Sub-surface Geological Modeling Based on Gravity Residual Data in Adang Volcanic Rock Area, Mamuju, West Sulawesi Province

Adhika Junara Karunianto[1]*, Dwi Haryanto[2], Ngadenin[3]
[1]Research Center for Mining Technology
Research Center for Nano Material Technology, National Research and Innovation Agency (BRIN)
Building 820, PUSPIPTEK Area, Tangerang Selatan, Banten 15314, Indonesia
[2]Directorate of Laboratory Management, Research Facilities, and Science and Technology Park
National Research and Innovation Agency (BRIN)
Grafika Sekip St., No. 2, Sleman, D. I. Yogyakarta 55284, Indonesia
[3]Research Center for Nuclear Fuel Cycle and Radioactive Waste Technology
Research Organization for Nuclear Energy (ORTN), National Research and Innovation Agency (BRIN)
Building 20, PUSPIPTEK Area, Tangerang Selatan, Banten 15314, Indonesia
*E-mail: adhi007@brin.go.id

Accepted: 3 November 2020, revised: 28 November 2021, accepted: 28 April 2021
DOI: 10.17146/eksplorium.2022.43.1.6089

ABSTRACT

The Mamuju area of West Sulawesi Province is composed of Adang volcanic rock that is a product of the process of volcanism in a volcanic complex with an eruption center and several lava domes. The geology of the study area is composed of eleven rock units, namely Adang breccia, Adang lava, lava dome, volcanic conglomerate, Ampalas breccia, Malunda breccia, Boteng lava, Tapalang breccia, limestone, reef limestone, and alluvium. The mineralization of uranium, thorium, and rare earth elements formed in Adang lava thorianite veins. Adang lava is intruded by a dioritoid found in the Mamuju river upstream. The gravity modeling technique has produced two 2-D subsurface models based on gravity data on 2-D cross-sections of the residual gravity map. It is known that the rock density range from 2.10 to 2.85 g/cm^3 in the study area. Based on the interpretation of two 2-D subsurface models, a batholith, a giant-sized intrusive rock, is found in the southeastern part of the study area with a rock density of about 2.85 g/cm^3 and is interpreted to be dioritoids. Furthermore, deep intrusion rocks also occur in the center part of the study area with a rock density of 2.8 g/cm^3. It is estimated to be the same as the rock in the southeastern part of the study area. Dioritoid intrudes a volcanic breccia sedimentary rock with a density of about 2.1 g/cm^3.

Keywords: Mamuju, gravity, modeling, density, batholith

INTRODUCTION

Mamuju, located in the West Sulawesi Province, is an area with high background environmental radiation dose rate [1]. Previous research activities related to geology and geophysics have been carried out. The studies include the identification of the tectonic setting of the Adang volcanic complex [3], volcano-stratigraphic interpretation of the Mamuju area based on Landsat-8 imagery [4], determination of residual gravity anomalies [5], identification of geological structure patterns based on Landsat-8 imagery [6], and determination of resistivity-conductivity patterns of rocks containing radioactive minerals in Botteng–Takandeang area, Mamuju [7].

Geologically, the Mamuju area is the remnant of continental crust that had separated from Kalimantan, then merged with other crusts, and eventually became the present-day Sulawesi. Paleomagnetic reconstructions [8] show that Sulawesi (the Sunda continent, including the Mamuju region) separated east from Kalimantan during the Cretaceous age. Several researchers have completed the concept and data that this crust is experiencing convergence and volcanism. Some of the results can be seen in Sulawesi, especially in the Mamuju area. Adang volcanic rock is the product of the volcanism process of a volcanic complex where it has an eruption center and several lava domes. In detail, they group into seven volcanic complexes. Adang Complex is one of the volcanic complexes whose morphological formation can still be identified well [3].

Uranium, thorium, and rare earth elements mineralizations were formed in thorianite and thorite ore veins [9]. These veins found in the Adang volcanic rock intruded by the deep intrusion rocks are the product of a hydrothermal process [10]. The purpose of this study is to obtain a subsurface geological model. This model shows rock density variations through modeling techniques to support the geological concept and produce a hypothesis.

METHODOLOGY

The use of the gravity method to determine subsurface geological models, especially in Sulawesi Island, has been published in several papers, such as the gravity method to model the Palu-Koro fault [11],[12], research on geothermal areas [13],[14], and identification of faults in Sulawesi [15]. In several countries, gravity measurements have been applied to the development exploration for Sn-W-Mo primary tin deposit in granitic batholith in Erzgebirge Central Europe [16], polymetallic Sn-Cu primary tin deposit in Gejiu granite, Southwest China [17], and primary tin deposit in Malaysian Bongsu granite [18]. For gold and platinum deposits, gravity measurements have been applied to Madibe Kraaipan granite [19], while to determine the vertical extension of S-type granite, gravity measurements have been applied to Moroccan Hercynian granite [20] and South China Santangan Yuanbaoshan granite [21].

The methodology used in this gravity interpretation study consists of preparing residual gravity anomaly data, modeling subsurface rock density distribution, and analyzing the gravity anomaly modeling results. The residual gravity anomaly map is the final data obtained through gravity data processing of the gravity data from survey results in the field. This data is the basis for doing gravity modeling. The modeling of gravity data is the modeling technique of rock density distribution below the earth's surface that causes the effect of the residual gravity anomaly measured on the surface. In the modeling technique, there is a process of comparing the calculated gravity data curve (g-calculated) and the observed gravity data curve (g-observed). This study uses two modeling methods: forward and inverse modeling. Interpretation of subsurface variation density models is an explanation or synthesis based on the modeling results and existing geological data.

Modeling data is obtained by making a cross-section of the residual gravity anomaly map from gravity measurements in the Mamuju area in 2017 [5] overlaid with a geological map of the Mamuju area [3] (Figure 1). Two 2D sections intersect the residual gravity anomaly maps: A-A' and B-B' (Figure 1). Analysis of residual gravity data using the inverse modeling techniques at the initial stage, then continued with the forward modeling techniques. The basis of the modeling is a residual gravity anomaly map showing the effects of near-surface anomalies that relate to geological maps,

p-ISSN 0854-1418
e-ISSN 2503-426X

where geological outcrops are compared with anomalies caused by rock formations near and below the surface.

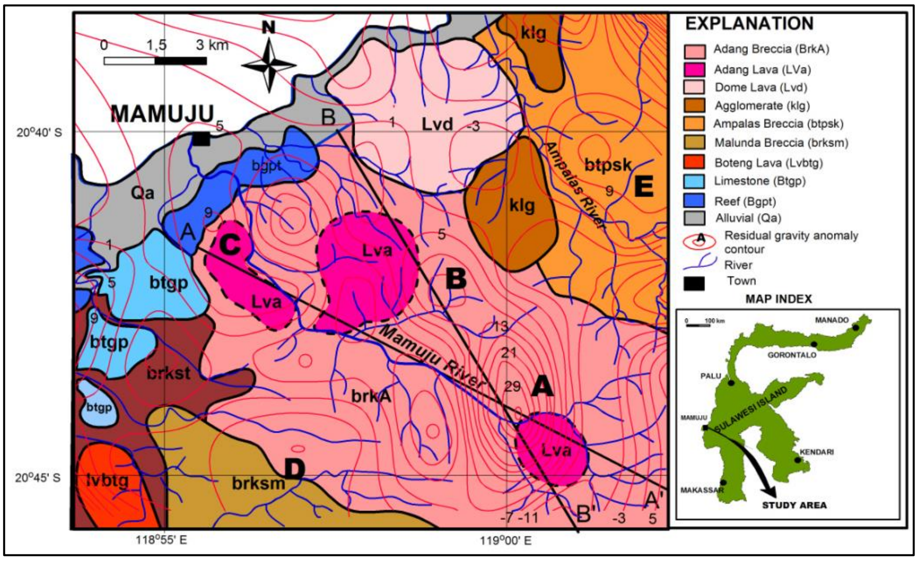

Figure 1. The residual gravity anomaly map overlaid on the geological map of the study area with five anomalous area clusters A, B, C, D, and E (modified from [3],[5])

The data used for modeling was collected in the area of volcanic rocks that experienced intrusion. Most crustal rock has a density between 2.0 and 2.9 g/cm^3. This study adopted 2.67 g/cm3 [22] as the density standard in the upper crust. Theoretically, in the gravity modeling method density chosen as the background reference is 2.67 g/cm^3, where the density variation changes causing the gravity anomaly of approximately ± 0.3 g/cm^3. However, for the equilibrium with field conditions, this gravity modeling selected a reference density of 2.4 g/cm^3 because the average surface rock density measured from surface rock samples representing the study area was 2.4 g/cm^3. Then, for the density value of rocks that are far deeper, it is estimated that the density value is greater than that of rocks near the surface.

RESULT AND DISCUSSION

The residual gravity map shows the presence of five clusters of anomalous areas, namely A, B, C, D, and E (Figure 1). Based on the geological map of the Mamuju area (Figure 1) [3], the study area is composed of 11 rock units, namely Adang breccia, Adang lava, lava dome, volcanic conglomerate, Ampalas breccia, Malunda breccia, Botteng lava, Tapalang breccia, limestone, reef limestone, and alluvium. In general, the cross-sectional path of the gravity map had dominated by volcanic rocks consisting of volcanic breccias and lava called volcanic sedimentary rocks in this paper. The 2-D gravity modeling carried out in 2-D sections data consisted of 2 cross-sections of gravity anomaly map, namely sections A-A' and B-B', as shown in Figure 2.

Section A-A' has a direction from northwest to southeast that passes through cluster area A, which is on the southeast side of the section, as shown in Figure 3. The trajectory of A-A', which has 15 km in length, shows a curve of gravity anomaly distribution from direction A to A'. The position X=0 to X=8 km shows the variation of gravity anomaly from -10 to 10 mGal. Three positive gravity anomalies consist of 10, 1, and 5 mGal, at the X-axis 1, 4, and 7 km, respectively. Lava with orange and pink color has a density range of 2.7–2.8 gram/cm^3 showing the possible response of those three anomalies. Then after the position of the X-axis at 8 km, the positive anomaly enlarges by more than 30 mGal until X-axis at 13 km, then it decreases towards the negative anomaly. In this 5 km anomalous range, there is the possibility of a maximum thickening of volcanic breccia rock with a density of 2.1 g/cm^3 (light green color) that is then intruded by the giant intrusion rock with a density of 2.85 g/cm^3. This intrusion rock is possibly a batholith body then thought to have influenced the emergence of anomalous clusters A and B that are still one unit (Figure 1).

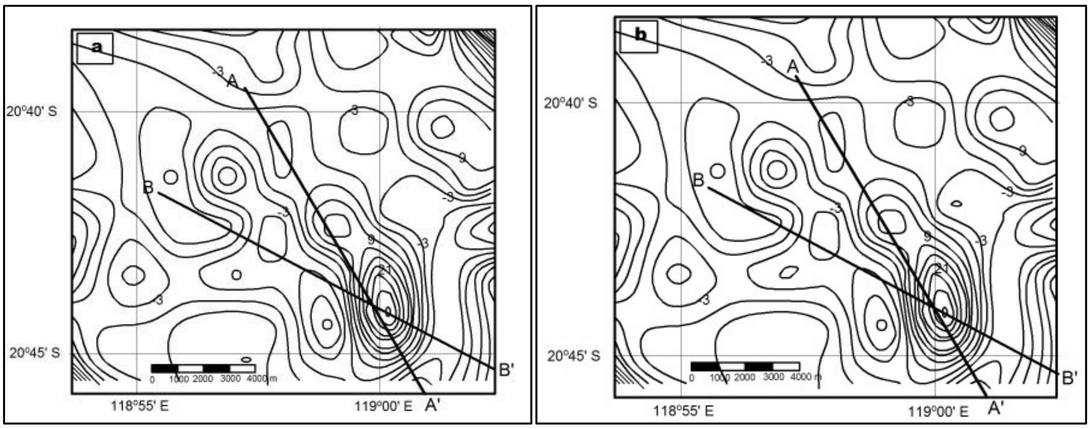

Figure 2. Map of residual gravity anomaly with reference density (a) 2.67 g/cm^3 and (b) 2.4 g/cm^3 (A-A' and B-B' are cross-sections for modeling)

Section B-B' (Figure 3) has a relative direction from north to south and shows the distribution of the gravity anomaly curve along the 13 km track. The trend along the trajectory B-B' shows an increase in the gravity anomaly from North to South. The gravity undulation value is visible from -2 to 10 mGal along 7 km and changes to a maximum of 30 mGal along the 3 km track. Negative anomalies reflect volcanic breccia rocks with a density of 2.1 g/cm^3 (green color) distributed along with a distance from 11 to 13 km. Positive anomalies reflect the presence of lava with a density of 2.1–2.8 g/cm^3 (red color) distributed along a distance from 0 to 7 km. In the range distance from 8 to 11 km, there is a significant increase in the value of the gravity anomaly by 30 mGal and possibly reflects a giant intrusion rock with a density of 2.85 g/cm^3.

Most of the cross-section of the gravity model crosses volcanic breccia rocks, mainly in the form of Adang breccia, with a density of about 2.1 g/cm^3. In the southeastern part of the study area, there is a density value of about 2.85 g/cm^3. An outcrop around the Mamuju River upstream is the location of many mineralizations for uranium, thorium, and rare earth elements. It is the source of a high anomaly in the gravity map estimated to be a deep intrusion rock, namely a dioritoid [23]. In the geological map (Figure 1), dioritoid is considered lava that appears highest anomaly response in the Mamuju gravity map. In addition, in the center of the study area, there is also a deep intrusion rock indicated by a relatively high gravity anomaly with a rock density of about 2.8 g/cm^3. It is possibly related to the dioritoid found in the Mamuju River upstream area. Regionally, the deep intrusion rock in the Mamuju Area possibly correlated with a deep intrusion rock found in the western part of Sulawesi Island. The volcanic and plutonic rocks in the west part of Sulawesi Island formed at the relatively same age in the Paleogene-Quarter [24],[25].

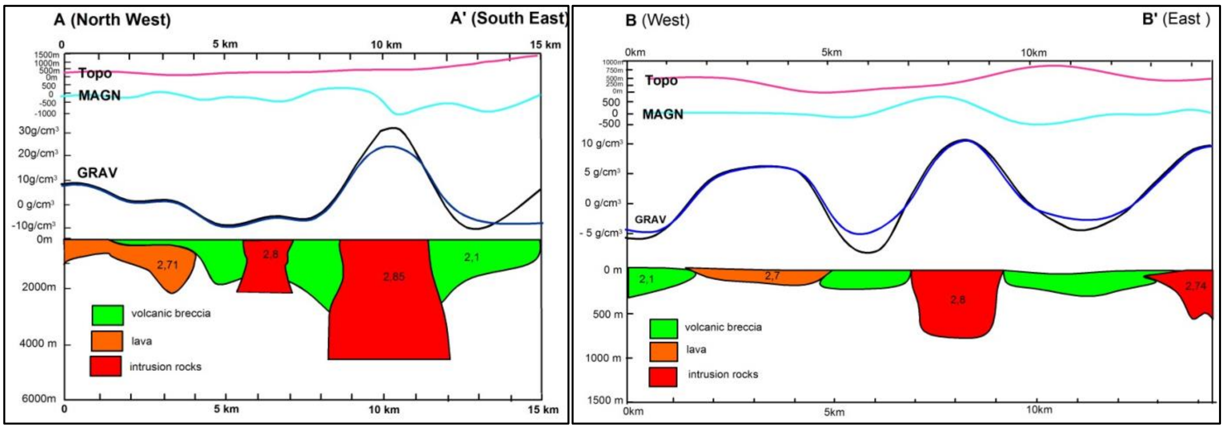

Figure 3. Section A-A' and Section B-B' with curves consisting of topo data (pink), magnetic data (light blue), observed gravity data (black), and calculated gravity data (dark blue)

CONCLUSION

The gravity modeling technique produced two 2-D subsurface section models in Mamuju volcanic area. The average surface rock density measured in the surface rock samples representing the study area is 2.4 g/cm^3, the reference density in the modeling. The rock density value from the gravity modeling in the Mamuju Area ranges from 2.10 to 2.85 g/cm^3. The cross-sections A-A' and B-B' show the presence of batholith in the southeastern part of the study area with a density of about 2.85 g/cm^3. It is estimated to be dioritoid intrudes volcanic breccia with a rock density of about 2.1 g/cm^3, which is suspected to be Adang breccia. Dioritoid, also found in the central part of the study area, has a rock density of about 2.8 g/cm^3 and is possibly correlated with the same batholith.

ACKNOWLEDGMENT

The authors would like to thank Mr. Yarianto Sugeng Budi Susilo, the head of the Center for Nuclear Minerals Technology, who has supported this research. We also extend our gratitude to Mr. Heri Syaeful, the coordinator of the Exploration Division, who has coordinated this research to run smoothly. Thank you to Mr. Agus Laesanpura has guided the author in processing the author's data.

REFERENCES

[1] Iskandar, D. Syarbaini, and Kusdiana, *Map of Environmental Gamma Dose Rate of Indonesian*. Jakarta: Tidak dipublikasikan, 2007.

[2] H. Syaeful, I. G. Sukadana, and A. Sumaryanto, "Radiometric Mapping for Naturally Occurring Radioactive Materials (NORM) Assessment in Mamuju, West Sulawesi," *Atom Indones.*, vol. 40, no. 1, pp. 33–39, 2014.

[3] I. G. Sukadana, A. Harijoko, and L. D. Setijadji, "Tataan Tektonika Batuan Gunung Api di Kompleks Adang Kabupaten Mamuju, Provinsi Sulawesi Barat," *Eksplorium*, vol. 36, no. 1, pp. 31–44, 2015.

[4] F. D. Indrastomo, I. G. Sukadana, A. Saepuloh, A. H. Harsolumakso, and D. Kamajati, "Interpretasi Vulkanostratigrafi Daerah Mamuju Berdasarkan Analisis Citra Landsat-8," *Eksplorium*, vol. 36, no. 2, p. 71, 2015.

[5] A. J. Karunianto, D. Haryanto, F. Hikmatullah, and A. Laensapura, "Penentuan Anomali Gaya berat Regional dan Residual Menggunakan Filter

Gaussian Daerah Mamuju, Sulawesi Barat," *Eksplorium*, vol. 38, no. 2, pp. 89–98, 2017.

[6] F. D. Indrastomo, I. G. Sukadana, and Suharji, "Identifikasi Pola Struktur Geologi Sebagai Pengontrol Sebaran Mineral Radioaktif Berdasarkan Kelurusan pada Citra Landsat-8 di Mamuju , Sulawesi Barat," *Eksplorium*, vol. 38, no. 2, pp. 71–80, 2017.

[7] A. G. Muhammad, F. D. Indrastomo, and I. G. Sukadana, "Pola Tahanan Jenis dan Konduktivitas Batuan Mengandung Mineral Radioaktif di Botteng dan Takandeang, Mamuju, Sulawesi Barat," *Eksplorium*, vol. 38, no. 1, pp. 49–62, 2017.

[8] R. Hall, M. A. Cottam, and M. E. J. Wilson, "The SE Asian Gateway: History and Tectonics of the Australia–Asia collision," *Geol. Soc. London Spec. Publ.*, vol. 355, pp. 1–6, 2011.

[9] M. I. N. Said, M. Anggraini, M. Z. Mubarok, and K. S. Widana, "Studi Ekstraksi Bijih Thorit dengan Metode Digesti Asam dan Pemisahan Thorium dari Logam Tanah Jarang dengan Metode Oksidasi-Presipitasi Selektif, " *Eksplorium*, vol. 38, no. 2, pp. 109–120, 2017.

[10] I. G. Sukadana, H. Syaeful, F. D. Indrastomo, K. S. Widana, and E. Rakhma, "Identification of Mineralization Type and Specific Radioactive Minerals in Mamuju, West Sulawesi," *J. East China Univ. Technol.*, vol. 39, no. 1, pp. 36–45, 2016.

[11] Jamidun, M. Rusydi, K. S. Brotopuspito, S. Pramumijoyo, and W. Suryanto, "Analisis dan Model Inversi Gaya Berat 2D untuk Penampakan Sesar Palu Koro Di Sulawesi Tengah Indonesia," *Nat. Sci. J. Sci. Technol.*, vol. 8, no. 1, pp. 77–86, 2019.

[12] A. D. Maulana and D. A. Prasetyo, "Analisa Matematis pada Koreksi Bouguer dan Koreksi Medan Data Gravitasi Satelit Topex dalam Penentuan Kondisi Geologi Studi Kasus Sesar Palu Koro, Sulawesi Tengah," *Geosaintek*, vol. 5, no. 3, pp. 91–100, 2019.

[13] A. Mangala, Yobel, and M. K. Alfadli, "Pemodelan Struktur Geologi dan Analisis Sumber Panas Menggunakan Metode Gravitasi, Magnetik dan Fault Fracture Density (Ffd) pada Daerah Panas Bumi Bittuang, Sulawesi Selatan," in *Seminar Nasional Kebumian ke-10: Peran Penelitian Ilmu Kebumian dalam Pembangunan Infrastruktur di Indonesia*, 2017, pp. 1566–1578.

[14] R. Efendi, Abdullah, E. Syamsuddin, M. Rusydi, Nirmayanti, A. Sugianto, and W. Joni, "Integrated of Gravity and Magnetic Data to Modeling Structure Subsurface in Bora Geothermal Field Central Sulawesi," in *IOP Conf. Series: Earth and Environmental Science*, 2019.

[15] A. Hartati, "Identifikasi Struktur Patahan Berdasarkan Analisa Derivative Metode Gaya Berat di Pulau Sulawesi," Universitas Indonesia, 2012.

[16] M. Štemprok and V. Blecha, "Variscan Sn–W–Mo Metallogeny in the Gravity Picture of the Krušné Hory/Erzgebirge Granite Batholith (Central Europe)," *Ore Geol. Rev.*, vol. 69, pp. 285–300, 2015.

[17] Y. Q. Chen, L. N. Zhang, and B. B. Zhao, "Application of Bi-Dimensional Empirical Mode Decomposition (BEMD) Modeling for Extracting Gravity Anomaly Indicating the Ore-Controlling Geological Architectures and Granites in the Gejiu Tin-Copper Polymetallic Ore Field, Southwestern China," *Ore Geol. Rev.*, vol. 88, pp. 832–840, 2017.

[18] F. A. Fauzi, M. H. Arifin, M. B. I. Basori, K. A. M. Noh, and M. R. Umor, "Application of Gravity Survey for Tin Exploration at Bongsu Granite, Kulim, Kedah, Malaysia," *Sains Malaysiana*, vol. 48, no. 11, pp. 2503–2509, 2019.

[19] C. D. Ramotoroko, R. T. Ranganai, and P. Nyabeze, "Extension of the Archaean Madibe-Kraaipan Granite-Greenstone Terrane in Southeast Botswana: Constraints from Gravity and Magnetic Data," *J. African Earth Sci.*, vol. 123, pp. 39–56, 2016.

[20] D. El Azzab, Y. Ghfir, and A. Miftah, "Geological Interpretation of the Rifian Foreland Gravity Anomalies and 3D Modeling of Their Hercynian Granites (Northeastern Morocco)," *J. African Earth Sci.*, vol. 150, pp. 584–594, 2019.

[21] C. Yan, L. Shu, Y. Chen, M. Faure, Z. Feng, and M. Zhai, "The Construction Mechanism of the Neoproterozoic S-Type Sanfang-Yuanbaoshan Granitic Plutons in the Jiangnan Orogenic Belt, South China: Insights from Geological Observation, Geochronology, AMS and Bouguer Gravity Modeling," *Precambrian Res.*, vol. 354, 2021.

[22] J. Milsom, *Field Geophysics - The Geological Field Guide Series*, 3rd Editio. London: John Wiley & Sons Ltd, 2003.

[23] I G. Sukadana, H. Syaeful, "Implication of Hydrothermal Process on Radioactive and Rare Earth Element Enrichment in Mamuju, West Sulawesi," in *Proceedings of Joint Convention Malang: Natural Resources and Infrastructure Development for National Sovereignty*, 2017.

[24] A. F. Sompotan, *Struktur Geologi Sulawesi*. Bandung: Perpustakaan Sains Kebumian Institut Teknologi Bandung, 2012.

[25] T. M. Van Leeuwen and P. E. Pieters, "Mineral Deposits of Sulawesi," in *Proceedings of the Sulawesi Mineral Resources 2011 Seminar MGEI-IAGI*, 2011.