3D gravity data inversion modeling for subsurface identification of Gondang area, Bojonegoro regency

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Abstract. Gondang area had experienced an earthquake of a 4.2 magnitude in the mid-2015, showing that tectonics in the area are active. Also, the Gondang area has a mountain categorized as one of the eleven earth thermal prospects in East Java, i.e., Pandan Mountain. It is exciting to study the subsurface structures of the Gondang area. To date, precedent studies only present geological reviews of the surface. This study presents information on subsurface structure conditions based on gravity. The technique used was 3D inversion modeling with Single Value Decomposition (SVD) inversion. The study’s primary data were gravity data from 61 points with a study area of 6.9 km x 5.5 km from 3-10 September 2019. Secondary data utilized were Bojonegoro geological map and local geological studies. From 3D modeling results, slicing was conducted for five cross-sections based on density contrast. Then, the subsurface 2D cross-section results were interpreted for each section. Subsurface model results illustrated density distributions in south, northeast, and northwest areas with high densities ranging from 2.8 g/cc to 3.0 g/cc in >500 m depths. Meanwhile, the north, southwest, and southeast areas had low densities ranging from 1.70 g/cc to 2.0 g/cc in >500 m depths. Furthermore, it indicates the continuity of andesite intrusion from the south to the study site in >500 m depths.

1. Introduction
Gondang Area, Bojonegoro Regency, East Java Province is where Pandan Mountain is located with geothermal manifestations of hot springs and mud pools [1]. Heat sources in Pandan Mountain’s geothermal system are estimated to correlate with plutonic stone bodies associated with magmatism activities generating the youngest volcanic stones. Based on Bojonegoro Regency’s regional geology, Pandan Mountain has intrusions where hot springs originated. One successful method to analyze and interpret subsurface structures is the gravity method with the correlation between Bouguer anomaly and regional geology [2].

The gravity method involves variations of earth’s gravity caused by subsurface stone density differences. Subsurface regions have different densities from the surrounding, contributing to gravity value deviations known as gravity anomaly. In geothermal exploration, the gravity method is employed in the preliminary survey stage to understand subsurface geological conditions better.

This study generated subsurface structure delineation in a 3D model surrounding the object interest. The modeling was conducted by 3D inversion against residual anomaly data, combining two inversion methods, i.e., Singular Value Decomposition and Occam inversion. Modeling results were density value distributions to identify the highest anomaly as intrusion stones and the lowest anomaly as the fault zone. Then, the density cross-section model was analyzed based on geological information and previous geophysics study results to generate a more accurate subsurface model interpretation.

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2. Method

2.1. Data Acquisition
The study’s data were primary data from the gravity method measurement results in the Gondang area, Bojonegoro Regency using Scintrex CG-5. Data collection was carried out in 61 points distributed across the study site with a 6900 x 5500-meter data collection area.

2.2. Pre-Processing Data
After obtaining field data, the authors applied drift correction, observational gravity value calculation, normal gravity or latitude correction calculation, free air correction calculation, simple Bouguer anomaly calculation, complete Bouguer anomaly calculation, and terrain correction calculation using Ms Excel. In generating excellent Bouguer anomaly values, one should calculate Bouguer density using the Parasnis method. The Parasnis method was sought by illustrating the graph between free air anomaly (FAA) in the Y-axis and FAC in the X-axis, then obtaining the linear regression value. This regression value is then used as the Parasnis density value. Then, the spectrum analysis was conducted to obtain regional and residual anomalies’ depths. This analysis was carried out in Oasis Montaj 8.4 and Ms Excel on the six measurement paths. Each path produced was spectrum-analyzed in Ms Excel using the L-curve graph principle, then be plotted. This graph was generated by using complete Bouguer anomaly data or CBA. Then, Fast Fourier Transform (FFT) was applied to CBA data, aided by the Fourier analysis feature in Ms Excel. After FFT, wave number values (k) and amplitudes (ln A) were calculated.

2.2.1 Filter Moving Average
Filter Moving Average generated the separation of regional and residual anomalies from the CBA map. This separation used window width results from the spectrum analysis.

2.2.2 Three-Dimensional Modeling
In this study, the 3D inversion modeling was carried out using Grablox 2.1 software [3] with inputs of residual anomalies (*.dat) and predetermined initial model (*.inp) to obtain outcomes of two-dimensional (2D) and three-dimensional (3D) density cross-sectional models. The 2D cross-section is a model incision perpendicular to the X- and Y-axis. The 3D model is a model incision perpendicular to the Z-axis (based on the depth) and overall model view in the major block. To display and edit modeling results, Bloxer 1.6 software was employed. The model displayed in Bloxer 1.6 had a format (*.inp), which was the final inversion result in Grablox 2.1 software [3]. Then, both cross-sectional (2D and 3D) were interpreted qualitatively and quantitatively.
2.3. Data Interpretation
The qualitative interpretation was conducted on several 2D cross-sectional models perceived to represent the study site. This interpretation was high, and low-density value distributions associated with the study target. Meanwhile, the quantitative interpretation was conducted on 3D cross-sectional models to obtain density value information in particular depths and locations. Both interpretation results were then analyzed against geological information, both stone types, and topography.

3. Results
The produced map had a value range from 14.8 mGal to 193.3 mGal, as shown in Figure (2), with an area of 38.35 km$^2$. High anomaly distributions marked red and pink were on the southern study site, while low anomalies marked blue were on the northern region. Cross-section locations in Figure (3) were taken as data samples to calculate the Fourier Transformation. Outputs of this analysis were residual and regional boundary field depth limits.

| Line | Regional Depth (m) | Residual Depth (m) | kc   | N     |
|------|--------------------|--------------------|------|-------|
| S1   | 3360.6             | 154.5              | 0.00150 | 55,656 |
| S2   | 1481.7             | 118.69             | 0.00266 | 31,433 |
| S3   | 1611.6             | 132.77             | 0.00227 | 36,957 |
| S4   | 1043.5             | 94.643             | 0.00388 | 21,586 |
| S5   | 1272.2             | 101.76             | 0.00320 | 26,145 |
| S6   | 1560.3             | 152.91             | 0.00391 | 21,405 |
| Average | 1721.65           | 125.88             | 0.0029 | 32,197 |

The Red dashed line generated a 1.481 regression value, the regional depth in meter (m) unit, while the grey dashed line generated a 118.69 regression value, the residual depth. Each path from the six paths was calculated for the average regional and residual depths to be used as the 3D modeling initial parameters. Besides generating depth limits, this analysis also estimated the optimum window width to be used during the moving average screening. From Table (1), obtained an overall $k_{cutoff}$ ($kc$) value of 0.0029 and $N$ value of 32.197.
From the regional anomaly map, obtained a value range from 12.7 mGal to 90.3 mGal. High anomalies were on the southern study site, while low anomalies were on the northeast. Meanwhile, the residual anomaly map had a value range from 0.5 mGal to 104.3 mGal. High anomaly distributions tended to be on the south region, while low anomalies were on the east region.

The initial model was processed using Single Value Decomposition (SVD) and Occam inversion processes with Grablox software [3]. The input model for data processing uses residual anomaly. From the major block of 21 x 17 x 12, achieved minor blocks for 4284 blocks. Hence, one minor block represents 328.6 x 323.5 x 333.3 (length x width x thickness). Then, the lowest density determination of 1.7 g/cc was caused by the lowest density stone type in the study site of sandstones with densities ranging from 1.61 g/cc – 2.76 g/cc based on Telford et al (1990) [4]. Meanwhile, the highest density stone type in the study site was andesite stones with densities ranging from 2.4 g/cc – 2.8 g/cc. Density parameters were determined using the Parasnis method, obtaining 1.7275 g/cc, in which its value was limited on the geology of the study site rather than using the extremely general earth crust’s density of 2.67 g/cc.

4. Discussion
The 2D cross-section interpretation was carried out by selecting formed sections in the initial 3D model production. There were 21 incisions on the X-axis, 17 incisions on the Y-axis, and ten incisions on the Z-axis in this model. Incision orientation directions considered secondary data of geological map having geological structures and intrusion locations. It also considered the study results from Aji et al. (2018) [5] employing modeling surrounding the Pandan Mountain with 2-3 km depth. Then, the model interpretation was strengthened by geological data.

There are two A-A’ incisions parallel to the X-axis; one of them was on section 4 with coordinate y=9177.64. The model central region had a density of 3 g/cc, while the western region seemed to clamp central blocks with densities from 1.7 g/cc to 2.0 g/cc. According to Telford et al (1990) [4], andesite stones have a density of approximately 2.85 g/cc, and according to Tan et al. (2003) [6], tuffaceous sandstone density is approximately 1.95 g/cc. Therefore, the central block of this model is interpreted as andesite stones between tuffaceous sandstones. It follows the cross-sectional geology data by
Pringgoprawiro (1992) [7], where pyroxene andesite stones breaking through the Kalibeng formation composed of tuffaceous sandstones and marls.

The B-B’ model cross-section is similar to the A-A’ model cross-section in the middle of the model with high densities from 2.86 g/cc - 3.0 g/cc. This model is interpreted as a continuation of intrusion from south to north, where this result is consistent with the modeling by Aji et al. (2018) [5] done with different software. Besides, in the geological data in Figure (1), there was also andesite intrusion.

The C-C’ path intersected two paths from the south to the north. This cross-section shows a density contrast from a density of 1.76 g/cc to 2.82 g/cc. In the southern part, the cross-section had a lower density than the northern part. It is interpreted as a lithological layer of tuffaceous sandstones to breccias. On the geological map, the formations arranged in the area are the Sonde, Klitik, Kalibeng, and Pandan Breksi formations.

The D-D’ path shows the density value from south to center of the study area of 3 g/cc, while the north had a lower density of around 2.68 g/cc. This section is interpreted as a continuation of the andesite intrusion from the south to the study area center. In the northern part of the section with a 1-kilometer depth, there was a lower density of about 1.93 g/cc. This section is interpreted as tuffaceous sandstones. It is consistent with the geological map where the intrusion broke through the southern part of the Kalibeng formation.

The last section, the E-E’ path, was located in the eastern part of the study, which cut from south to north. The cross-section shows that the southern part had a low density of around 2.46 g/cc, while the northern part shows a high density of about 2.92 g/cc. The model is interpreted as a continuation of the intrusion zone. Based on the geological map of the low-density areas, the Pucangan formation in the south and Breksi Pandan in the north.

The results of the 3D model inversion show varying density distributions. The rock density values in the model range from 1.7 g/cc to 3 g/cc. A hollow block indicates the similarity in value to the surrounding blocks. The high-density blocks of 2.8 g/cc - 3.0 g/cc located in the southern and eastern parts are interpreted as igneous intrusion zone, while densities of 2.35 g/cc - 2.5 g/cc are interpreted as a breached zone. Both of these are following the geological conditions of the study area based on geological maps where the andesite intrusion had densities of 2.4 g/cc - 2.8 g/cc according to Telford et al (1990) [4] breaks through the Kalibeng formation, which is composed of tuffaceous sandstones of 1.95 g/cc according to Tan et al. (2003) [6].
Figure 7. (a) 2D cross-section results (b) A-A' path (c) B-B' path (d) C-C' path (e) D-D' path (f) E-E' path (g) 3D inversion model cross-section
5. Conclusion
Based on this study, the distribution of subsurface density in the south, northeast, and west had high densities of about 2.8 g/cc to 3.0 g/cc at >500m depths. Meanwhile, the northern, southwestern, and southeastern parts had low densities of around 1.70 g/cc to 2.0 g/cc at >500m depths. Geologically, it indicates the distribution of andesite rocks in the south, northeast, and west, while in the north, southwest, and southeast, it indicates the distribution of tuffaceous sandstones. Besides, the study area's subsurface geological structure based on 3D inversion modeling obtained continuity of andesite intrusion from the south to the center of the study area with >500m depths.

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References
[1] Pratama O Y, Ramadhan H, Wijayanti H D K and Trisnaning P T 2018 Analisis Tipe Fluida Dan Geotermometer Reservoir Panas Bumi Berdasarkan Data Geokimia Air Daerah Gunung Pandan, Bojonegoro, Jawa Timur. RetII, 00.
[2] Sihombing J, Lestari W, Mariyanto M and Joni W 2019 Subsurface Analysis Using Gravity Data at Lili Sepporaki Geothermal Area IOP Conference Series: Materials Science and Engineering 588 (1) 012009
[3] Parttijavri M 2004 GRABLOX: Gravity Interpretation and Modelling Software Based on 3D Block Model, User’s Guide Geological Survey of Finland
[4] Telford W M, Geldart L P and Sheriff R E 1990 Applied Geophysics 2nd Edition (Cambridge: Cambridge University)
[5] Aji W, Wahyudi E J, Santoso D, Kadir W G A 2018 Pemodelan Inversi 3-D Data Gaya Berat dengan Perhitungan Iteratif pada Area Gn. Pandan, Jawa Timur, Indonesia, Jurnal Geofisika (2018) Vol. 16 No 03 pp 27-33.
[6] Tan T S, Phoon K K, Hight D W and Lerouiel S 2003 Characterization and Engineering Properties of Natural Soils (Tokyo: A A Balkema Publishers)
[7] Pringgoprawiro H and Sukido 1992 Peta Geologi Lembar Bojonegoro (Bandung: Pusat Penelitian dan Pengembangan Geologi)