Identification of low to moderate fault-controlled geothermal system using satellite gravity method – A comparative study

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ABSTRACT

Currently, most of the high-temperature geothermal system in Indonesia has been developed into power plants, leaving only low-to-moderate-temperature potential. Out of 349 geothermal locations in Indonesia, 46% of them (167 locations) have moderate temperature potential. Most of them are associated with fault-controlled geological settings. To carry out the exploration phase, a method to detect the characteristics of a fault-controlled system is needed. This method is expected to map effectively and efficiently considering the need for cost savings since the amount of electricity generated is smaller than the high-temperature system. One of the geophysical methods that is often used in geothermal exploration is the gravity method. With the availability of the satellite gravity method, geothermal system mapping is now more accessible and more efficient. This study aims to map and identify the characteristics of a fault-controlled geothermal system in several geothermal fields on Sulawesi Island, Indonesia. In several research areas, the results show some high-low-high anomaly patterns associated with fault structures on Sulawesi Island, one of which is the Palu-Koro fault. These results show appropriateness after being compared with the field gravity data. Therefore, the satellite gravity method is expected to be one of the "key" methods for identifying the distinctive patterns between fault-controlled and volcanic systems in delineating reservoirs, permeable zones, and structural patterns.

1. INTRODUCTION

Indonesia has a geothermal energy potential of 23.7 GW (EBTKE, 2020) spread across almost all provinces. Most of Indonesia's high-temperature geothermal potential has been developed into PLTP, leaving low to medium-temperature potential. Out of 349 geothermal locations in Indonesia, 46% of them (167 locations) have moderate temperature potential. Most are associated with fault-controlled geological settings, such as the Palu-Koro fault, located on Sulawesi Island. Therefore, delineating the main faults that control the formation of geothermal reservoirs is required in the exploration stage.

The Palu-Koro Fault is a sinistral shear fault that divides Central Sulawesi Province. This 460 km long fault stretches from the North Sulawesi trench (Minahasa Trench), to be precise on the border between the Makassar Strait and the Sulawesi Sea to Dondowa, North Luwu Regency bordering the Matano fault (Liu & Shi, 2021). This fault is even expected to continue until it ends in Bone Bay. The presence of surface manifestations that appear in several segments of this fault indicates the existence of a geothermal system controlled by the Palu-Koro fault.

This study compares the results of satellite gravity and land gravity measurements from several low-medium geothermal prospect areas along the Palu-Koro fault. The good similarity of the anomaly patterns between satellite gravity and land surveys is expected to be the primary consideration for satellite gravity as an initial reference before conducting field surveys. Thus, field surveys can be carried out more effectively and efficiently. With satellite gravity technology, graben patterns or possible structures that control the appearance of geothermal systems with low to moderate temperatures can also be identified.

2. METHODOLOGY

2.1 Data and Method

This research was conducted by utilizing the gravity disturbance data of Global Gravity Model Plus (GGMplus). GGMplus is a combined solution based on the three key constituents of GOCE/GRACE satellite gravity, EGM2008, and topographic gravity with a resolution of up to 200 m (Hirt et al., 2013). Since satellite gravity has an original resolution of 100 km and is combined with gravity from modeling and high pass filtering to get a 200 m resolution, this technology still requires case studies to prove the accuracy of the shown anomalies.

In this study, GGMplus gravity disturbance is used as raw data. Unlike field gravity data, gravity disturbance corrections used in processing only involve Bouguer correction and Terrain correction because it is considered equivalent to the Free Air Anomaly in field gravity (Suprianto et al., 2021). Even so, there is a slight difference between the FAA and the gravity disturbance, namely the difference in the reference datum plane. Free Air correction adjusts the elevation between the observation points and the mean sea level, which means the reference datum is Geoid (Blakely, 1996). Meanwhile, gravity disturbance is a kind of free air anomaly that is reduced to the normal Earth ellipsoid surface, which is a reference surface for estimating geoidal height (Segawa, 1984).

This paper will not discuss the correction adjustment between the ellipsoid and the geoid datum plane. However, it will compare the significant difference and assess the feasibility of satellite gravity. The Complete Bouguer Anomaly (CBA) map of GGMplus was compared with the CBA map of land gravity to test the effectiveness and efficiency of satellite gravity data. The land gravity CBA map was obtained from various published research, primarily from the Center for Mineral, Coal, and Geothermal Resources.

2.2 Study Area

This research uses three areas as case studies: the Bora Geothermal Field, Marana Geothermal Field, and Kadidia-South Kadidia Geothermal Prospect Area **(Figure 1**). The Bora and Marana geothermal fields are crossed directly by the Palu-Koro fault. While the Kadidia-South Kadidia Prospect Area is crossed by a branching segment trending NW-SE, which is still correlated with the Palu-Koro fault (Wibowo et al., 2015).

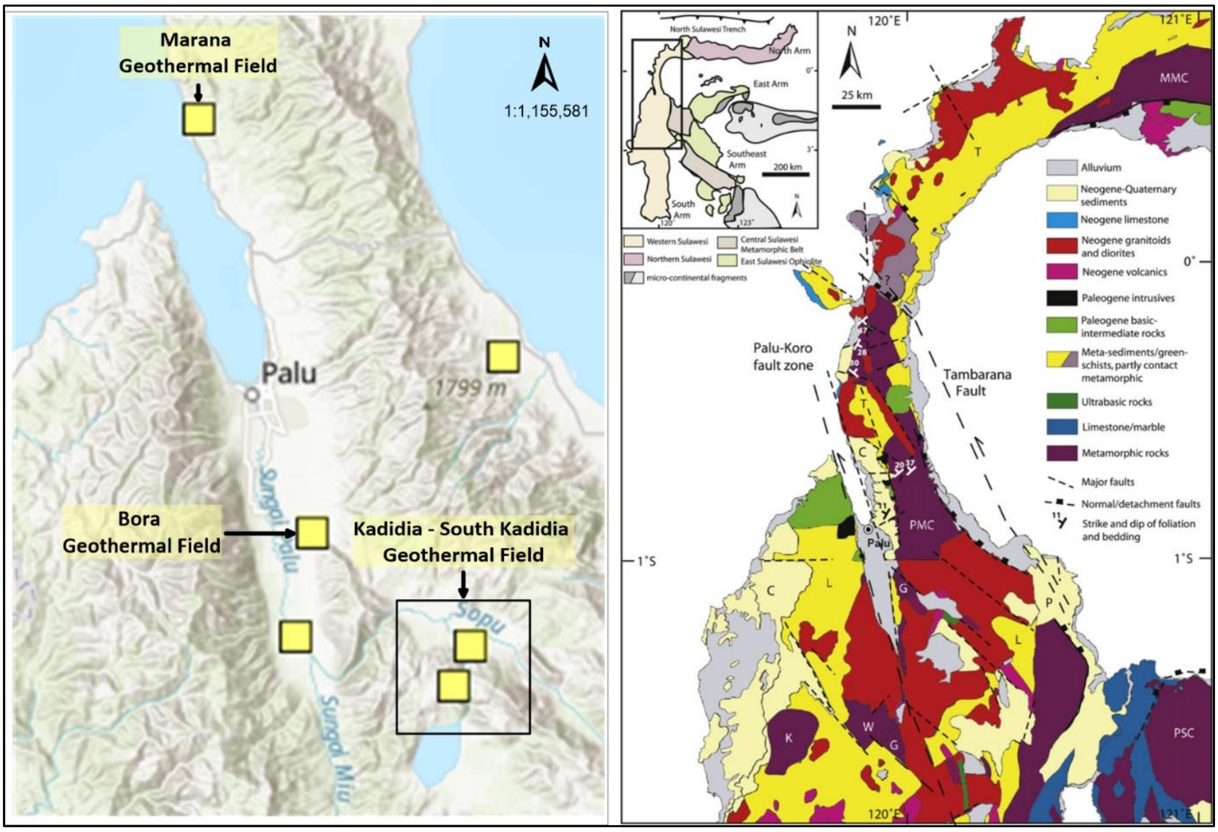

Figure 1. (Left) Study areas include Marana, Bora, and Kadidia - South Kadidia Geothermal Area. All in Central Sulawesi Province. (Right) Geological map of west Central Sulawesi from Hennig et al. (2017) include structures through the study area.

3. RESULT AND DISCUSSION

Below are the results of Bora, Marana, and Kadidia-South Kadidia gravity data. Each area is presented with three maps: a Complete Bouguer Anomaly (CBA) map from land measurement and two CBA maps from GGMplus satellite data. The CBA map of land measurement results is obtained from published article sources with modifications to the map layout. Meanwhile, the GGMplus satellite CBA map is presented in two results: the CBA map with full grid points in the area and the CBA map with selected grid points similar to land measurement stations. However, because the spacing of GGMplus grid points is constant to ~200 m both in latitude and longitude, not all GGMplus grid points are located in the same coordinate positions as the field data. Therefore, to anticipate data gaps, two to four GGMplus gravity points are used to cover the field station that is located not exactly the same but between the GGMplus gravity points. In addition, to determine whether there is a difference anomaly pattern due to the influence of the subsurface average density, GGMplus data with full grid points are processed using density from Parasnis curve calculation, which is the original result. Meanwhile, the GGMplus data with adjusted grid points to field gravity is processed using a density value similar to the field gravity reference for more apple-to-apple comparison.

3.1 Bora Geothermal Field Gravity Result

In the Bora Geothermal Field (**Figure 2)**, the GGMplus results have the same anomaly contour pattern as field measurement data that form a high-low-high pattern. There is a slight difference on the easternmost side of the area, where a low anomaly is formed in the land measurement CBA map while a high anomaly is formed in the satellite CBA map. In addition, land CBA anomaly values are in the range of -22 to 26 mgal, while the full grid GGMplus CBA ranges from 28 to 48 mgal, and the selected grid ranges from 28 to 45 mgal. Although there are slight differences in the anomaly values between the GGMplus data, they both show the same pattern. Even though the values of the anomaly ranges are very different, the high-low-high pattern that is formed is quite consistent with the field data and has been able to adequately describe the graben that is formed on the Palu-Koro fault path.

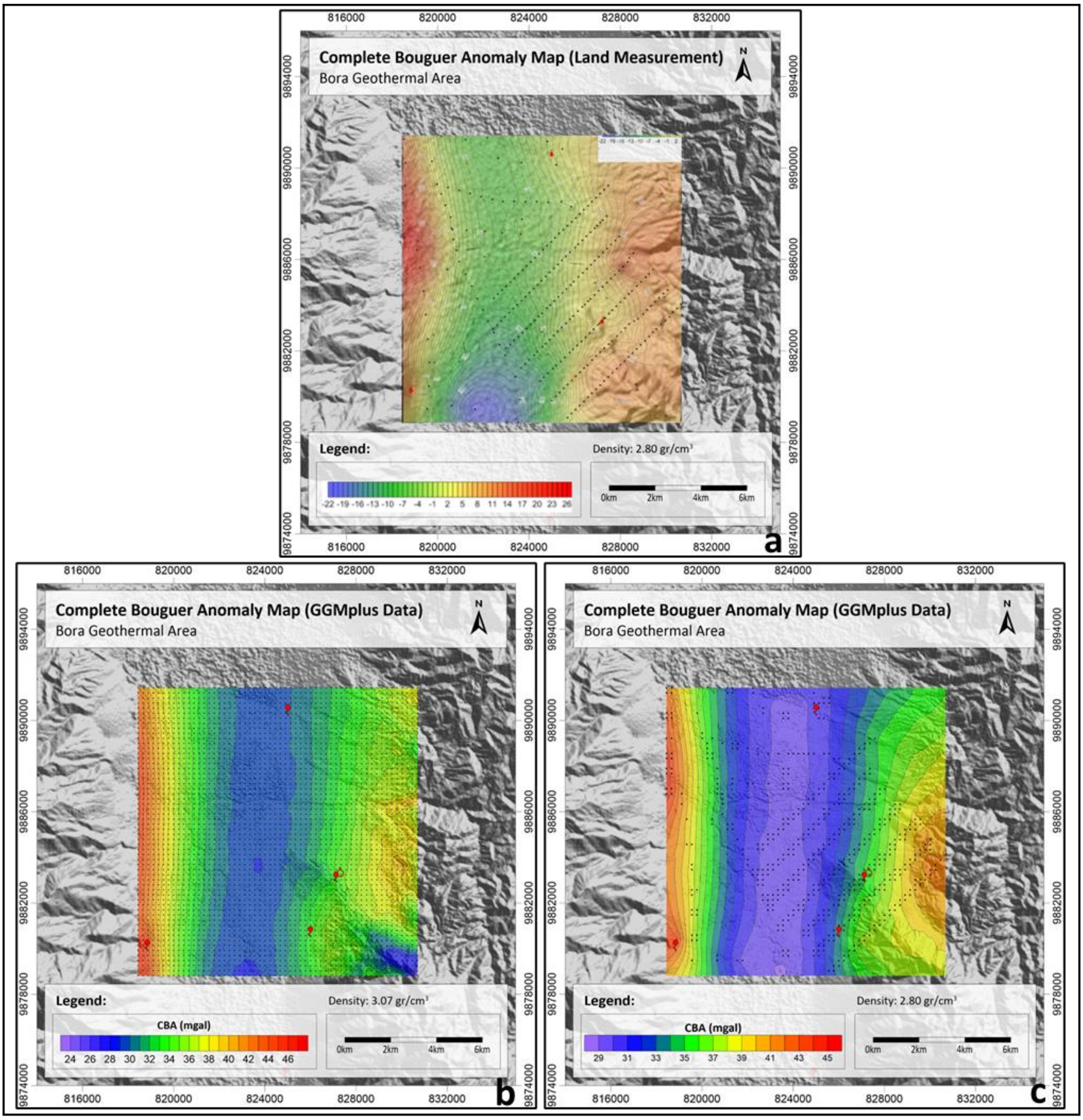

Figure 2. Bora gravity results: (a) CBA map from land measurement (modified from Zarkasyi & Yushantarti, 2010), (b) CBA map from GGMplus data using density obtained by Parasnis curve and grid using all GGMplus stations, (c) CBA map from GGMplus data using density value and grid stations selected similar to land measurements.

3.2 Marana Geothermal Field Gravity Result

In the Marana Geothermal Field (**Figure 3**), the anomaly pattern formed by the original GGMplus CBA map is quite different from the field data anomaly. Only the northwest, north, northeast, and east areas have the same pattern. The existence of a local high anomaly pattern in the middle of the field data area is not visible in **Figure 3b**. This phenomenon could be caused by the difference in average density value that is used to correct the Bouguer anomaly since **Figure 3b** uses Parasnis density value of 3.07 gr/cm^3 and **Figure 3c** uses the same density as **Figure 3a** 2.80 gr/cm^3. **Figure 3c** not only shows a similar CBA value and pattern to Figure 3b but also shows the local anomaly pattern in the center area similar to **Figure 3a**. If viewed regionally, the anomalies shown by the GGMplus data also correlate well with the indication of the Palu-Koro fault line that crosses the Marana area, as shown in **Figure 1**. Then, if full grid points (**Figure 3b**) and selected grid points (**Figure 3c**) of GGMplus data are compared, the anomaly contour pattern on the full grid points follows the surface topography pattern. This also proves the statement of Hirt et al. (2013) that GGMplus utilizes topographic gravity to increase the resolution of anomalies, making it influenced by surface topography.

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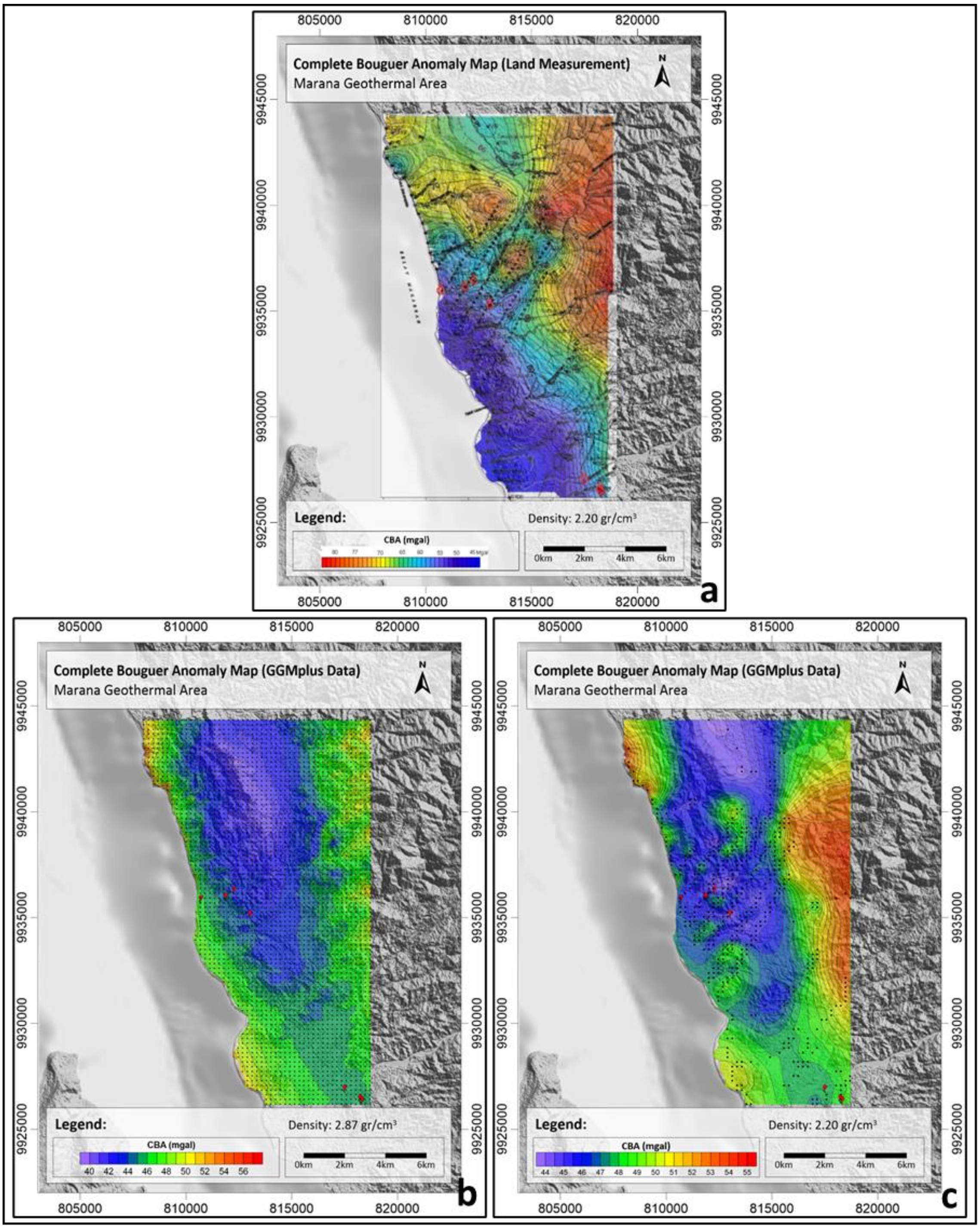

Figure 3. Marana gravity results: (a) CBA map from land measurement (modified from Putra, 2006), (b) CBA map from GGMplus data using density obtained by Parasnis curve and grid using all GGMplus stations, (c) CBA map from GGMplus data using density value and grid stations selected similar to land measurements.

3.3 Kadidia - South Kadidia Geothermal Prospect Area Gravity Result

In the Kadidia - South Kadidia Geothermal Prospect Area (**Figure 4**), although on the south side, there is a difference where gravity field measurements tend to form low anomalies, and GGMplus shows an anomalous gradation, overall, the GGMplus CBA anomaly pattern has a good pattern in common with field gravity. These results also indicate an indication of a graben from the middle to the east and southeast of the study area, which is characterized by low anomalies. This low anomaly is likely to be closely correlated with the presence of the Palu-Koro fault segment that emerges towards the Kadidia area.

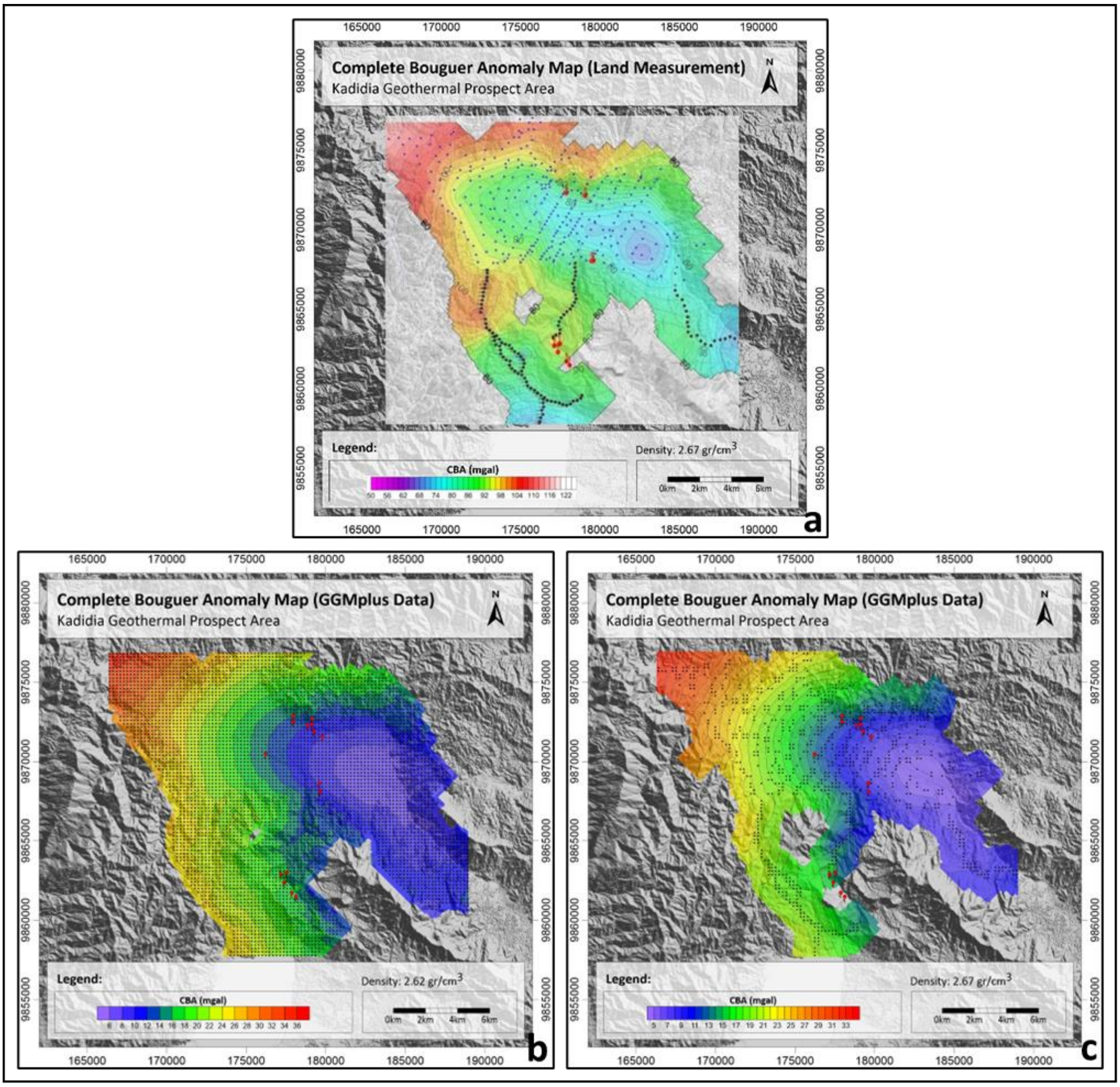

Figure 4. Kadidia-South Kadidia gravity results: (a) CBA map from land measurement (modified from Rahadinata & Nurdin, 2014), (b) CBA map from GGMplus data using density obtained by Parasnis curve and grid using all GGMplus stations, (c) CBA map from GGMplus data using density value and grid stations selected similar to land measurements.

4. CONCLUSION

Based on the CBA comparison results, GGMplus data generally correlate well with field gravity data. All study areas show a slight anomaly pattern difference when using full grid points and original Parasnis density. In contrast, all study areas show more similar anomaly patterns when using selected grid points and the same average density as each land gravity reference. These results conclude that additional gravity stations can change the average density value, which affects the CBA anomaly pattern. The difference in anomaly range value is likely caused by the GGMplus data sources, which use the gravity model and topographic value. However, if the GGMplus results compare apple to apple using the same grid points and average density value, they show the same anomaly pattern with land measurement. Thus, GMplus data is proven to get similar patterns with land measurements and effectively detect high-low-high patterns that form grabens in the Palu-Koro fault zone. These results conclude that GGMplus satellite data can be helpful effectively and efficiently for mapping faults that control low-to-moderate-temperature geothermal systems.

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