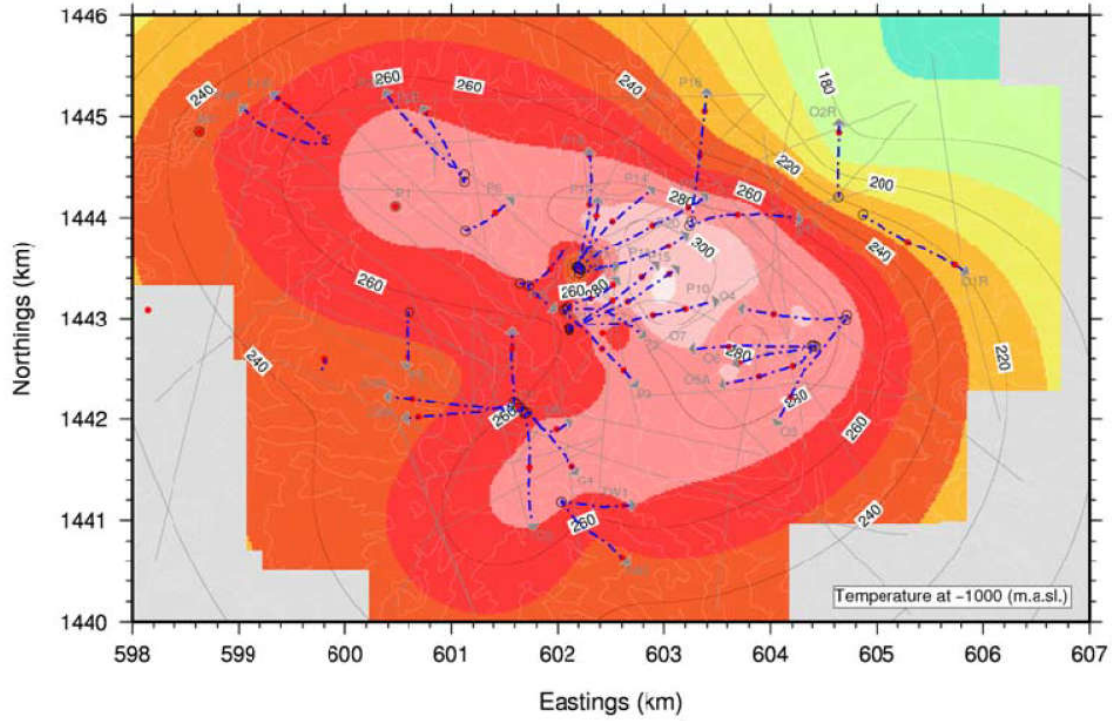


93
94 **Figure 3.** An isoresistivity map at a depth of -1100 m from MSL which is correlated with the
95 geological structure in the area shows that the central part of the Bac-Man fault zone has a
96 low resistivity value (Tugawin *et al.*, 2015).

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

101 Research related to reservoir temperature was carried out by Austria, 2008, in which the
102 eastern part of Palayan - Bayan has a high temperature of 326 ° C (Austria, 2008). The

103 temperature contour map at a depth of -1000 meters from MSL is shown in Figure 4.



104

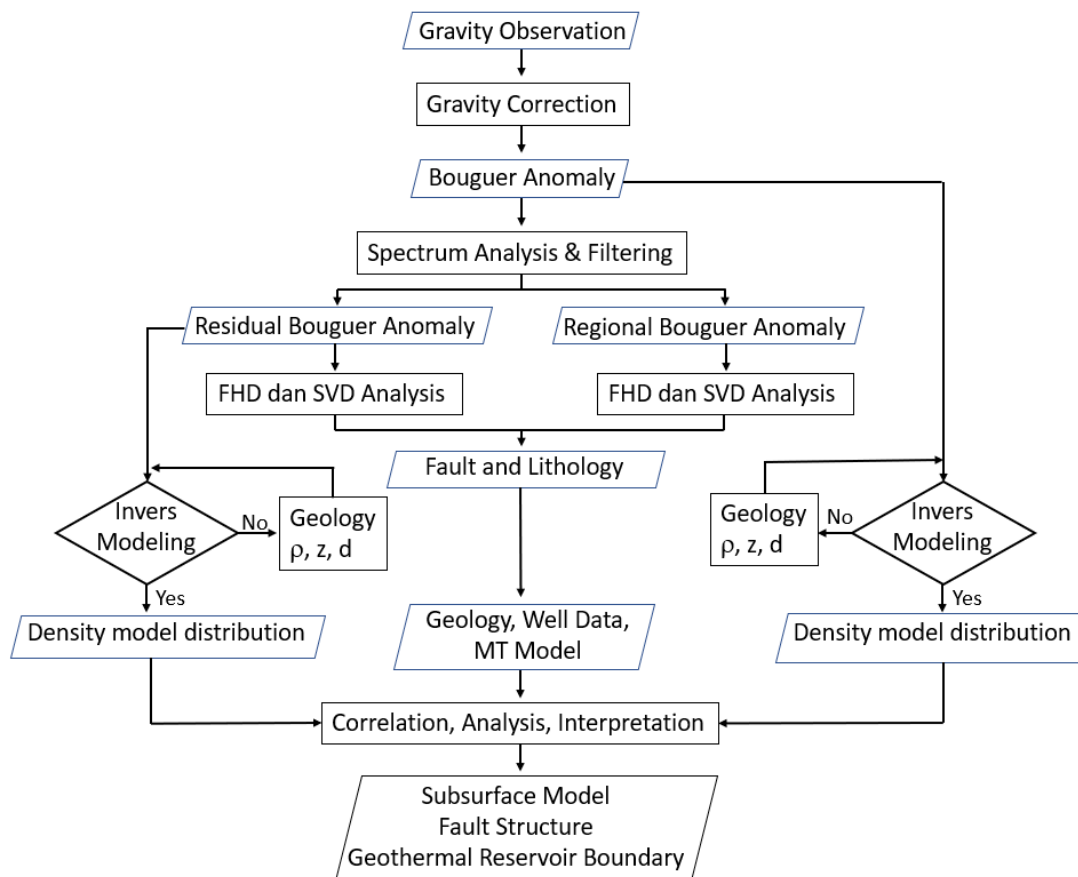
105 **Figure 4.** Temperature contour map at a depth of -1000 meters from MSL (Austria, 2008)

106

107

108 **3. Methods**

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



118

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

120 Density determination was carried out using the Parasnis method and the Nettleton
 121 method. The results of calculations using the Parasnis method get a value of 2.24 g/cc, while
 122 calculations using the Nettleton method for 2 (two) cross sections get a value of 2.35 g/cc and
 123 2.38 g/cc. This density value when compared with geological conditions in the field has an
 124 appropriate value, so that in research for the calculation of Bouguer correction and modeling
 125 using a density of 2.35 g/cc.

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

$$130 \quad g_{\phi} = 978.032,7(1 + 5.3024 \cdot 10^{-2} \sin^2 \phi - 5,8 \cdot 10^{-6} \sin^2 2\phi) \quad (1)$$

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

$$134 \quad g_{\phi,h} = g_{\phi} + \frac{\partial g_{\phi}}{\partial h} h \quad (2)$$

$$135 \quad \frac{\partial g_{\phi}}{\partial h} = -\frac{2g_{\phi}}{a} (1 + f + m - 2f \sin^2 \phi) = -0,308 \text{ mGall/m} \quad (3)$$

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

$$138 \quad Bc = 2\pi G\rho h = 0.04193\rho h \quad (4)$$

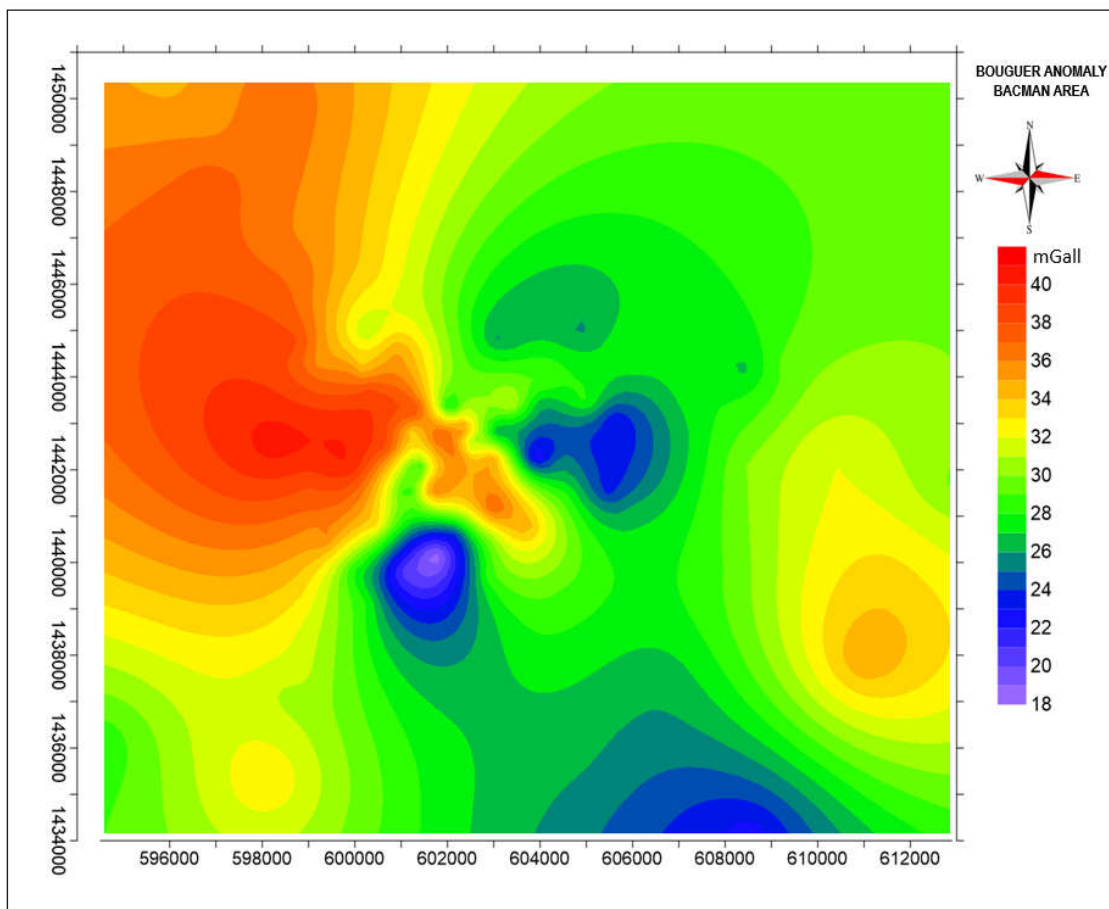
139 Where ρ is rock density (g/cc), h is height (m), and Bc is Bouguer correction (mGall).

140 Terrain corrections were calculated using a combination of the equations given by Nagy
141 (1966) and Kane (1962). In the calculation of terrain correction, the topographic model is
142 approached with a prism-shaped arrangement of objects measuring 1 km x 1 km with a height
143 in accordance with the topography of the area up to a radius of 50 km. The topographical data
144 used is DEM data taken from INA Geoportal.

145

146 **4. Result and Discussions**

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



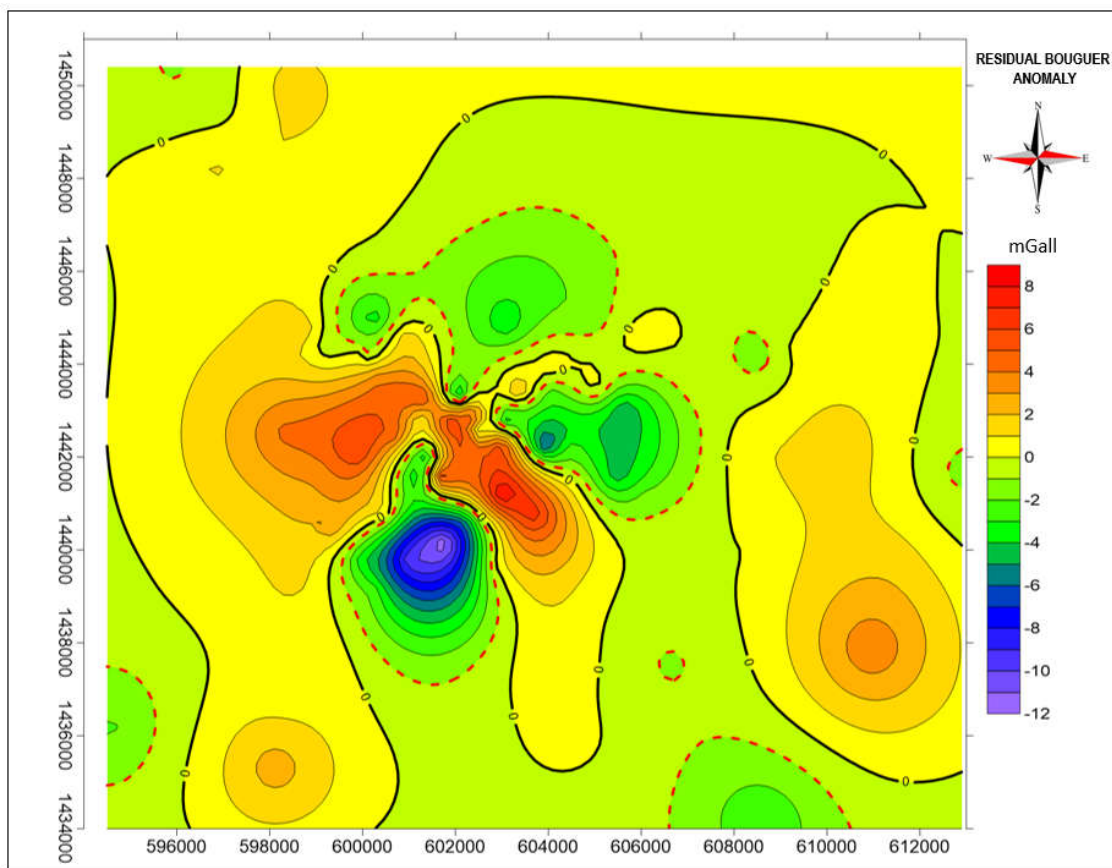
153

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

155 Spectral analysis was carried out to determine the boundary of the regional bouguer
156 anomaly and the residual area of the study. The results of this spectral analysis are then used

157 to estimate the window width for gravity anomaly filtering. In general, a Fourier
158 transformation is to reconstruct/unravel an arbitrary wave into a sine wave with a variable
159 frequency where the sum of the sine waves is the original waveform (Bhattacharyya and Leu
160 (1977); Ghosh and Singh (2014)). Spectrum analysis is used to determine the depth of the
161 structure of the anomaly. In this study, the analysis of the spectrum analysis used Fourier
162 transform, where the results are used to estimate the width of the filtering window. The
163 spectrum analysis was carried out by making a cross section of the Bouguer anomaly as many
164 as 5 trajectories with a point interval of 250 m. The result of spectrum analysis from 5 lines
165 of Bouguer anomaly shows that the average regional Bouguer anomaly depth is 2500 meters.
166 Based on these results, the separation of regional Bouguer anomalies and residual Bouguer
167 anomalies is used a moving average filter with a window width of 5 km x 5 km.

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



178

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

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

184
$$\nabla^2 \Delta g = 0 \text{ atau } \frac{\partial^2 \Delta g}{\partial x^2} + \frac{\partial^2 \Delta g}{\partial y^2} + \frac{\partial^2 \Delta g}{\partial z^2} = 0 \quad (5)$$

185
$$\frac{\partial^2 \Delta g}{\partial z^2} = - \frac{\partial^2 \Delta g}{\partial x^2} + \frac{\partial^2 \Delta g}{\partial y^2} \quad (6)$$

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

188

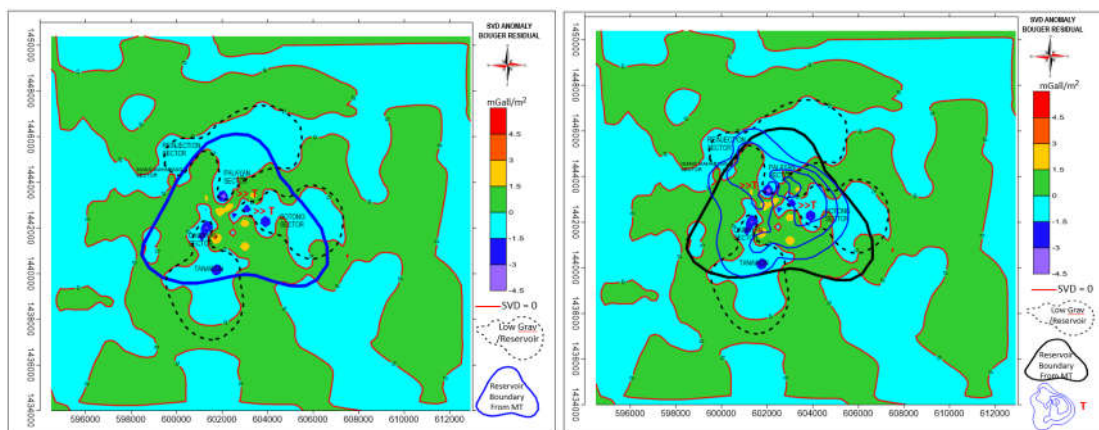
$$\Delta G_{SVD}(\Delta x, \Delta y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \Delta g(x, y) F(x - \Delta x, y - \Delta y) dx dy \tag{7}$$

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

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

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

203



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

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

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

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

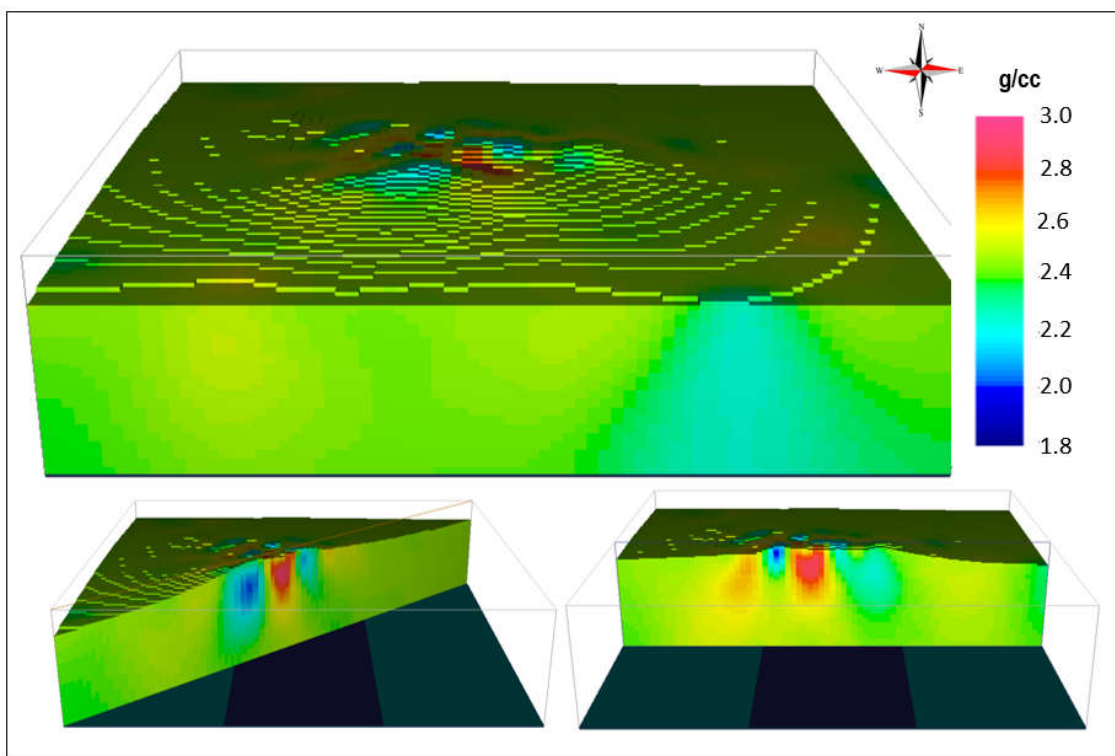
218 To obtain a model of the subsurface structure of the Bac-Man Geothermal Field in this
 219 study, a 3D inversion modeling of Bouguer Residual anomaly was carried out. The equation
 220 used and the calculation of 3D inversion modeling is the subsurface model approach which is
 221 composed of prisms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

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

224

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

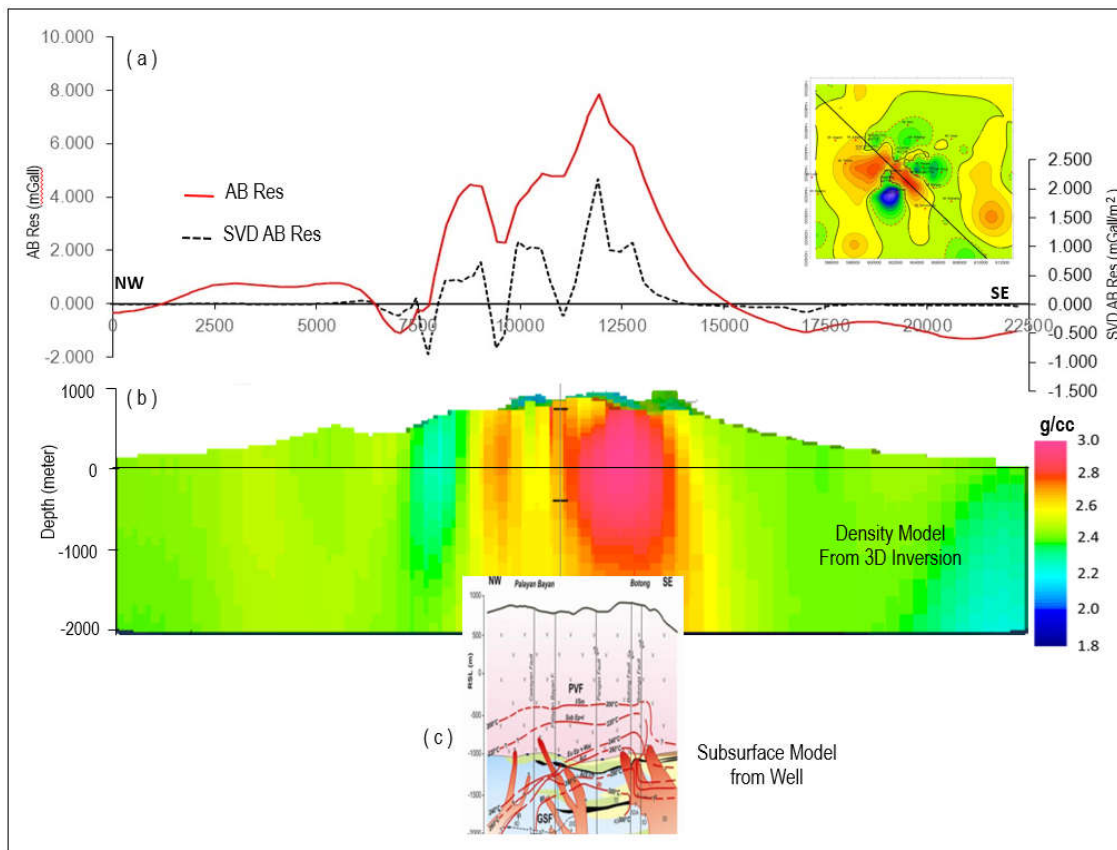
226 The results of Bouguer Residual anomaly 3D inversion modeling using the Grav3D
227 program are shown in Figure 9. The density distribution model of the 3D inversion modeling
228 results shows the distribution of high and low density in the middle of the study area with a
229 value of 2 g/cc to 2.9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



233
234 **Figure 9.** The subsurface density distribution model from the 3D inversion modeling result of
235 Bouguer Residual anomaly in Bac-Man geothermal field

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

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

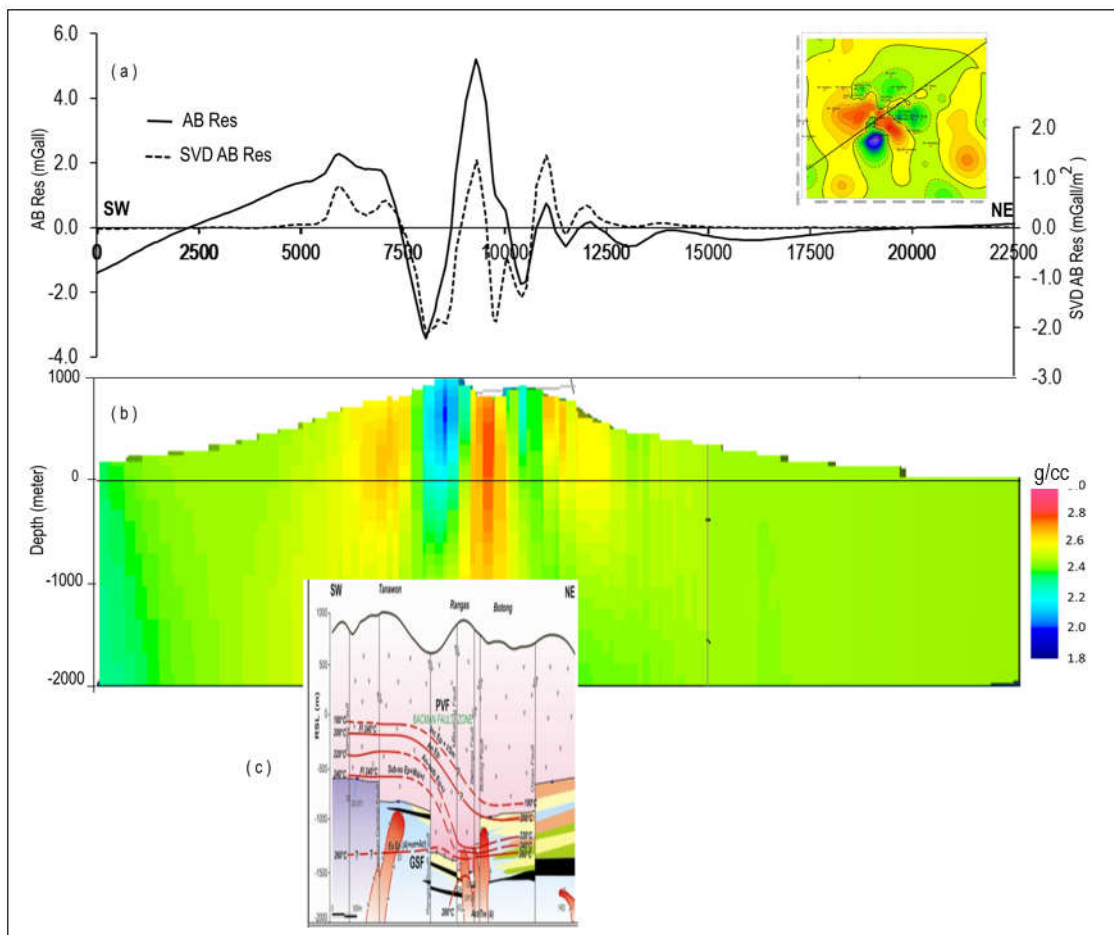


244

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

248 The density distribution model resulting from the 3D Bouguer anomaly residual
 249 inversion which is correlated with the temperature cross-section model and the intrusion
 250 structure on the NE-SW trajectory is shown in Figure 11. The results of the 3D Bouguer
 251 anomaly residual inversion result which correlated the temperature cross-section model and

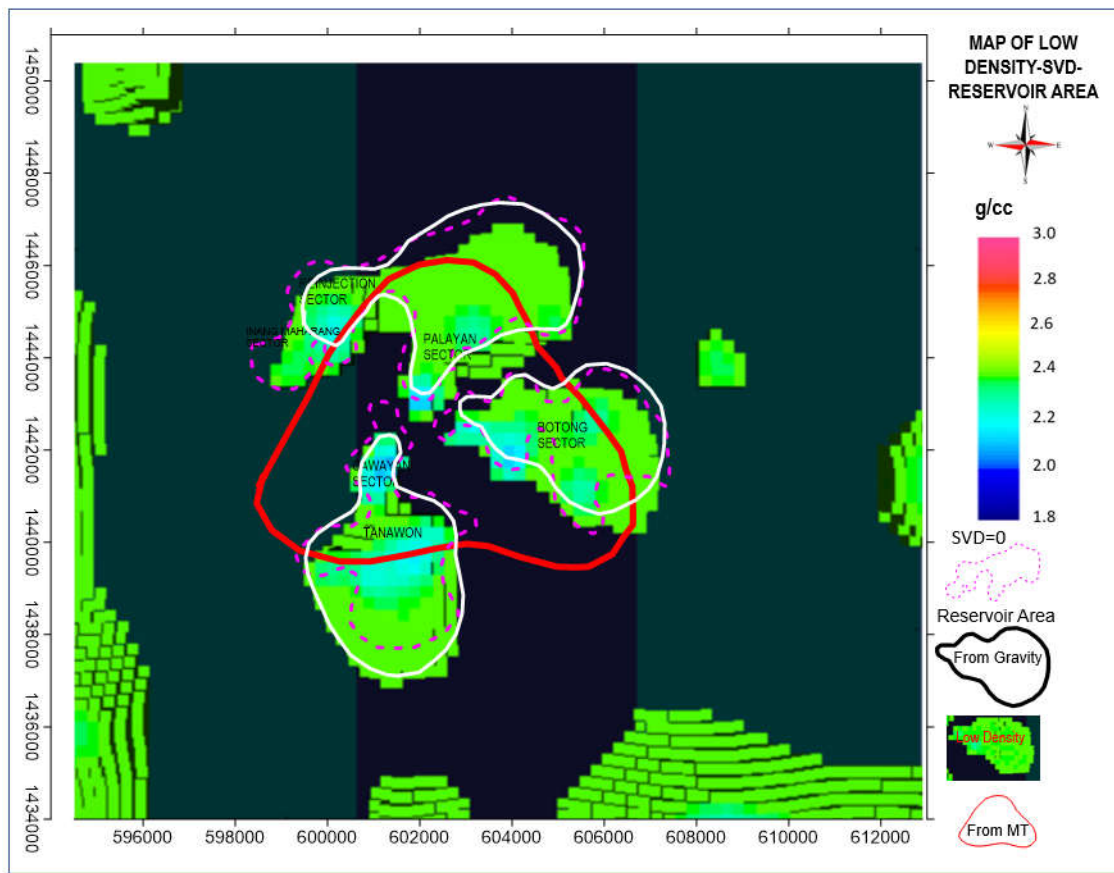
252 the intrusion structure show the existence of good correlation, the presence of intrusion
 253 correlates with high density in the area. Likewise, the SVD section indicates that the intrusion
 254 is no single but separated into two parts according to the model derived from well data and
 255 temperature data.



256
 257 **Figure 11.** The cross section of the density distribution model resulted from the Bouguer
 258 Residual anomaly 3D inversion which is correlated with the temperature and intrusion
 259 structure cross-sectional model for the NE-SW trajectory.

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

263 The results of the correlation analysis between the cut density distribution models for
264 density 2.1 g/cc - 2.4 g/cc (interpreted as a geothermal reservoir) and the reservoir prospect
265 boundary derived from MT indicate that the reservoir locations have similarities, but the
266 reservoir area derived from the gravity model is more broad and in more detail. From the
267 gravity modeling shows that the geothermal reservoir in the Bac-Man field is divided into 3
268 areas, namely: the southern part (Cawayan and Tanawon sector), the eastern part (Boton
269 sector) and the northern part (Palayan -Inang Maharang sector) where each reservoir area is
270 separated by the presence of fault structures or intrusions in the area. The division of the 3
271 reservoir areas is in accordance with the well data and the results of reservoir modeling
272 research in the area, where the geothermal reservoir area of the Bac-Man field is divided into
273 3 sectors, namely the south (Cawayan and Tanawon sectors), the east (Boton sector) and the
274 north (the North sector). Palayan-Inang Maharang) (Figure 12). The reservoir sectors are
275 separated by intrusion in the area, this is supported by the temperature of the reservoir in the
276 area which has a higher temperature than the surrounding area.



277

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

283

284

285 **5. Conclusions**

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

- 289 1. Bouguer anomaly in the study area has a value of 18 - 41 mGall, with a high
290 anomaly in the West to the Northwest and a little in the middle, while the anomaly is
291 low in the middle. From the analysis of the Bouguer anomaly spectrum, it is found
292 that the Bouguer Regional and Residual anomaly limits are at a depth of 2500 m.
- 293 2. Residual Bouguer anomaly calculated using a moving average filter with windows 5
294 km x 5 km shows that the residual Bouguer anomaly has a value of -12 mGall to 9
295 mGall with high anomalies occupying the eastern and central parts. There are 3 low
296 anomaly closures in the middle which are separated by high anomalies, which can be
297 interpreted that the geothermal reservoir in the Bac-Man field may be divided into 3
298 reservoirs, namely the North, South and East.
- 299 3. The density distribution model from the 3D inversion modeling shows that the
300 density distribution model cut for density 2.1 g/cc - 2.4 g/cc has a correlation with
301 the reservoir boundary derived from MT, but the reservoir area derived from the
302 gravity model is wider and more detailed. The results of gravity modeling show that
303 the geothermal reservoir in the Bac-Man field is divided into 3 areas, namely: the
304 southern part (Cawayan and Tanawon sector), the eastern part (Boton sector) and the
305 northern part (Palayan - Inang Maharang sector) where each reservoir area is
306 separated by the presence of fault structures or intrusions in the area. The division of
307 the 3 reservoir areas is in accordance with the well data and the results of reservoir
308 modeling research in the area. The reservoir sectors are separated by intrusion in the

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

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

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321

322 **Acknowledgements**

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

326

327 **References**

- 328 [1] Africa, J. R. (2013) *1D Inversion of MT and TEM Data With Application of Soundings*
329 *From Krýsuvík , Sw-Iceland and a Review of MT/TEM Data From Bac-Man*
330 *Geothermal Project , Central Philippines*. Reykjavik.
- 331 [2] Austria, J. J. C. (2008) *Production Capacity Assessment of the Bacon-Manito*
332 *Geothermal Reservoir, Philippines*.
- 333 [3] Bhattacharyya, B. K. and Leu, L. K. (1977) ‘Spectral Analysis of Gravity and Magnetic
334 Anomalies Due To Rectangular Prismatic Bodies.’, *Geophysics*, 42(1), pp. 41–50. doi:
335 10.1190/1.1440712.
- 336 [4] Dimabayao, J. J. T., Rowe, M. C. and Barker, S. (2019) ‘Stable isotope systematics of
337 fluids and epidote in the Bacon-Manito Geothermal Field, Philippines: Indicators of
338 fluid origin and evolution’, *Geothermics*, 80, pp. 31–43. doi:
339 10.1016/j.geothermics.2019.02.009.
- 340 [5] Elkins, T. A. (1951) ‘The second derivative method of gravity interpretation’,
341 *Geophysics*, 16(1), pp. 29–50. doi: 10.1190/1.1437648.
- 342 [6] Espartinez, C. M. R. and See, F. S. (2005) ‘The BacMan Geothermal Field, Philippines:
343 Geochemical Changes and Challenges After Twenty Years of Operation’, in *World*
344 *Geothermal Congress 2015*, p. 8.

- 345 [7] Ghosh, G. K. and Singh, C. L. (2014) ‘Spectral analysis and Euler deconvolution
346 technique of gravity data to decipher the basement depth in the Dehradun-Badrinath
347 area’, *Journal of the Geological Society of India*, 83(5), pp. 501–512. doi:
348 10.1007/s12594-014-0077-3.
- 349 [8] Kane, M. F. (1962) ‘A Comprehensive System of Terrain Corrections Using A Digital
350 Computer’, *GEOPHYSICS*, XXVII(4), pp. 455–462.
- 351 [9] Lagmay, A. M. F., Tengonciang, A. M. P. and Uy, H. S. (2005) ‘Structural setting of the
352 Bicol Basin and kinematic analysis of fractures on Mayon Volcano, Philippines’,
353 *Journal of Volcanology and Geothermal Research*, 144(1-4 SPEC. ISS.), pp. 23–36. doi:
354 10.1016/j.jvolgeores.2004.11.015.
- 355 [10] Layugan, D. B. *et al.* (2005) ‘Magnetotelluric (MT) Resistivity Surveys in Various
356 Geothermal Systems in Central Philippines’, in *Proceedings World Geothermal
357 Congress*. Antalya, pp. 24–29.
- 358 [11] Monasterial, J. L. (2015) *Microgravity Survey in 2009-2010 Around Bacman
359 Geothermal Field, Philippines - Gravity Corrections and Interpretations*. Reykjavik.
- 360 [12] Nagy, D. (1966) ‘The prism method for terrain corrections using digital computers’,
361 *Pure and Applied Geophysics PAGEOPH*, 63(1), pp. 31–39. doi: 10.1007/BF00875156.
- 362 [13] Plouff, D. (1976) ‘Gravity and Magnetic Fields of Polygonal Prisms and Application to

- 363 Magnetic Terrain Corrections’, *GEOPHYSICS*, 41(4), pp. 727–741.
- 364 [14] Ramos, S. G. (2002) ‘POTENTIAL CONSTRAINTS TO THE DEVELOPMENT OF
365 THE RANGAS SECTOR BASED ON PETROLOGIC EVALUATION OF THE
366 BACMAN GEOTHERMAL FIELD , PHILIPPINES’, in *27th Workshop on
367 Geothermal Reservoir Engineering*. Stanford.
- 368 [15] Resyes, A. G., Delfin, M. C. Z. and Bueza, E. L. (1995) ‘PETROLOGICAL
369 IDENTIFICATION OF MULTIPLE HEAT SOURCES IN THE BACON-MANITO
370 GEOTHERMAL SYSTEM, THE PHILIPPINES’, in *Proceedings World Geothermal
371 Congress*. Florence, pp. 713–717.
- 372 [16] See, F. S., Fragata, J. J. and Solis, R. P. (2005) ‘The BacMan Geothermal Field ,
373 Philippines : Geochemical Changes and Operational Challenges After Ten Years of
374 Production’, *Proceedings World Geothermal Congress 2005*, (April), pp. 24–29.
- 375 [16] Tugawin, R. J. *et al.* (2015) ‘Resistivity Model Based on 2D Inversion of
376 Magnetotelluric Sounding Data in Bacon- Manito, Southern Luzon, Philippines’,
377 *Proceedings World Geothermal Congress 2015*, (April), pp. 1–6.
- 378 [17] Wellenhof, B. H. and Moritz, H. (2005) *Physical Geodesy*, SpringerWienNewYork.
379 Austria: SpringerWienNewYork.
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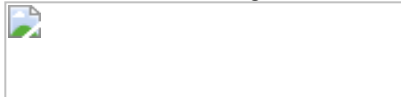
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Reservoir Identification of Bac-Man Geothermal Field Based on Gravity Anomaly Analysis and Modeling

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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

23 **1. Introduction**

24 The Bacon - Manito (Bac-Man) geothermal field is located in the Podcol mountains on
25 the island of Luzon, about 350 km southeast of Manila. The exploration of the Bac-Man
26 geothermal field has been carried out since 1977. The reservoir model has 23 km², 1500 m
27 depth, and a temperature of 240°C to 320°C. Based on geological, geochemical, and
28 geophysical data, a conceptual model of the Bac-Man geothermal system has been made [1].

29 Tugawin *et al.* (2015) [2] carried out 2D magneto-telluric (MT) inversion modeling in
30 the Bac-Man field, which shows the existence of 3 (three) geothermal reservoir areas, namely
31 Palayan Bayan, Tikolob, and Malobago areas. These results follow the results of data
32 interpretation of resistivity vertical electric sounding (VES) and Schlumberger Resistivity
33 Traversing (SRT) [2]. The reservoir in the Palayan Bayan area has been in production since
34 1993, while the Tikolob prospect is on the west side of the Bac-Man field, separate from the
35 Palayan Bayan system [2].

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

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

46

47 **2. Bac-Man Geothermal System**

48 The exploration of the Bac-Man geothermal field has been carried out since 1977.
49 Several studies have been carried out, ranging from geology, geochemistry, geophysics
50 (gravity, magnetic, micro earthquake, MT, temperature, etc.) to determine the geothermal
51 reservoir, caprocks, heat-source, the geothermal system model, and geothermal potential in
52 the area. The total capacity of the power plant in the Bac-Man area is 150 MWe generated
53 from 4 generating units, namely: Unit I began operating in 1993 and unit II in 1995 which
54 was named Palayang Bayan (2 x 55 Mwe), in 1996 the Cawayan geothermal plant began
55 operating (20 Mwe), and in 1998 the Unit III power plant in the Botong area began operating
56 (20 Mwe). The Bac-Man geothermal field is located in the Podcol mountains 350 km
57 southeast of Manila. The local fault system is known as the Bac-Man Fault Zone (BFZ) [5].
58 The fault zone is indicated by a series of volcanoes that are mostly NW-SE (Figure 1).
59 Structurally controlled by a fault system, which is believed to be an extension of the San
60 Vicente Linao Fault (SVLF), is a stretch of the Philippine fault. The most prominent regional
61 geological structure in the area is the San Vicente-Linao Fault in the Northwest - Southeast
62 (NW-SE), which slopes across the Bico Peninsula [6].

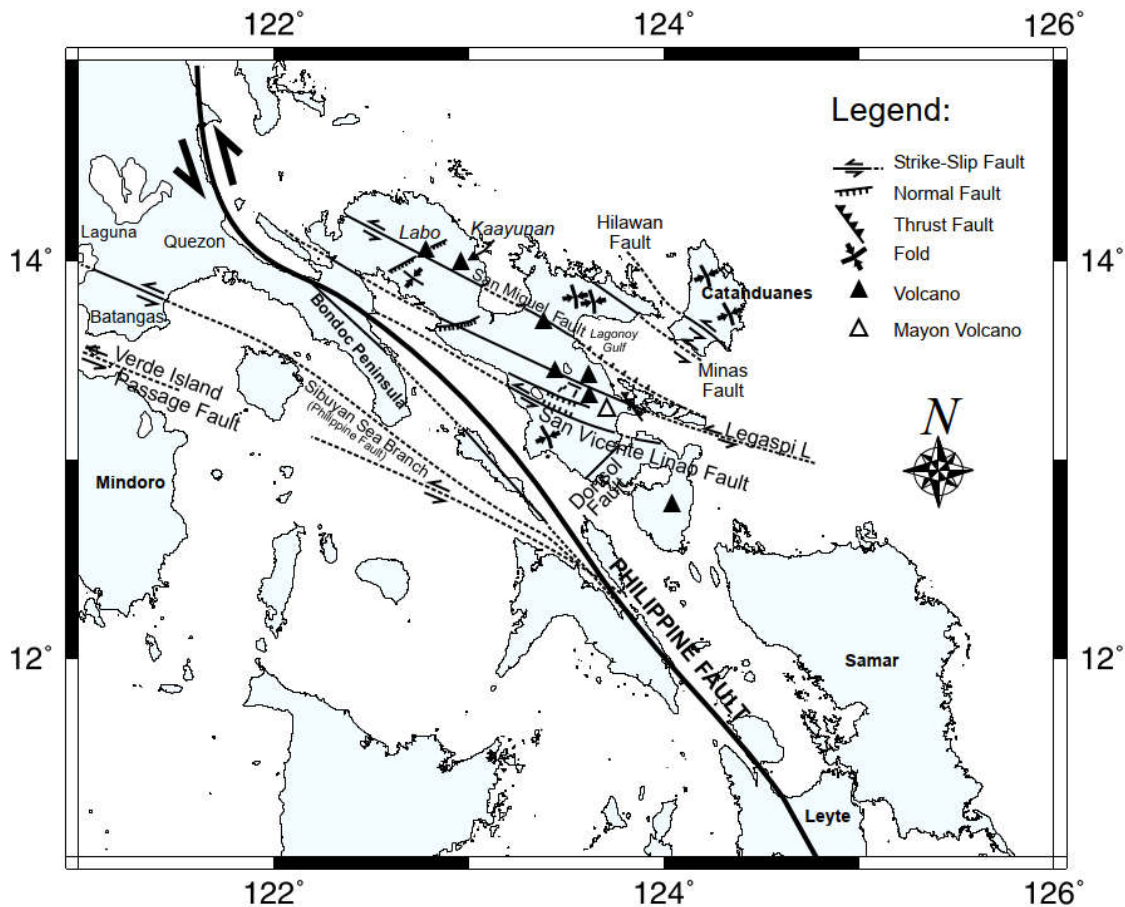


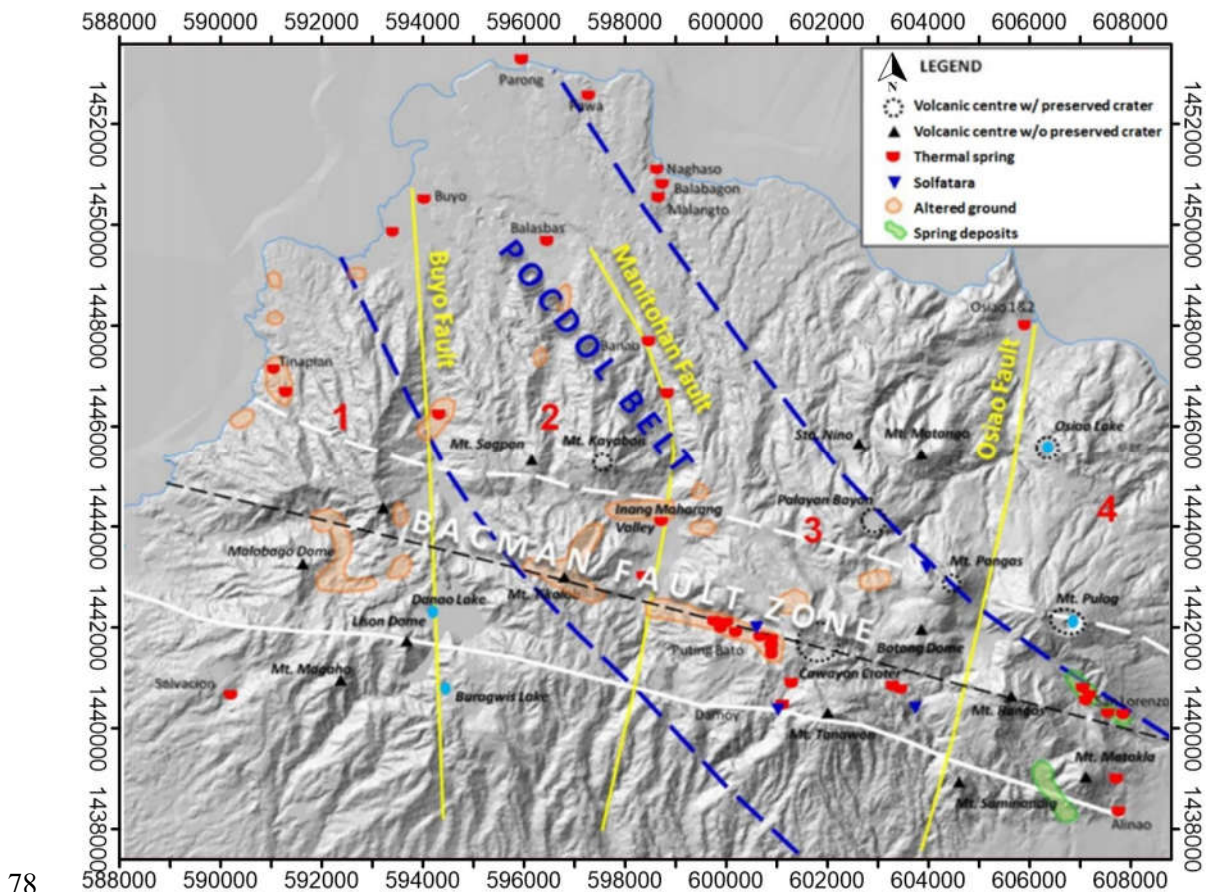
Figure 1. Bicol Peninsula fault area, San Vicente-Linao fault (SVLF) [7].

63
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65

66 The Bac-Man geothermal system is divided into two regions, namely the western and
67 eastern parts of Bac-Man. The eastern part of Bac-Man is further divided into the North
68 Namito lowlands and the Podcol highlands. The Podcol plateau can be divided into eight
69 geographic sectors: Inang Maharang, Putting Bato, Palayan Bayan, Cawayan, Tanawon,
70 Osiao, Bangas, and Botong [6]. Neutral chloride hot springs with a temperature of 89 °C - 96
71 °C are found in the lowlands of Manito. In Cawayan and Pangas, Solfatara is found in West
72 Bac-Man, cold to warm and cold SO₄ springs are found.

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

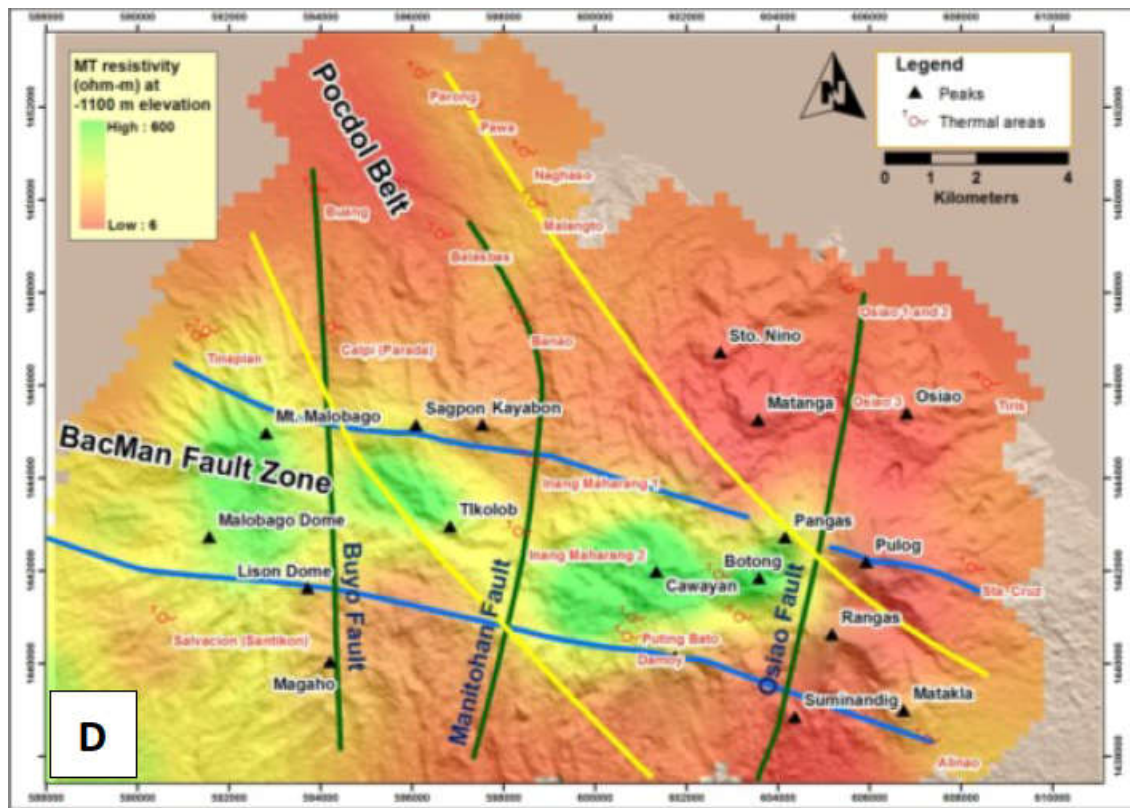
75 Botong and Pangas domes extrusion. The youngest volcanoes generally occur in subsurface
76 areas with high temperatures, permeable formations, and active thermal manifestations
77 (Figure 2) [6].



78
79 **Figure 2.** Structure and manifestations at the Bac-Man geothermal field [8].

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

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

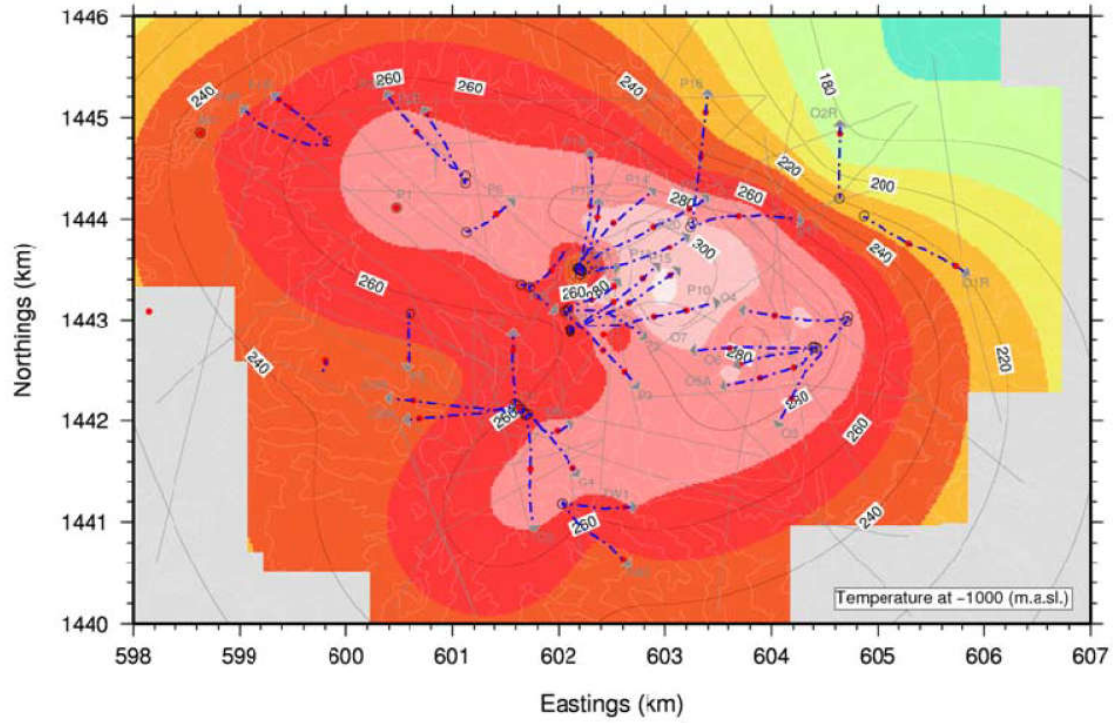


87

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

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

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



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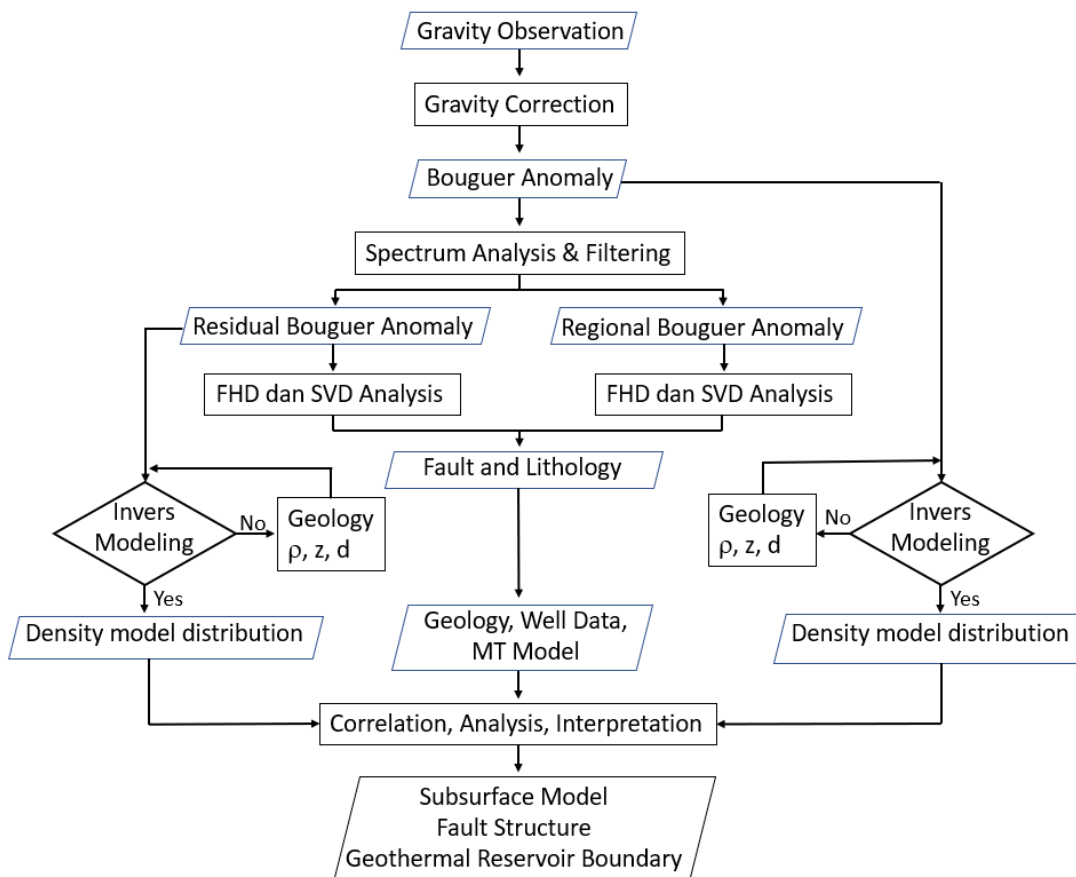
Figure 4. Temperature contour map at a depth of -1000 meters from MSL [1].

100

101

102 **3. Methods**

103 The gravity data used in this study were 125 points: the results of measurements from
 104 2009 to 2010 [10]. Processing gravity data includes determination of surface density using
 105 the Parasnis and Nettleton method, the determination of Bouguer anomaly, Bouguer anomaly
 106 filtering, Bouguer anomaly separation, and horizontal and vertical gradient analysis Bouguer
 107 anomaly, and Bouguer anomaly modeling. Analysis and interpretation were carried out to
 108 verify the Bac-Man geothermal reservoir area and structures in the area. The analysis and
 109 interpretation are carried out by correlating the gravity model with geological data, well data,
 110 and other geophysical data. The research flow carried out is shown in Figure 5.



111

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

113 Density determination was carried out using the Parasnis method and the Nettleton

114 method. The calculations using the Parasnis method get a value of 2.24 g/cc, while
 115 calculations using the Nettleton method for 2 (two) cross-sections get a value of 2.35 g/cc and
 116 2.38 g/cc. When compared with geological conditions in the field, this density value has an
 117 appropriate value, so that in research for the calculation of Bouguer correction and modeling
 118 using a density of 2.35 g/cc.

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

$$123 \quad g_{\phi} = 978.032,7(1 + 5.3024 \cdot 10^{-3} \sin^2 \phi - 5,8 \cdot 10^{-6} \sin^2 2\phi) \quad (1)$$

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

$$127 \quad g_{\phi,h} = g_{\phi} + \frac{\partial g_{\phi}}{\partial h} h \quad (2)$$

$$128 \quad \frac{\partial g_{\phi}}{\partial h} = -\frac{\gamma_{\phi}}{a} (1 + f + m - 2f \sin^2 \phi) = -0,308 \text{ mGal/m} \quad (3)$$

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

$$131 \quad Bc = 2\pi G\rho h = 0.04193\rho h \quad (4)$$

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

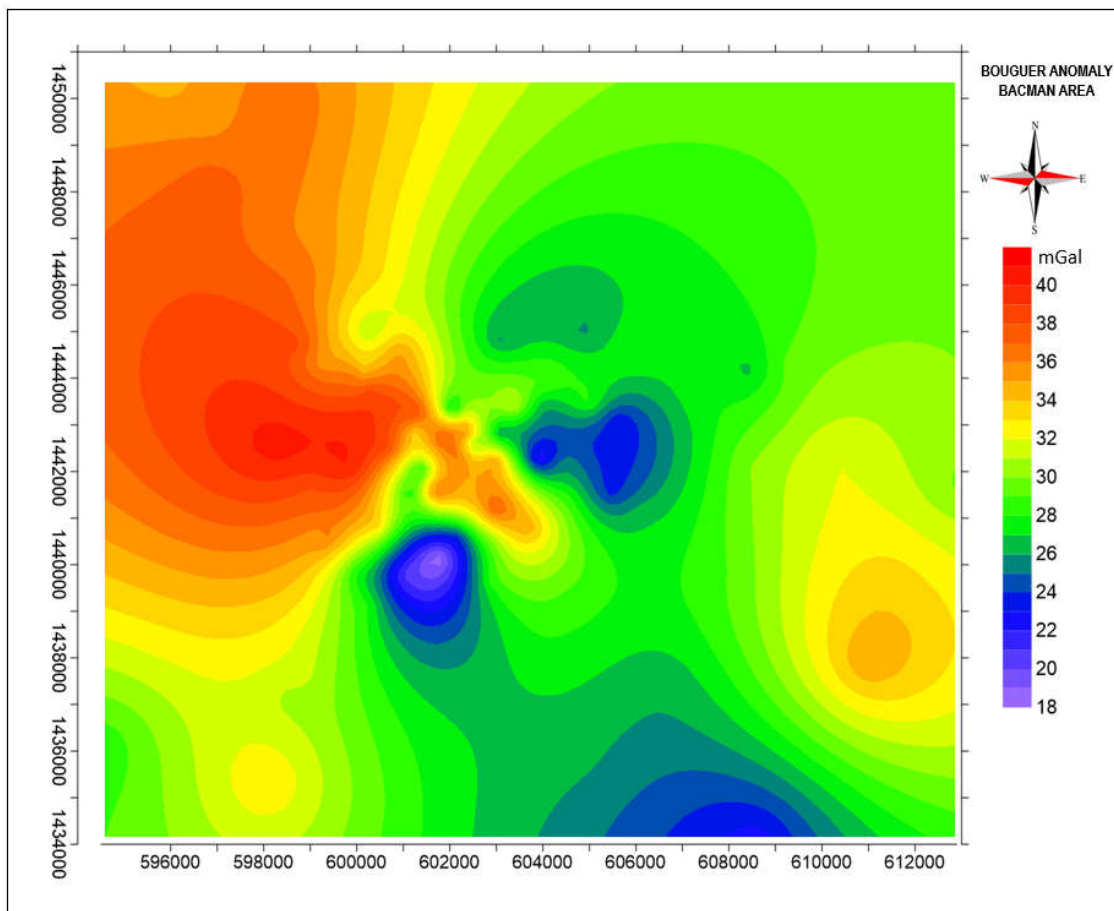
133 Terrain corrections were calculated using a combination of the equations given by Nagy

134 (1966) [12] and Kane (1962) [13]. In the calculation of terrain correction, the topographic
135 model is approached with a prism-shaped arrangement of objects measuring 1 km x 1 km
136 with a height following the topography of the area up to a radius of 50 km. The topographical
137 data used is DEM data taken from INA Geoportal.

138

139 **4. Result and Discussions**

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



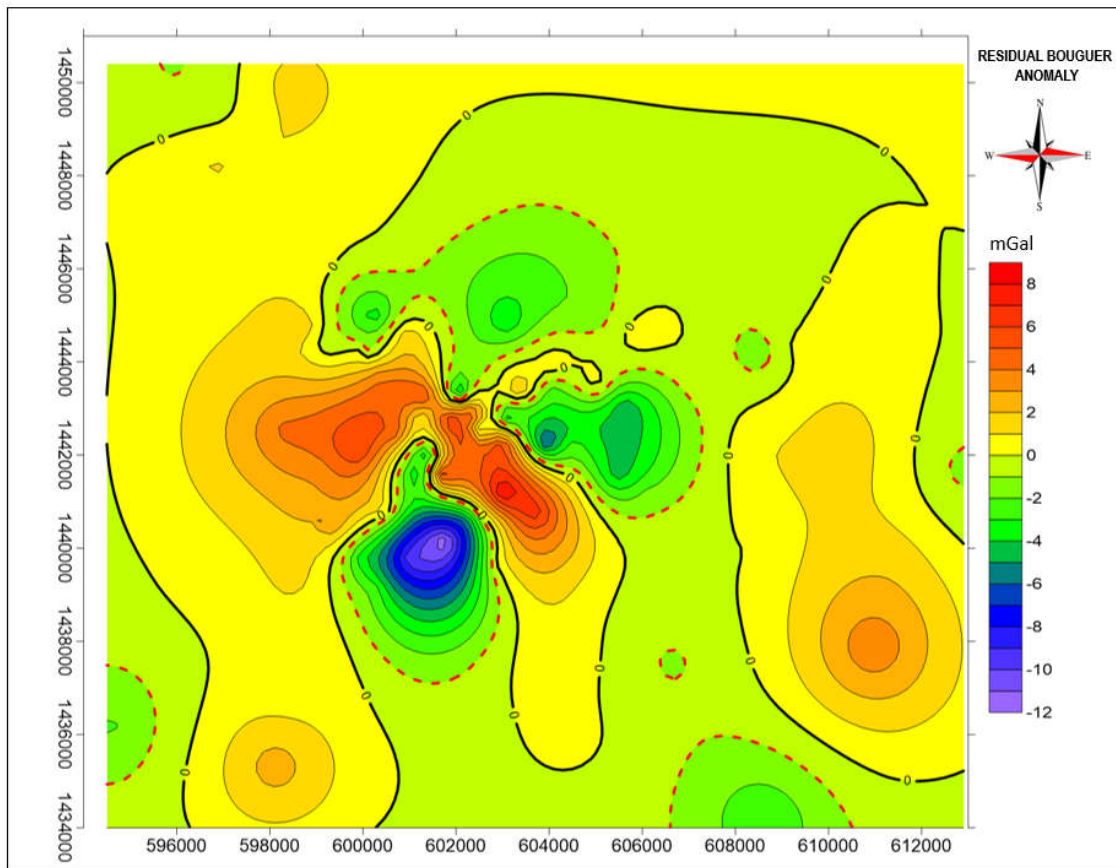
145

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

147 Spectral analysis was carried out to determine the boundary of the regional Bouguer
148 anomaly and the residual area of the study. The results of this spectral analysis are then used
149 to estimate the window width for gravity anomaly filtering. In general, a Fourier

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

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



170

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

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

176
$$\nabla^2 \Delta g = 0 \text{ atau } \frac{\partial^2 \Delta g}{\partial x^2} + \frac{\partial^2 \Delta g}{\partial y^2} + \frac{\partial^2 \Delta g}{\partial z^2} = 0 \tag{5}$$

177
$$\frac{\partial^2 \Delta g}{\partial z^2} = - \frac{\partial^2 \Delta g}{\partial x^2} + \frac{\partial^2 \Delta g}{\partial y^2} \tag{6}$$

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

180

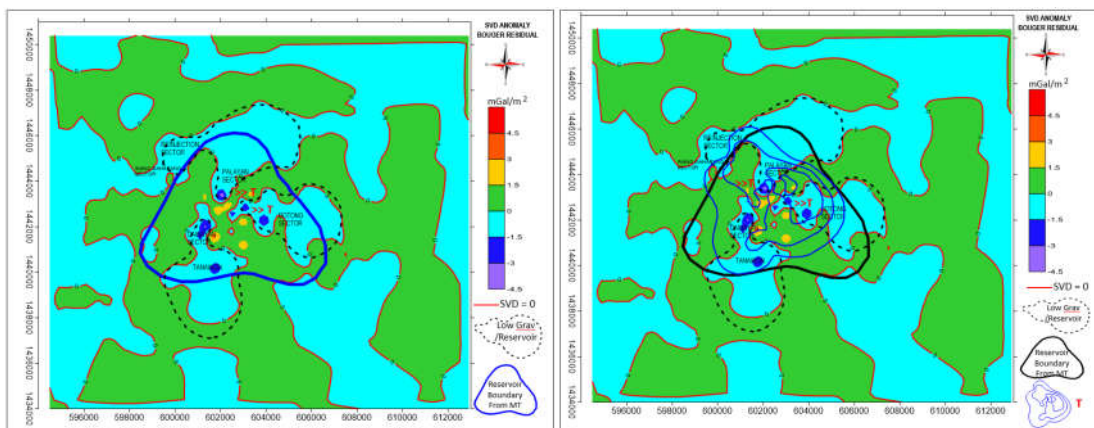
$$\Delta G_{SVD}(\Delta x, \Delta y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \Delta g(x, y) F(x - \Delta x, y - \Delta y) dx dy \tag{7}$$

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

183 This study’s second vertical derivative filter is the Elkins (1951) [16] type. The SVD
 184 map compiled Bouguer Residual anomaly with low residual Bouguer anomaly contours. The
 185 boundaries of the Bac-Man field geothermal prospects from the MT data are shown in Figure
 186 8.

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

195



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

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

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

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

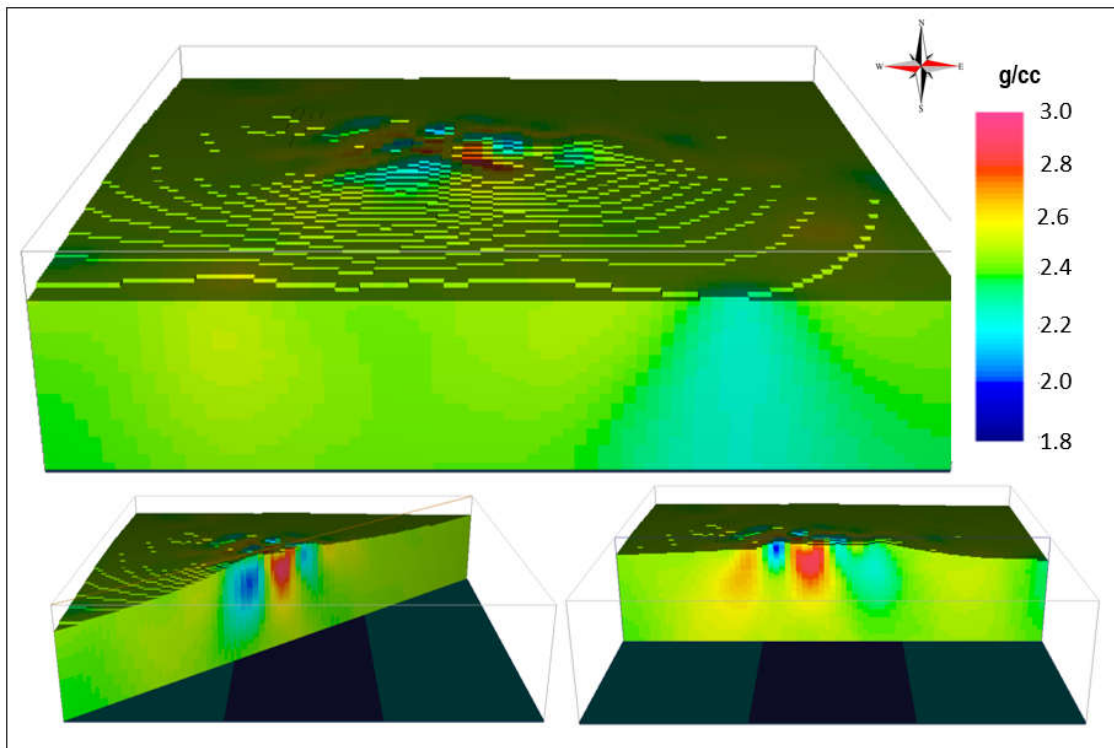
210 A 3D inversion modeling of Bouguer Residual anomaly was carried out to obtain a
211 structural model of the Bac-Man Geothermal Field. The equation used and the calculation of
212 3D inversion modeling is the subsurface model approach composed of prisms with the
213 amount according to measurement area, data grid, thickness, and depth of objects. The
214 calculation of the gravity response for each prism block uses the Plouff (1976) equation [17]:

$$215 \quad g = G\Delta\rho \sum_{i=1}^2 \sum_{j=1}^2 \sum_{k=1}^2 \mu_{ijk} \left[z_k \arctan \frac{x_i y_i}{z_k R_{ijk}} - x_i \log(R_{ijk} + y_i) - y_i \log(R_{ijk} + x_i) \right] \quad (8)$$

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

217 The results of Bouguer Residual anomaly 3D inversion modeling using the Grav3D

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

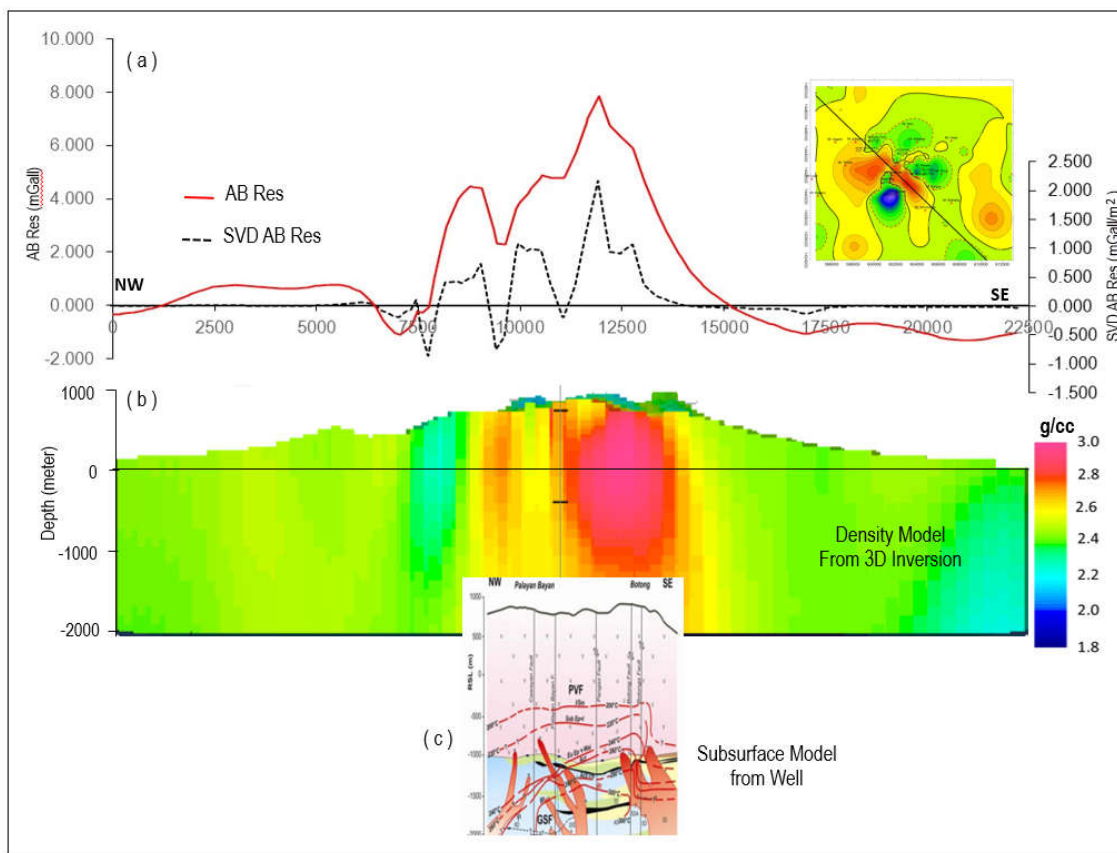


223

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

226 The density distribution model resulting from the 3D Bouguer anomaly residual
227 inversion which is correlated with the cross-sectional temperature model and the intrusion
228 structure on the NW-SE trajectory, is shown in Figure 10. The 3D Bouguer anomaly residual
229 inversion result correlated with the temperature section model [18], and the intrusion
230 structure shows a good correlation. The presence of intrusion is correlated with high density
231 in the area. Likewise, the SVD section indicates that the intrusion is no single but separated

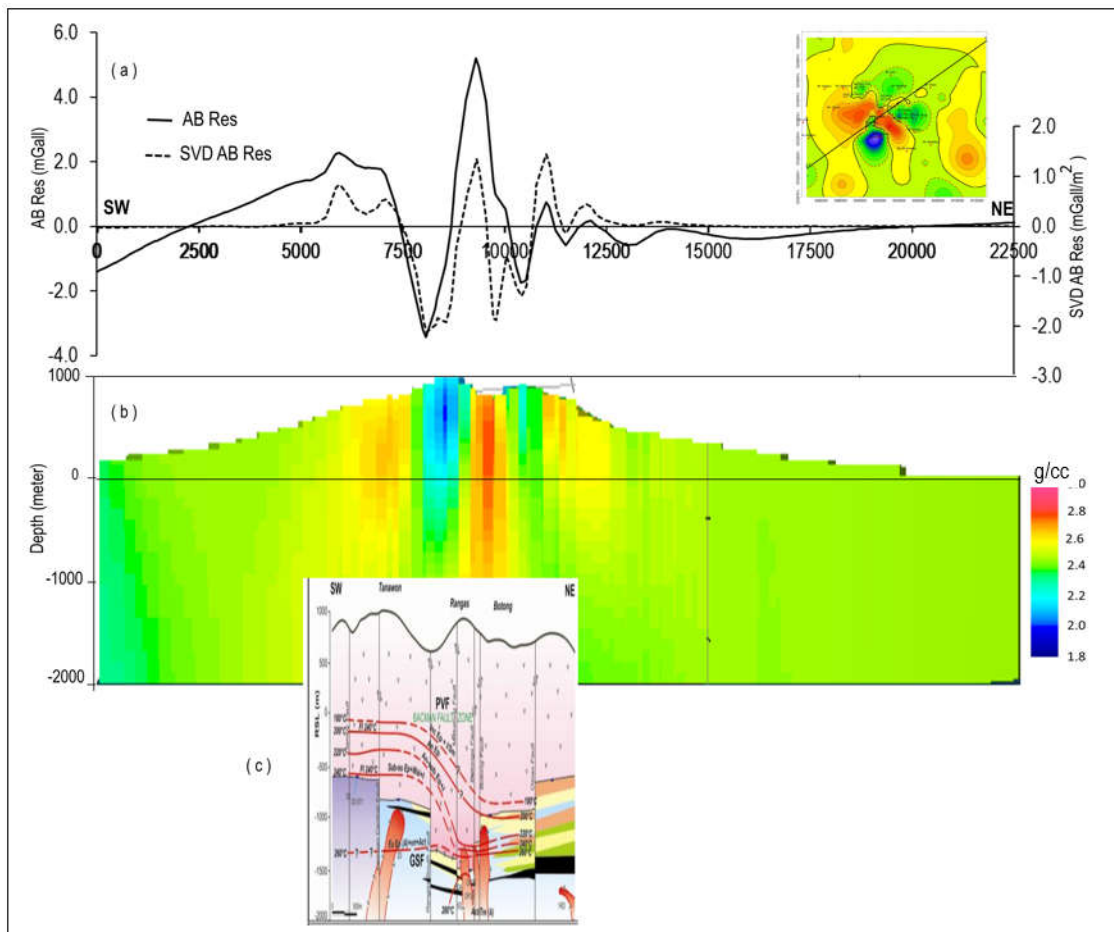
232 into three parts according to the model derived from well data and temperature data.



233

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

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



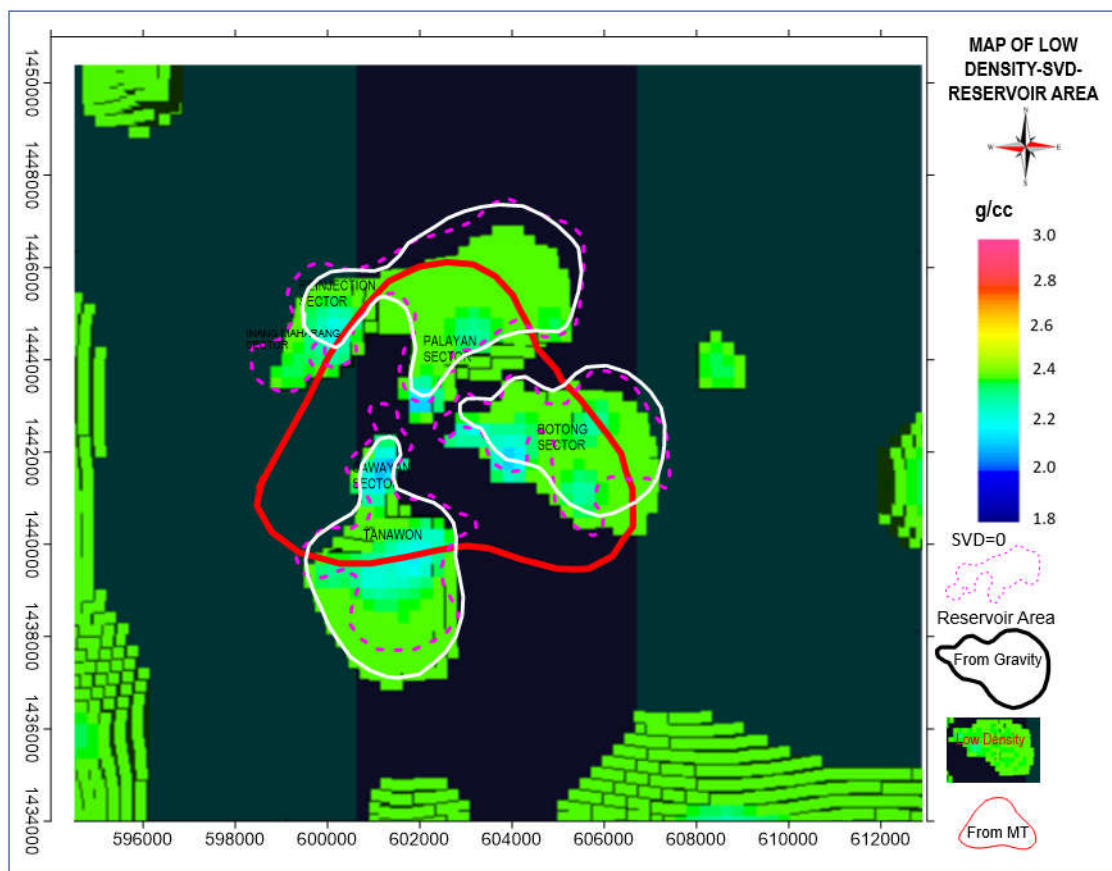
244

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

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

251 The results of the correlation analysis between the cut density distribution models for
 252 density 2.1 g/cc - 2.4 g/cc (interpreted as a geothermal reservoir) and the reservoir prospect
 253 boundary derived from MT indicate that the reservoir locations have similarities. However,
 254 the reservoir area derived from the gravity model is broader and in more detail. The gravity

255 modeling shows that the geothermal reservoir in the Bac-Man field is divided into 3 areas:
 256 the southern part (Cawayan and Tanawon sector), the eastern part (Botong sector), and the
 257 northern part (Palayan-Inang Maharang sector). Each reservoir area is separated by the
 258 presence of fault structures or intrusions in the area. The division of the 3 reservoir areas
 259 follows the well data and the results of reservoir modeling research in the area. That the
 260 geothermal reservoir area of the Bac-Man field is divided into 3 sectors, namely the south
 261 (Cawayan and Tanawon sectors), the east (Botong sector), and the north (the North sector).
 262 Palayan-Inang Maharang) (Figure 12). The reservoir sectors are separated by intrusion in the
 263 area. This is supported by the reservoir temperature in the area with a higher temperature than
 264 the surrounding area.



265

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

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

271

272

273 **5. Conclusions**

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

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

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

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

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

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

301

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308

309 **Acknowledgments**

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

312

313 **References**

- 314 [1] Austria, J. J. C. (2008) *Production Capacity Assessment of the Bacon-Manito*
315 *Geothermal Reservoir, Philippines*.
- 316 [2] Tugawin, R. J. *et al.* (2015) ‘Resistivity Model Based on 2D Inversion of
317 Magnetotelluric Sounding Data in Bacon- Manito, Southern Luzon, Philippines’,
318 *Proceedings World Geothermal Congress 2015*, (April), pp. 1–6.
- 319 [3] Espartinez, C. M. R. and See, F. S. (2005) ‘The BacMan Geothermal Field, Philippines:
320 Geochemical Changes and Challenges After Twenty Years of Operation’, in *World*
321 *Geothermal Congress 2015*, p. 8.
- 322 [4] See, F. S., Fragata, J. J. and Solis, R. P. (2005) ‘The BacMan Geothermal Field ,
323 Philippines : Geochemical Changes and Operational Challenges After Ten Years of
324 Production’, *Proceedings World Geothermal Congress 2005*, (April), pp. 24–29.
- 325 [5] Dimabayao, J. J. T., Rowe, M. C. and Barker, S. (2019) ‘Stable isotope systematics of
326 fluids and epidote in the Bacon-Manito Geothermal Field, Philippines: Indicators of
327 fluid origin and evolution’, *Geothermics*, 80, pp. 31–43. doi:
328 10.1016/j.geothermics.2019.02.009.
- 329 [6] Reyes, A. G., Delfin, M. C. Z. and Bueza, E. L. (1995) ‘Petrological Identification Of
330 Multiple Heat Sources in The Bacon-Manito Geothermal System, Tiie Philippines’, in

- 331 *Proceedings World Geothermal Congress*. Florence, pp. 713–717.
- 332 [7] Lagmay, A. M. F., Tengonciang, A. M. P. and Uy, H. S. (2005) ‘Structural setting of the
333 Bicol Basin and kinematic analysis of fractures on Mayon Volcano, Philippines’,
334 *Journal of Volcanology and Geothermal Research*, 144(1-4 SPEC. ISS.), pp. 23–36. doi:
335 10.1016/j.jvolgeores.2004.11.015.
- 336 [8] Africa, J. R. (2013) *1D Inversion of MT and TEM Data With Application of Soundings
337 From Krýsuvík , Sw-Iceland and a Review of MT/TEM Data From Bac-Man
338 Geothermal Project , Central Philippines*. Reykjavik.
- 339 [9] Layugan, D. B. *et al.* (2005) ‘Magnetotelluric (MT) Resistivity Surveys in Various
340 Geothermal Systems in Central Philippines’, in *Proceedings World Geothermal
341 Congress*. Antalya, pp. 24–29.
- 342 [10] Monasterial, J. L. (2015) *Microgravity Survey in 2009-2010 Around Bacman
343 Geothermal Field, Philippines - Gravity Corrections and Interpretations*. Reykjavik.
- 344 [11] Wellenhof, B. H. and Moritz, H. (2005) *Physical Geodesy, SpringerWienNewYork.
345 Austria: SpringerWienNewYork*.
- 346 [12] Nagy, D. (1966) ‘The prism method for terrain corrections using digital computers’,
347 *Pure and Applied Geophysics PAGEOPH*, 63(1), pp. 31–39. doi: 10.1007/BF00875156.
- 348 [13] Kane, M. F. (1962) ‘A Comprehensive System of Terrain Corrections Using A Digital

- 349 Computer’, *GEOPHYSICS*, XXVII(4), pp. 455–462.
- 350 [14] Bhattacharyya, B. K. and Leu, L. K. (1977) ‘Spectral Analysis of Gravity and Magnetic
351 Anomalies Due To Rectangular Prismatic Bodies.’, *Geophysics*, 42(1), pp. 41–50. doi:
352 10.1190/1.1440712.
- 353 [15] Ghosh, G. K. and Singh, C. L. (2014) ‘Spectral analysis and Euler deconvolution
354 technique of gravity data to decipher the basement depth in the Dehradun-Badrinath
355 area’, *Journal of the Geological Society of India*, 83(5), pp. 501–512. doi:
356 10.1007/s12594-014-0077-3.
- 357 [16] Elkins, T. A. (1951) ‘The second derivative method of gravity interpretation’,
358 *Geophysics*, 16(1), pp. 29–50. doi: 10.1190/1.1437648.
- 359 [17] Plouff, D. (1976) ‘Gravity and Magnetic Fields of Polygonal Prisms and Application to
360 Magnetic Terrain Corrections’, *GEOPHYSICS*, 41(4), pp. 727–741.
- 361 [18] Ramos, S. G. (2002) ‘Potential Constraints to The Development of The Rangas Sector
362 Based On Petrologic Evaluation Of The Bacman Geothermal Field, Philippines’, in
363 *27th Workshop on Geothermal Reservoir Engineering*. Stanford.
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1 **Reservoir Identification of Bac-Man Geothermal Field Based on**
2 **Gravity Anomaly Analysis and Modeling**

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8 **Abstract**

9 The Bac-Man gravity modeling was carried out to describe the geological structures that
10 control the geothermal system and estimate the area of the geothermal reservoir. A total of
11 125 data points were used to produce a complete Bouguer anomaly map of the area. The
12 gravity data are separated into regional and residual components to enhance the structural
13 features of the sedimentary and basement rocks in the study area. Gravity data were analyzed
14 using gradient interpretation techniques for edge detection, such as vertical descent. To
15 perform three-dimensional (3-D) modeling, a 5 × 5 km volume and a depth of 2.5 km were
16 selected. This study presents the interpretation of various gravity anomaly maps and 3-D
17 inversion models. The interpretation of the vertical derivative of the gravity data indicates the
18 presence of a low gradient anomaly. The anomaly map is used to identify several faults or
19 intrusions compared to the faults or intrusions that are mapped. The 3-D model reveals that
20 there are 3 geothermal reservoirs, and the average block density value is 2.25 g/cc. These
21 reservoirs are spread over the Southern area (Cawayan and Tanawon Sector), East area
22 (Boton Sector), and Palayan-Inang Maharang area. Faults or rock intrusions are the limiting
23 factors for the three existing reservoirs. The results obtained from this study will lead to a
24 better understanding of the geothermal system in the study area, in particular, reservoir

25 boundaries, and assist in future geothermal exploration.

26

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

28

29 **1. Introduction**

30 Geothermal energy is a natural source of heat contained within the Earth, and it can be
31 extracted and used to generate electricity or for heating applications. A geothermal system
32 consists of three elements: a heat source, reservoir rock, and caprock [1]. The Bacon - Manito
33 (Bac-Man) geothermal field is located in the Podcol mountains on Luzon, about 350 km
34 southeast of Manila. The exploration of the Bac-Man geothermal field has been carried out
35 since 1977. The reservoir model has 23 km², 1500 m depth, and a temperature of 240°C to
36 320°C. Based on geological and geophysical data, a conceptual model of the Bac-Man
37 geothermal system has been made [2]. Tugawin et al. (2015) [3] carried out 2D
38 magneto-telluric (MT) inversion modeling in the Bac-Man field, which shows the existence
39 of 3 (three) geothermal reservoir areas, namely Palayan Bayan, Tikolob, and Malobago areas.
40 These results follow the results of data interpretation of resistivity vertical electric sounding
41 (VES) [4] and Schlumberger Resistivity Traversing (SRT). The reservoir in the Palayan
42 Bayan area has been in production since 1993, while the Tikolob prospect is on the west side
43 of the Bac-Man field, separate from the Palayan Bayan system [3].

44 The gravity method is applied to determine the geometry of the geothermal reservoir and
45 describe the geological structures that control the system. The gravity method is generally
46 used to describe the subsurface structures that control geothermal systems in geothermal
47 exploration. Certain geothermal reservoirs and their fluid content cause density differences
48 between the geothermal reservoir and the surrounding rock. The basis of the gravity method
49 is the density contrast in the rock. Gravity studies in various regions of the world have
50 yielded valuable results for geothermal exploration, such as the investigation of basement
51 topography in geothermal fields [5]; magma chambers and intrusion bodies associated with
52 heat source from the geothermal system; and faults delineation and fracture zones
53 corresponding to geothermal system reservoirs [6]. Therefore, the gravity method is one of

54 the most economical geophysical methods for modeling geothermal systems. The gravity
55 anomaly interpretation procedure consists of many techniques depending on the quality of the
56 data set and the purpose of the analysis [7]. Gravity anomaly maps are generally analyzed
57 using multiple linear transformations, directional derivative-based techniques, and inverse
58 modeling techniques. Gravity data in the form of a Bouguer anomaly map is used to describe
59 the study area's geological characteristics and subsurface structures. Observations of gravity
60 at the Earth's surface reflect the superimposed effects of broader and deeper mass variations
61 as well as shallower and more localized changes near the point of observation. This research
62 focuses on the 3D modeling of gravity data to estimate the geothermal reservoir extent and
63 understand the subsurface structure of the geothermal system.

64

82 **Figure 1.** Map of the study area location and faults structure in the Bac-Man geothermal field

83 [3][10].

84

85 The Bac-Man geothermal system is divided into two regions, namely the western and
86 eastern parts of Bac-Man. The eastern part of Bac-Man is further divided into the North
87 Namito lowlands and the Podcol highlands. The Podcol plateau can be divided into eight
88 geographic sectors: Inang Maharang, Putting Bato, Palayan Bayan, Cawayan, Tanawon,
89 Osiao, Bangas, and Botong [9]. Neutral chloride hot springs with a temperature of 89 °C - 96
90 °C are found in the lowlands of Manito. In Cawayan and Pangas, Solfatara is found in West
91 Bac-Man, cold to warm, and cold SO₄ springs are found.

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

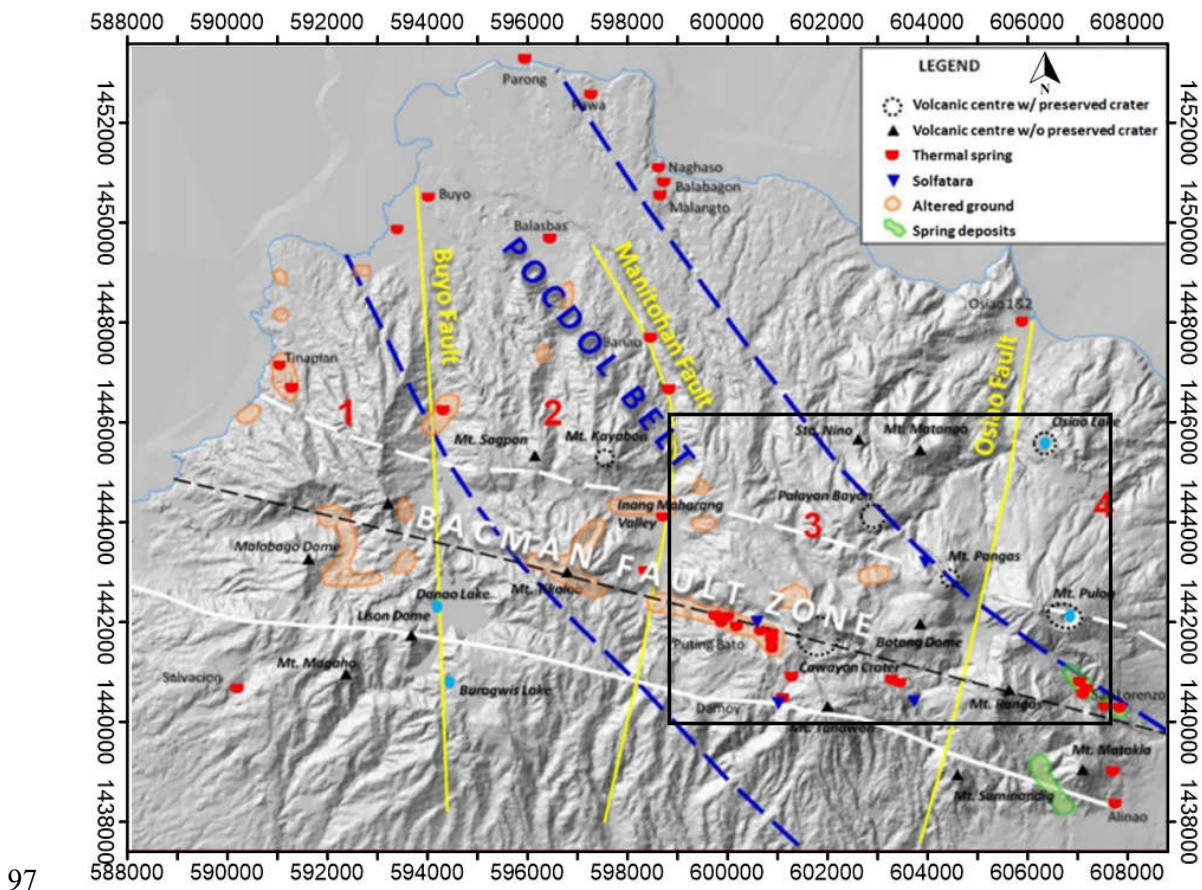
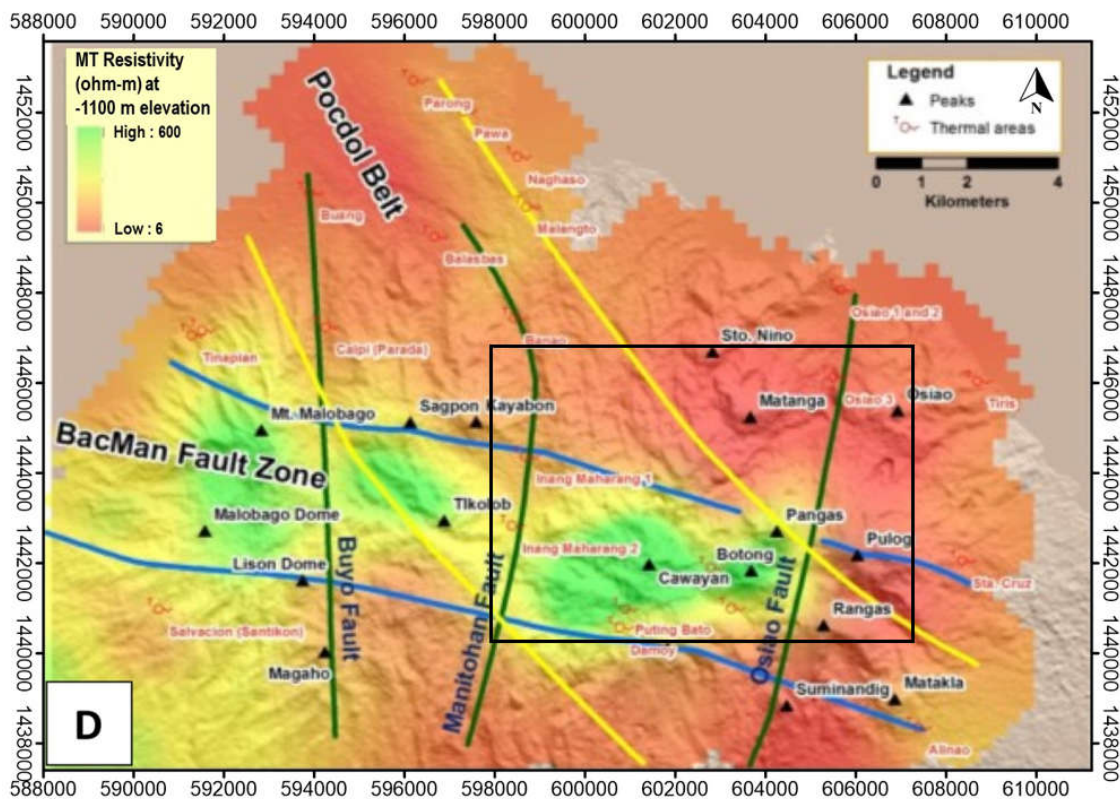


Figure 2. Structure and manifestations at the Bac-Man geothermal field [10].

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).

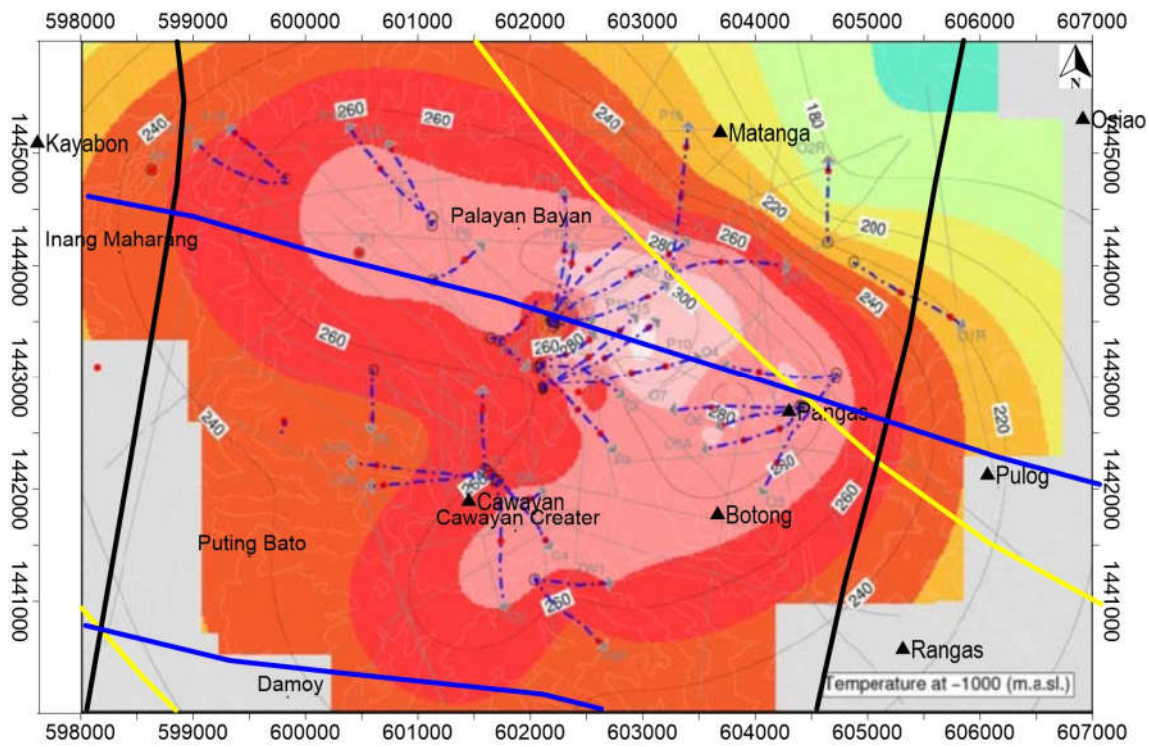


106

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

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

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



117

118

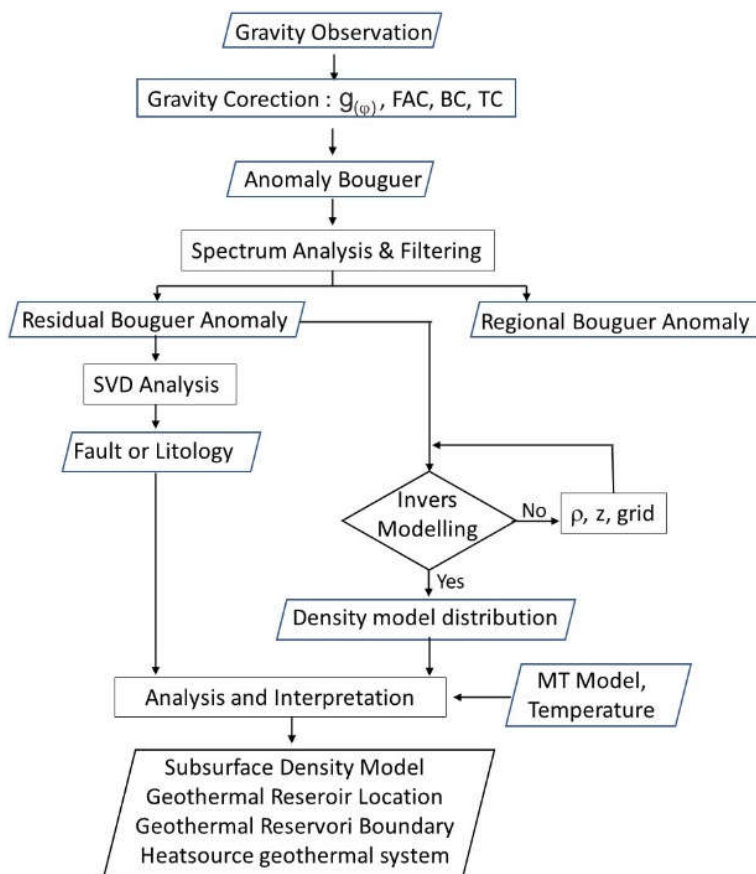
Figure 4. Temperature contour map at a depth of -1000 meters from MSL [2].

119

120

121 **3. Methods**

122 The gravity data used in this study were 125 points: measurements from 2009 to 2010
 123 [12]. Processing gravity data includes determination of surface density using the Parasnis and
 124 Nettleton method, Bouguer anomaly, Bouguer anomaly filtering, Bouguer anomaly
 125 separation, vertical gradient analysis Bouguer anomaly, and Bouguer anomaly modeling.
 126 Analysis and interpretation were carried out to verify the Bac-Man geothermal reservoir area
 127 and structures in the area. The analysis and interpretation are carried out by correlating the
 128 gravity model with geological data, well data, and other geophysical data. The research flow
 129 carried out is shown in Figure 5.



130

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

132 Density determination was carried out using the Parasnis method and the Nettleton

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

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

$$141 \quad g_{\phi} = 978.032,7(1 + 5.3024 \cdot 10^{-3} \sin^2 \phi - 5,8 \cdot 10^{-6} \sin^2 2\phi) \quad (1)$$

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

$$145 \quad g_{\phi,h} = g_{\phi} + \frac{\partial g_{\phi}}{\partial h} h \quad (2)$$

$$146 \quad \frac{\partial g_{\phi}}{\partial h} = -\frac{2g_{\phi}}{a} (1 + f + m - 2f \sin^2 \phi) = -0,308 \text{ mGal/m} \quad (3)$$

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

$$149 \quad Bc = 2\pi G\rho h = 0.04193\rho h \quad (4)$$

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

151 Terrain corrections were calculated using a combination of the equations given by Nagy
 152 (1966) [14] and Kane (1962) [15]. In the calculation of terrain correction, the topographic

153 model is approached with a prism-shaped arrangement of objects measuring 1 km x 1 km
 154 with a height following the area's topography up to a radius of 50 km. The topographical data
 155 used is DEM data taken from INA Geoportal [16].

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

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

$$172 \quad F(g) = 2\pi\gamma m \frac{e^{k|(\tau_0 - z_1)}}{|k|} \quad (5)$$

173 The energy spectrum of the equation is:

$$174 \quad E(k) = \frac{4\pi^2 \gamma^2 \rho^2}{|k|^2} e^{-2|k|z} \quad (6)$$

$$175 \quad \log E(k) = \log(4\pi^2 \gamma^2 \rho^2) - 2|k|z - 2 \log|k| \quad (7)$$

176
$$\log E(k) = \log A - 2|k|z \quad (8)$$

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

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

183
$$\Delta g_{R,g}(i,j) = \frac{(\Lambda g(i-n,j-n) + \dots + \Lambda g(i,j) + \dots + \Lambda g(i+n,j+n))}{N} \quad (9)$$

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

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

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

193
$$\nabla^2 \Delta g = 0 \text{ atau } \frac{\partial^2 \Delta g}{\partial x^2} + \frac{\partial^2 \Delta g}{\partial y^2} + \frac{\partial^2 \Delta g}{\partial z^2} = 0 \quad (10)$$

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

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].

$$\Delta G_{svd}(\Delta x, \Delta y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \Delta g(x, y) F(x - \Delta x, y - \Delta y) dx dy \quad (12)$$

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]:

213
$$g = G\Delta\rho \sum_{i=1}^2 \sum_{j=1}^2 \sum_{k=1}^2 \mu_{ijk} \left[z_k \arctan \frac{x_i y_i}{z_k R_{ijk}} - x_i \log(R_{ijk} + y_i) - y_i \log(R_{ijk} + x_i) \right] \quad (8)$$

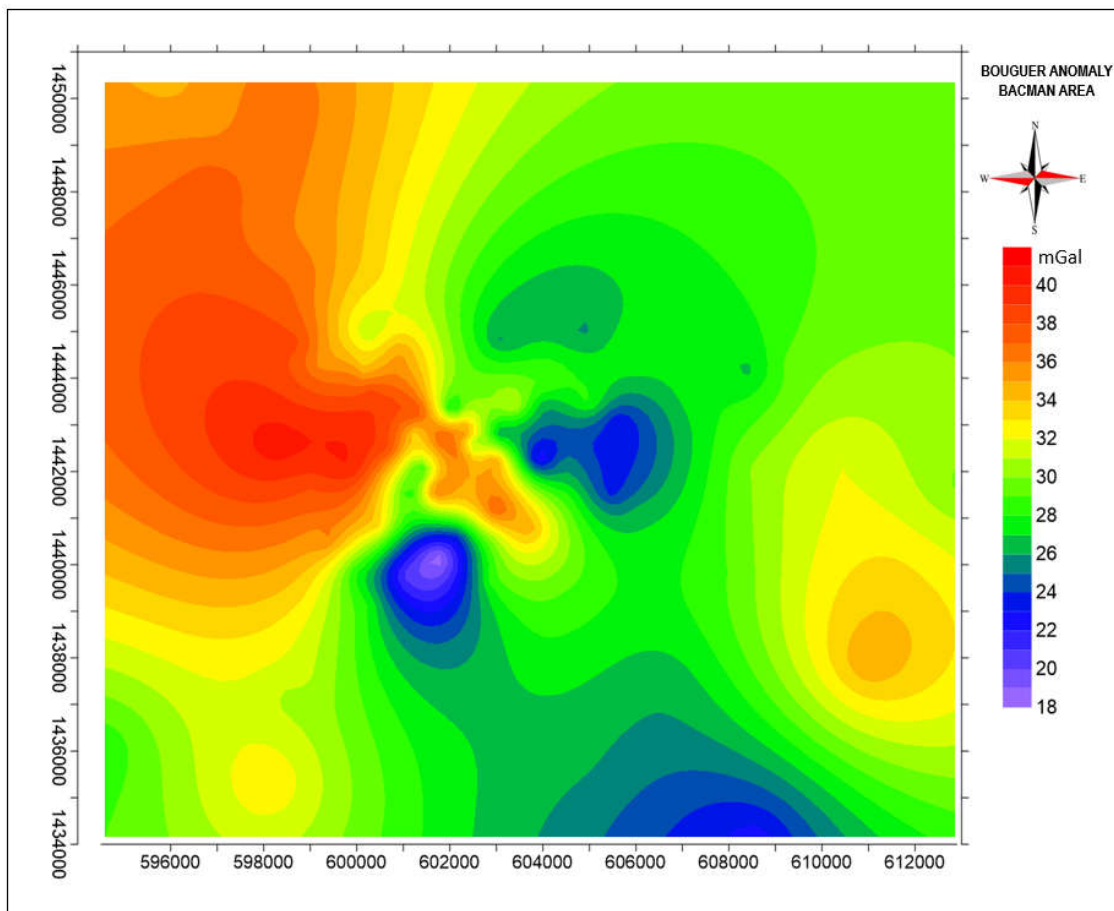
214 Where: $R_{ijk} = \sqrt{x_i^2 + y_j^2 + z_k^2}$; $\mu_{ijk} = (-1)^i (-1)^j (-1)^k$

215

216

217 **4. Result and Discussions**

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

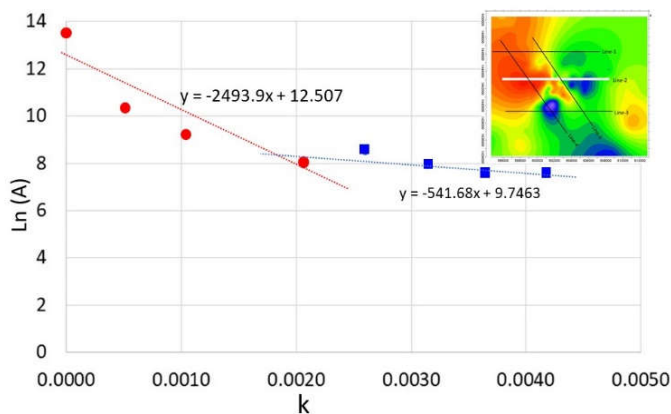


223

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

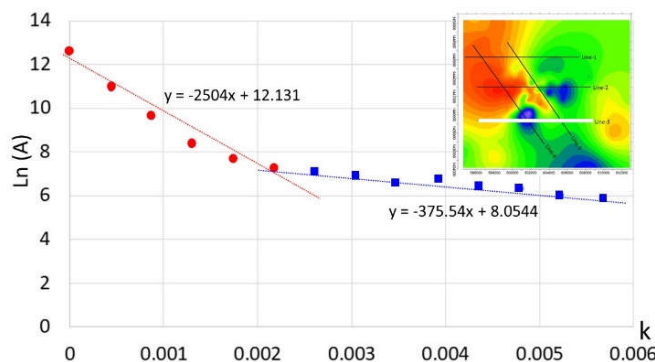
225 The spectrum analysis was carried out by cross-sectioning the Bouguer anomaly as
226 many as 5 trajectories with a point interval of 250 m (Figure 7). The spectrum analysis result
227 from 5 lines of Bouguer anomaly shows that the average regional Bouguer anomaly depth is

228 2500 meters (Figure 8). Based on these results, the separation of regional Bouguer anomalies
 229 and residual Bouguer anomalies is a moving average filter with a 5 km x 5 km window width.



230

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

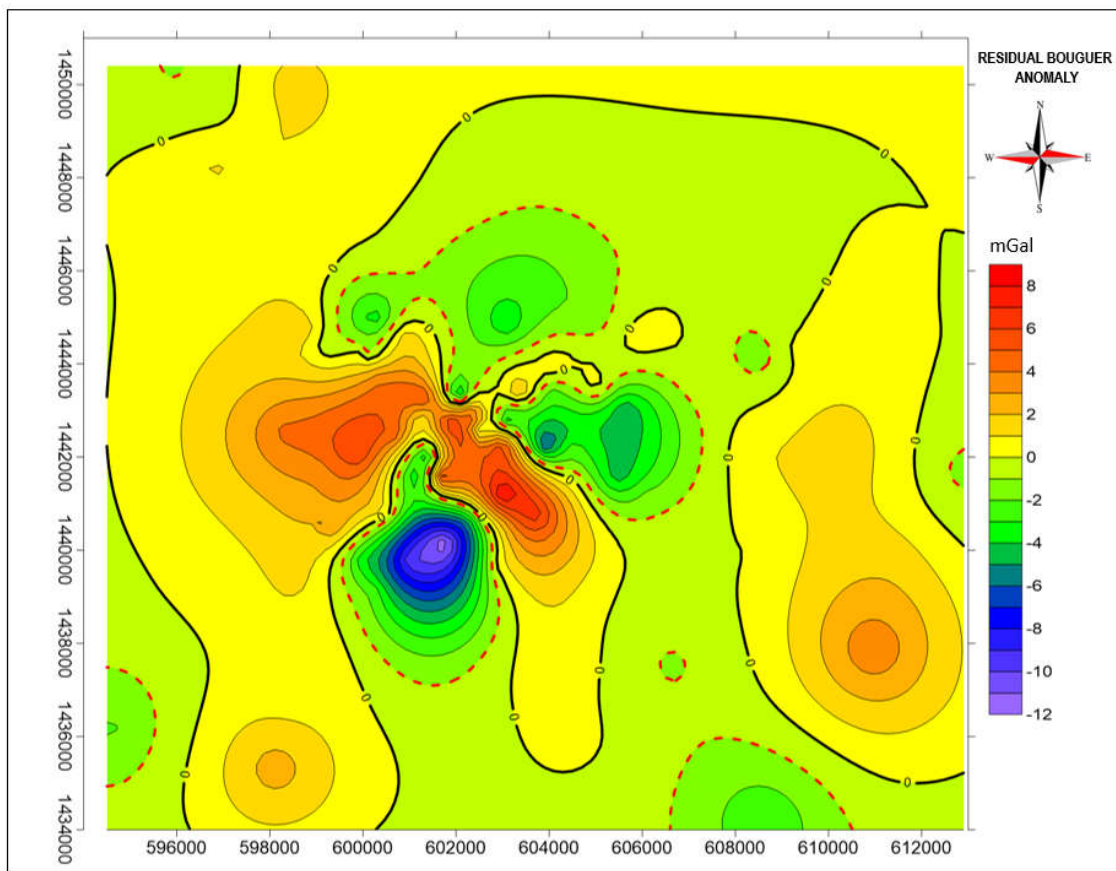


234

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

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

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



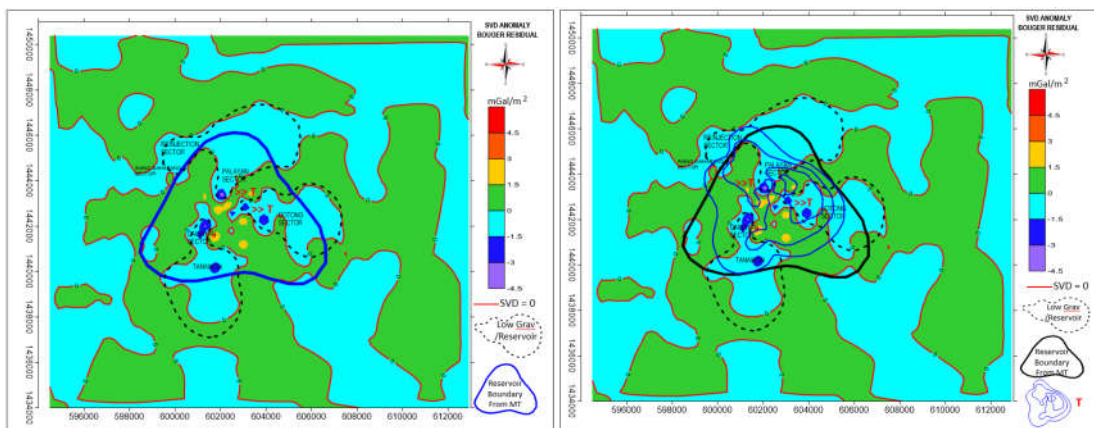
248

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

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

253 Data compilation of low Bouguer Residual anomaly, Bouguer Residual anomaly SVD,

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



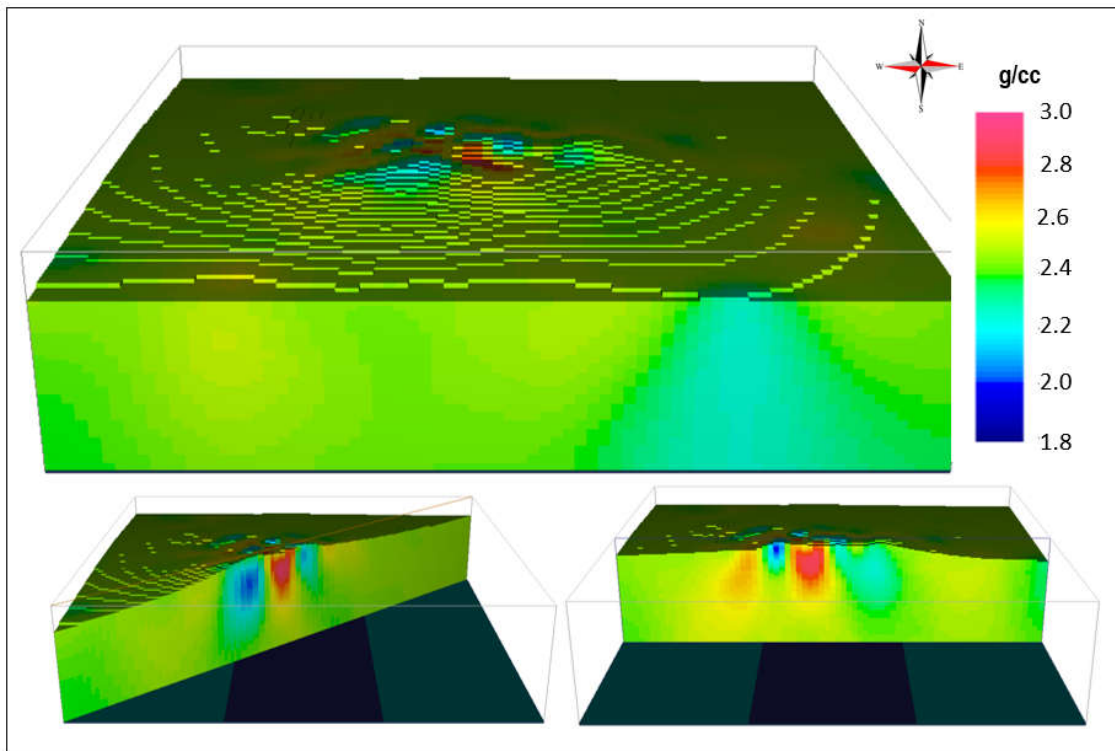
261

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

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

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

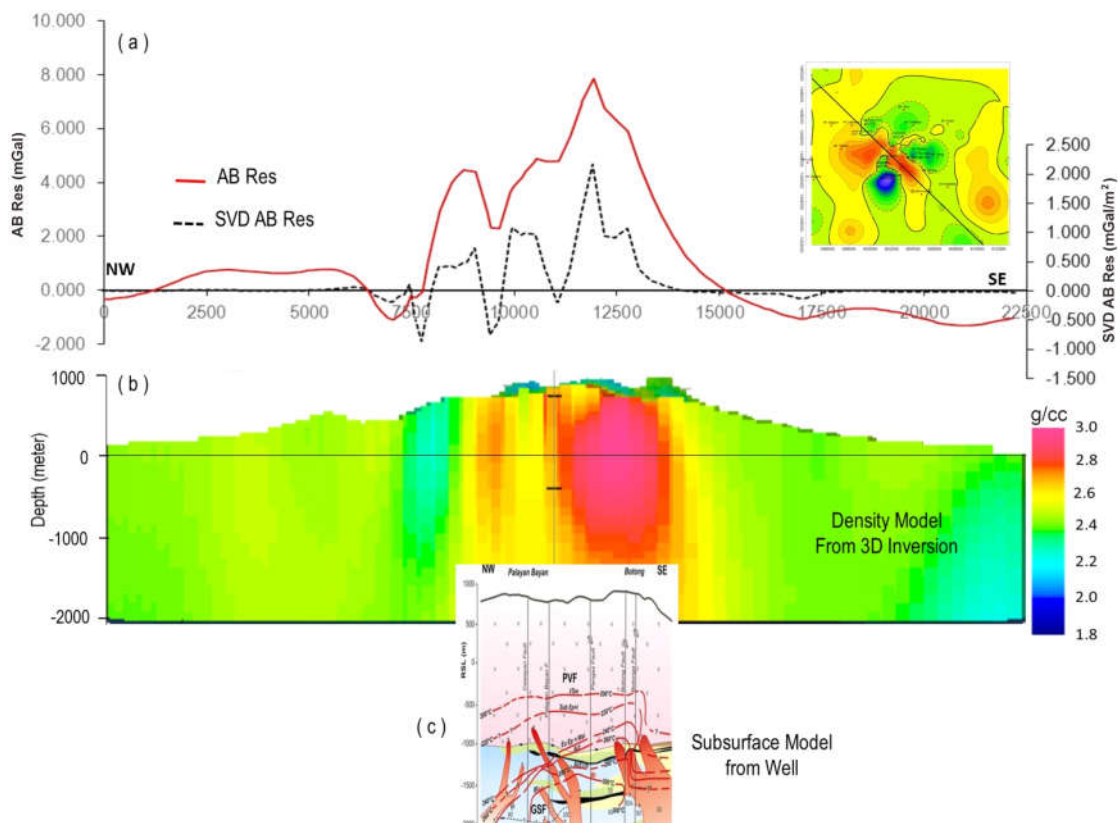
280 The results of Bouguer Residual anomaly 3D inversion modeling using the Grav3D
281 program are shown in Figure 11. The 3D inversion modeling result, density distribution
282 model, shows high and low density in the middle of the study area with a value of 2 g/cc to
283 2.9 g/cc. The model is then carried out by slicing the selected paths, which will be compared
284 and correlated with temperature data models, MT cross-sectional models, structural models,
285 and others to obtain a structural model.



286

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

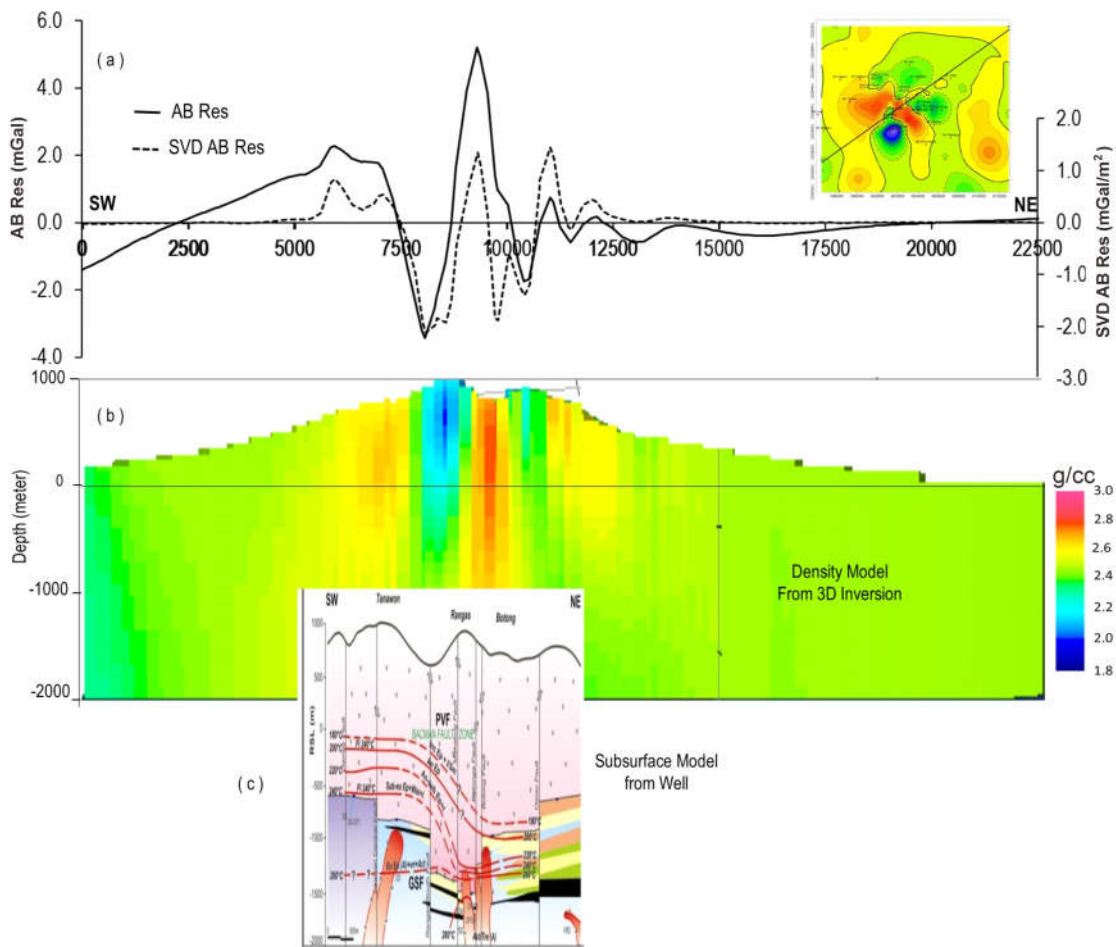
289 The density distribution model resulting from the 3D Bouguer anomaly residual
 290 inversion which is correlated with the cross-sectional temperature model and the intrusion
 291 structure on the NW-SE trajectory is shown in Figure 12. The 3D Bouguer anomaly residual
 292 inversion result correlated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



296

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

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



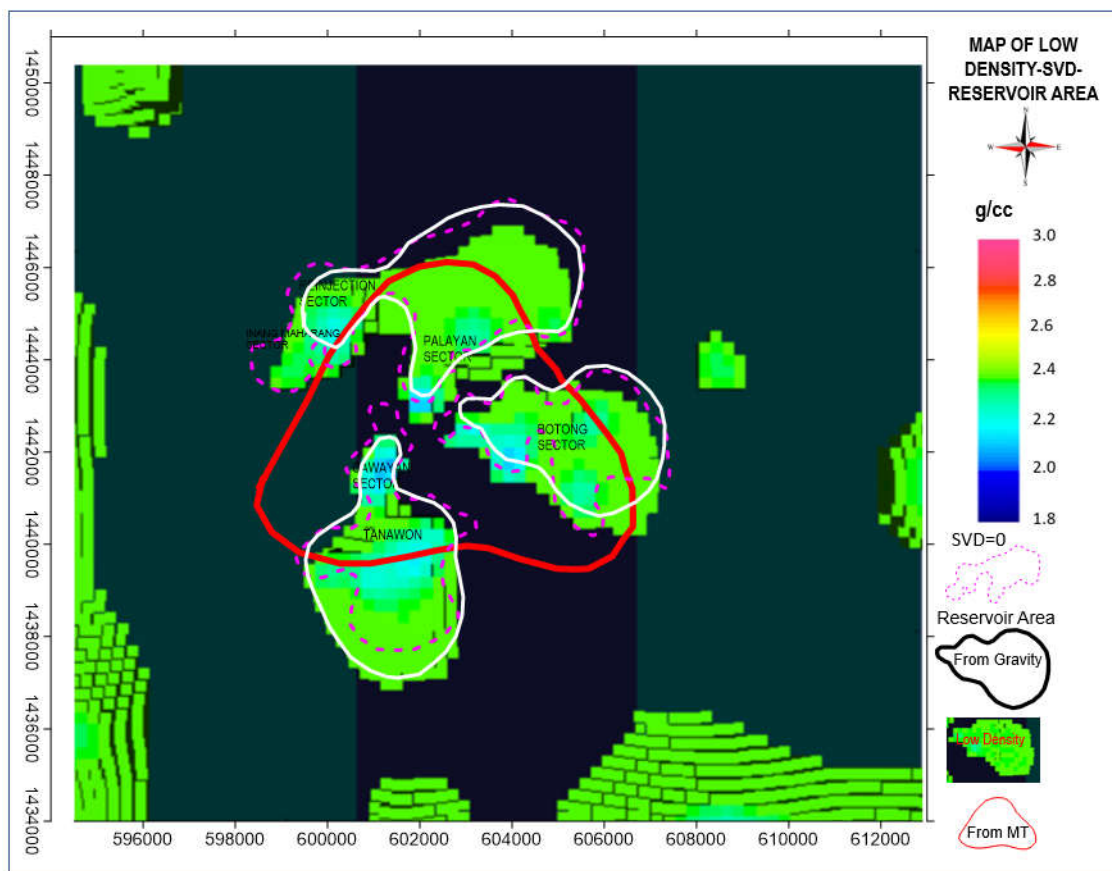
307

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

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

314 The results of the correlation analysis between the cut density distribution models for
 315 density 2.1 g/cc - 2.4 g/cc (interpreted as a geothermal reservoir) and the reservoir prospect
 316 boundary derived from MT indicate that the reservoir locations have similarities. However,
 317 the reservoir area derived from the gravity model is broader and in more detail. The gravity

318 modeling shows that the geothermal reservoir in the Bac-Man field is divided into 3 areas:
319 the southern part (Cawayan and Tanawon sector), the eastern part (Botong sector), and the
320 northern part (Palayan-Inang Maharang sector). Each reservoir area is separated by the
321 presence of fault structures or intrusions in the area. The division of the 3 reservoir areas
322 follows the well data and the results of reservoir modeling research in the area. That the
323 geothermal reservoir area of the Bac-Man field is divided into 3 sectors, namely the south
324 (Cawayan and Tanawon sectors), the east (Botong sector), and the north (the North sector).
325 Palayan-Inang Maharang) (Figure 14). The reservoir sectors are separated by intrusion in the
326 study area and supported by the reservoir temperature in the area with a higher temperature
327 than the surrounding area.



328

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

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

333

334

335 **5. Conclusions**

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

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

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

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

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

360 4. Detailed reservoir boundaries, especially the outer reservoir boundaries, suggest

361 adding more detailed gravity measurement points in the north, east, and south.

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370 **Acknowledgments**

371 We want to thank all those who have helped implement this research, especially the

372 Geophysical Engineering Department, Faculty of Engineering, University of Lampung.

373

374 **References**

- 375 [1] Zarrouk, S. J. and Mclean, K. (2019) *Geothermal Well Test Analysis*.
- 376 [2] Austria, J. J. C. (2008) “Production Capacity Assessment of the Bacon-Manito
377 Geothermal Reservoir, Philippines”.
- 378 [3] Tugawin, R. J., Rigor, D. M., Los Baños, C. E. F., and Layugan, D. B. (2015)
379 “Resistivity Model Based on 2D Inversion of Magnetotelluric Sounding Data in
380 Bacon- Manito, Southern Luzon, Philippines,” *Proc. World Geotherm. Congr. 2015*, no.
381 April, pp. 1–6.
- 382 [4] Abiye, T. A. and Haile, T. (2008) “Geophysical exploration of the Boku geothermal
383 area, Central Ethiopian Rift,” *Geothermics*, vol. 37, no. 6, pp. 586–596, doi:
384 10.1016/j.geothermics.2008.06.004.
- 385 [5] Soengkono, S. (2011) “Deep interpretation of gravity and airborne magnetic data of
386 the Central Taupo volcanic zone,” in *New Zealand Geothermal Workshop Proceedings*
387 *(21-23 November 2011)*, no. 1955.
- 388 [6] Represas, P. *et al.* (2013) “Interpretation of gravity data to delineate structural features
389 connected to low-temperature geothermal resources at Northeastern Portugal,” *J. Appl.*
390 *Geophys.*, vol. 92, pp. 30–38, doi: 10.1016/j.jappgeo.2013.02.011.
- 391 [7] Hinze, W. J., von Frese, R. R. B., and Saad, A. (2013) *Gravity and magnetic*

- 392 *exploration: principles, practices and exploration*. Cambridge University Press.
- 393 [8] Dimabayao, J. J. T., Rowe, M. C., and Barker, S. (2019) “Stable isotope systematics of
394 fluids and epidote in the Bacon-Manito Geothermal Field, Philippines: Indicators of
395 fluid origin and evolution,” *Geothermics*, vol. 80, pp. 31–43, doi:
396 10.1016/j.geothermics.2019.02.009.
- 397 [9] Reyes, A. G., Delfin, M. C. Z., and Bueza, E. L. (1995) “Petrological Identification Of
398 Multiple Heat Sources In The Bacon-Manito Geothermal System, Tiie Philippines,” in
399 *Proceedings World Geothermal Congress*, pp. 713–717.
- 400 [10] Africa, J. R. (2013) “1D Inversion of MT and TEM Data With Application of
401 Soundings From Krýsuvík , Sw-Iceland and a Review of MT/TEM Data From
402 Bac-Man Geothermal Project , Central Philippines,” Reykjavik.
- 403 [11] Layugan, D. B., Rigor, D. M., Apuada, N. A., Olivar, R. E. R., City, M. and Leyte, S.
404 (2005) “Magnetotelluric (MT) Resistivity Surveys in Various Geothermal Systems in
405 Central Philippines,” in *Proceedings World Geothermal Congress*, vol. 2000, no. April,
406 pp. 24–29.
- 407 [12] Monasterial, J. L. (2015) “Microgravity Survey in 2009-2010 Around Bacman
408 Geothermal Field, Philippines - Gravity Corrections and Interpretations,” Reykjavik.
- 409 [13] Wellenhof, B. H. and Moritz, H. (2005) *Physical Geodesy*. Austria:

- 410 SpringerWienNewYork.
- 411 [14] Nagy, D. (1966) “The prism method for terrain corrections using digital computers,”
- 412 *Pure Appl. Geophys. PAGEOPH*, vol. 63, no. 1, pp. 31–39, doi: 10.1007/BF00875156.
- 413 [15] Kane, M. F. (1962) “A Comprehensive System of Terrain Corrections Using A Digital
- 414 Computer,” *GEOPHYSICS*, vol. XXVII, no. 4, pp. 455–462.
- 415 [16] Ina-Geoportal, “DEM Data.” <https://tanahair.indonesia.go.id/portal-web> (accessed Feb.
- 416 10, 2021).
- 417 [17] Bhattacharyya, B. K. and Leu, L. K. (1977) “Spectral Analysis of Gravity and
- 418 Magnetic Anomalies Due To Rectangular Prismatic Bodies.,” *Geophysics*, vol. 42, no.
- 419 1, pp. 41–50, doi: 10.1190/1.1440712.
- 420 [18] Ghosh, G. K. and Singh, C. L. (2014) “Spectral analysis and Euler deconvolution
- 421 technique of gravity data to decipher the basement depth in the Dehradun-Badrinath
- 422 area,” *J. Geol. Soc. India*, vol. 83, no. 5, pp. 501–512, doi:
- 423 10.1007/s12594-014-0077-3.
- 424 [19] Blakely, R. J. (1995) *Potential Theory in Gravity and Magnetic Applications*.
- 425 Cambridge University Press.
- 426 [20] Setiadi, I., Styanta, B., and Widijono, B. S. (2010) “Delineasi cekungan sedimen
- 427 sumatra selatan berdasarkan analisis data gaya berat,” *J. Geol. dan Sumber Daya*

- 428 *Miner.*, vol. 20, no. April, pp. 93–106.
- 429 [21] Elkins, T. A. (1951) “The second derivative method of gravity interpretation,”
430 *Geophysics*, vol. 16, no. 1, pp. 29–50, doi: 10.1190/1.1437648.
- 431 [22] Zhu, Z., Lei, X., Xu, N., Shao, D., Jiang, X., and Wu, X. (2020) “Integration of 3D
432 geological modeling and geothermal field analysis for the evaluation of geothermal
433 reserves in the Northwest of Beijing Plain, China,” *Water (Switzerland)*, vol. 12, no. 3,
434 doi: 10.3390/w12030638.
- 435 [23] Januari, E., Santoso, D., and Ulum, A. F. M. (2019) “Gravity Survey in Pandan
436 Mountain - East Java , Indonesia Gravity Survey in Pandan Mountain – East Java ,
437 Indonesia,” in *IOP Conf. Series: Journal of Physics: Conf. Series*, p. 11, doi:
438 10.1088/1742-6596/1204/1/012006.
- 439 [24] Adhi, A., Suryanto, W., and Sarkowi, M. (2018) “GRAV3D Validation using
440 Generalized Cross- Validation (GCV) Algorithm by Lower Bounds Approach for 3D
441 Gravity Data Inversion,” *Sci. J. Informatics*, vol. 5, no. 2, pp. 271–277.
- 442 [25] Plouff, D. (1976) “Gravity and Magnetic Fields of Polygonal Prisms and Application
443 to Magnetic Terrain Corrections,” *GEOPHYSICS*, vol. 41, no. 4, pp. 727–741.
- 444 [26] Telford, W. M., Geldart, L. P., and Sheriff, R. E. (1990) *Applied Geophysics: Second*
445 *Edition*. Cambridge University Press.

- 446 [27] Ramos, S. G. and Santos, B. N. E. A. (2012) “Updated Hydrogeological Model of the
447 Bacon-Manito Geothermal Field , Philippines,” in *Proceedings of 37th Stanford*
448 *Geothermal Workshop*, pp. 1–4.
449
450