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Research Article

Preliminary Study of Subsurface Geological Setting Based on the Gravity Anomalies in Karangrejo-Tinatar Geothermal Area, Pacitan Regency, Indonesia

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As per the Geothermal Potential Book published by the Ministry of Energy and Mineral Resources (MEMR) in 2017, Pacitan Regency in East Java Province, Indonesia, has the potential for geothermal energy. Two hot spring manifestations, namely, Karangrejo and Tinatar, located in the Arjosari and Punung districts of Pacitan Regency, respectively, have a combined resource of 25 MWe. We acquired ground-gravity data and evaluated gravity anomalies to explore the underlying geological structure in order to understand the geothermal system behind these manifestations. The results of the study show that the gravitational anomaly in the Karangrejo-Tinatar region ranges from 163 to 176 mGal. Additional analysis of the complete Bouguer anomaly (CBA) map, first horizontal derivative (FHD) map, and field observations points to the existence of three NW-SE trending faults. Two of the faults, which are the Karangrejo fault and the Tinatar fault, may be the flow paths for the manifestation of Karangrejo and Tinatar hot springs.

1. Introduction

Indonesia possesses significant geothermal potential and ranks among the top countries in the world in this regard. Based on Wardani [1], Indonesia has 331 prospective geothermal points with a reserve capacity of 17,506 MWe and a resource capacity of 11,073 MWe spread throughout volcanic formations in Sumatra, Java, Bali, Nusa Tenggara, and Maluku. The primary characteristic of this potential, which denotes the existence of geothermal energy below the surface, is the existence of geothermal manifestations. Such manifestations may appear as hot springs, fumaroles, steamy earth, or warm soil, among other things.

In Indonesia, Pacitan Regency is a region rich in natural resources, including geological resources like karst geoparks, metal and nonmetal mineral mining, and geothermal potential. Geographically, Pacitan is situated in East Java's southern region, and its geological features are found in the mountains there, which together make up Java Island's quaternary forearc basin. Sedimentary rocks, which were created in sedimentary basins that subsequently rose to become a part of the Java mainland, are among the many diverse types of rocks that can be found in the area. Different geological structures were created as a result of tectonic and volcanic activity, as well as magma extrusions that resulted in the formation of distinct igneous and volcanic rocks. Researchers had already looked at the geological phenomena of the Pacitan area and its surroundings [2–6].

Four rock units that also express the geothermal system of the Karangrejo-Tinatar geothermal area were discovered through the geological mapping research in Pacitan (Figure 1), particularly in Karangrejo-Tinatar and its environs. The rock units are as follows: (1) Mandalika Formation volcanic sandstone and breccia; (2) Arjosari Formation volcanic rock and sandstone; (3) igneous diorite rock as an intrusive body; and (4) sedimentary alluvial in the Pacitan

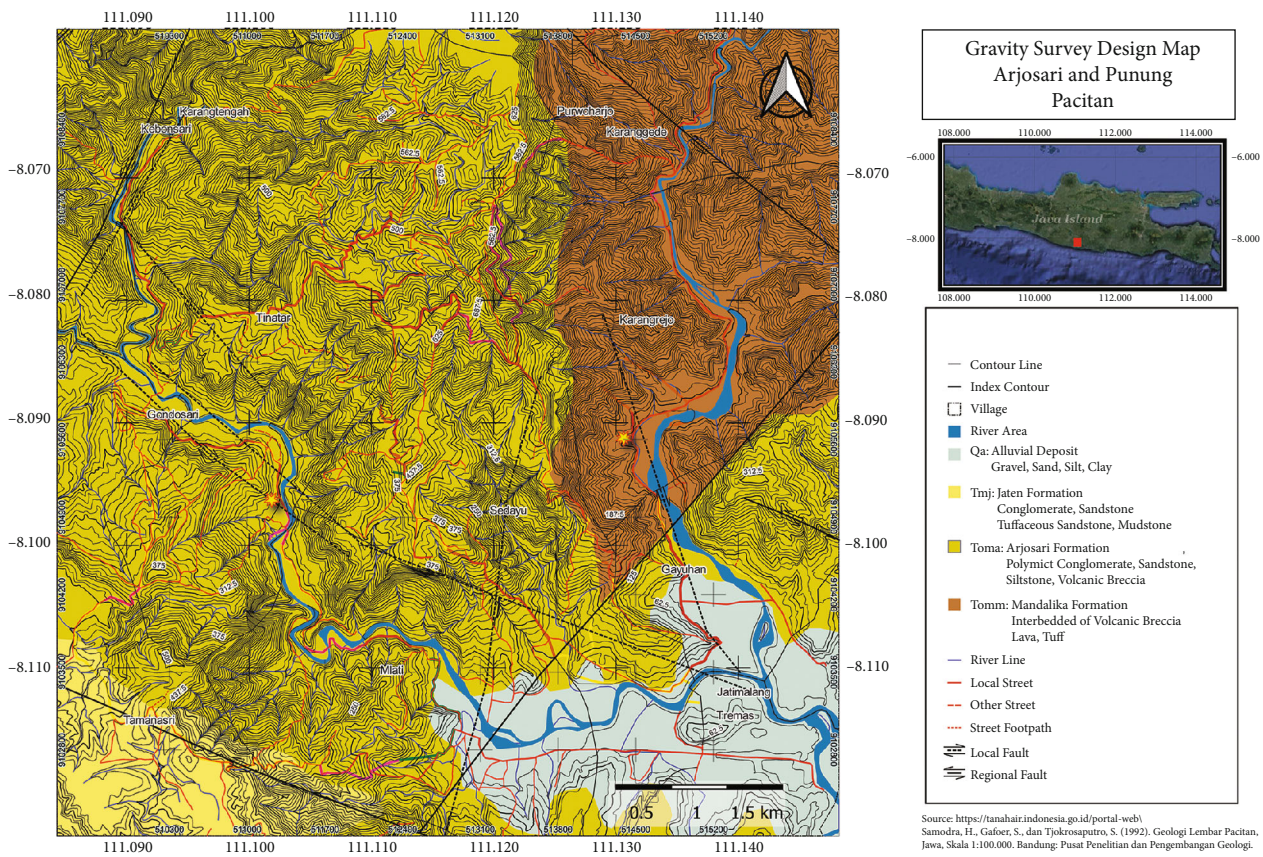


Figure 1: Geological map of Arjosari and Punung District, Pacitan Regency, modified from Samodra et al. [3]. Measurement points are made in a grid by looking at the terrain that will be traversed. These points have been strategically positioned in the middle of its rugged and challenging terrain that renders human traversal virtually impossible.

River Basin [7]. Lestari [8] conducted a subsurface interpretation study of the Karangrejo hot spring and found volcanic and intrusive igneous rocks. The modeling by Lestari [8] corresponds with the Pacitan geological map which states that the study area consists of the Arjosari and Mandalika formations which are dominated by volcanic breccias and lava. In addition, the andesitic lava was identified as the caprock of the Karangrejo-Tinatar geothermal system.

According to the Geothermal Potential Book published by the Ministry of Energy and Mineral Resources (MEMR) in 2017, it is stated that geothermal manifestations in Pacitan Regency are located at two points, Karangrejo at Arjosari District and Tinatar at Punung District. The speculative resource at both points of 25 MWe is too small to be utilized as electric power. Thus, not much research has been conducted on geothermal exploration in Pacitan Regency [9].

The gravity method is a geophysical technique that is commonly utilized to map geothermal potential and identify subsurface geological structures in geothermal areas [10]. This potential method has been extensively used for geothermal exploration worldwide [11–13] and identification of geological structures [14–16]. The primary objective of this research is to provide additional information using gravity data on the subsurface geological structure of the Karangrejo-Tinatar geothermal area in Pacitan Regency. The data obtained from geophysical studies and geological modeling of the subdistrict will facilitate this goal.

2. Materials and Methods

The survey design of the gravity method was carried out with the aim to make a gravity field anomaly map in the Karangrejo-Tinatar area. The instrumentation used on the survey was Gravitymeter Lacoste & Romberg Type G-1053 which uses Zero Length Spring as the sensor. The elevation of each location was determined using GPS Altus, employing a rapid static method [17]. The survey area is 5 km × 5 km filled with 53 gravity measurement points (Figure 2). Measurement points are made in a grid by looking at the terrain that will be traversed. These points have been strategically positioned in the middle of its rugged and challenging terrain that renders human traversal virtually impossible. We conducted several corrections commonly used in gravity data processing to minimize disturbances that occur during the data acquisition process. The observed gravity values that have been obtained still need to be corrected to obtain a gravity anomaly in the study area, which is called the complete Bouguer anomaly (CBA). The corrections made are normal gravity correction, free-air correction, Bouguer correction, and terrain correction [10]. Before obtaining the

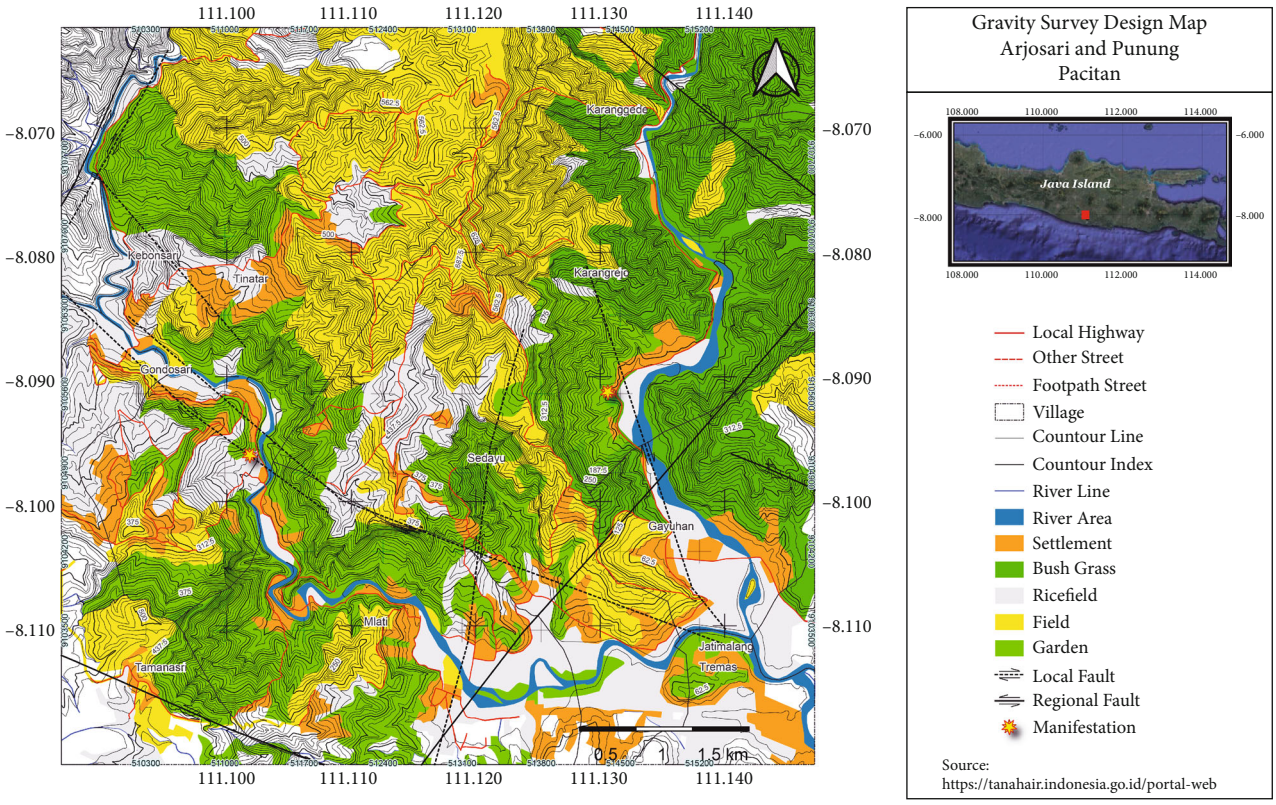


Figure 2: Survey map of gravity method in Karangrejo-Tinatar. Black points are gravity observation points.

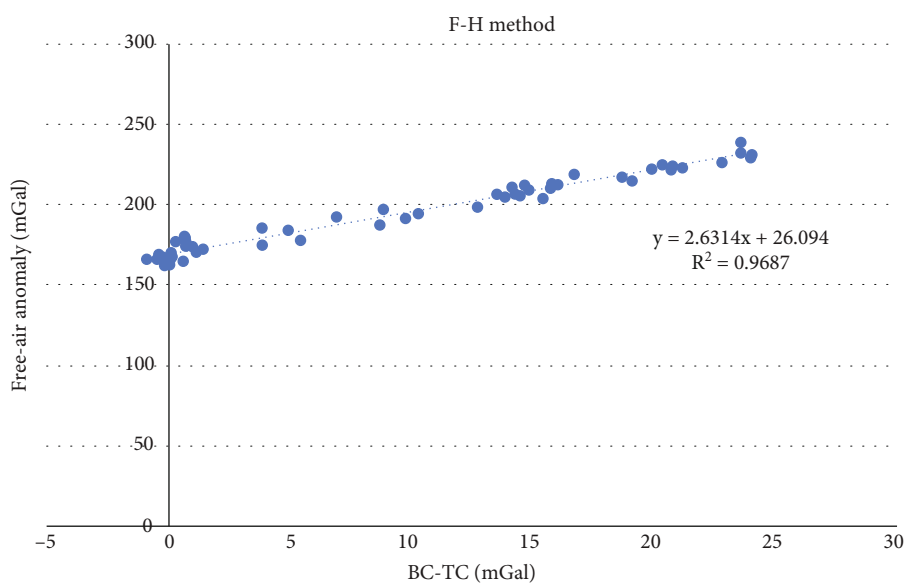
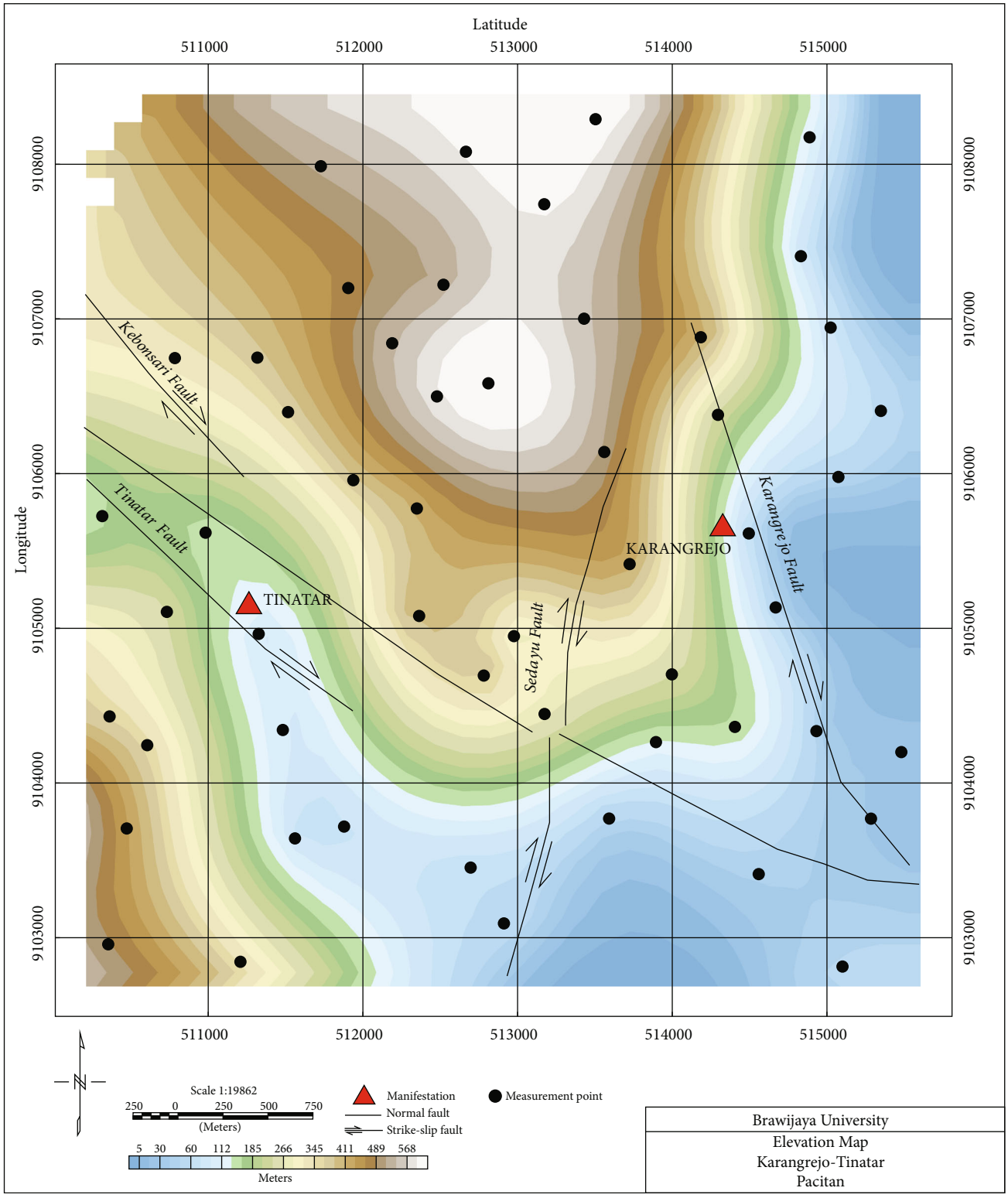


Figure 3: Determination of the Bouguer density using the F-H method. The X axis is the Bouguer correction–terrain correction (BC-TC) in mGal, while the Y axis is the free-air anomaly in mGal.

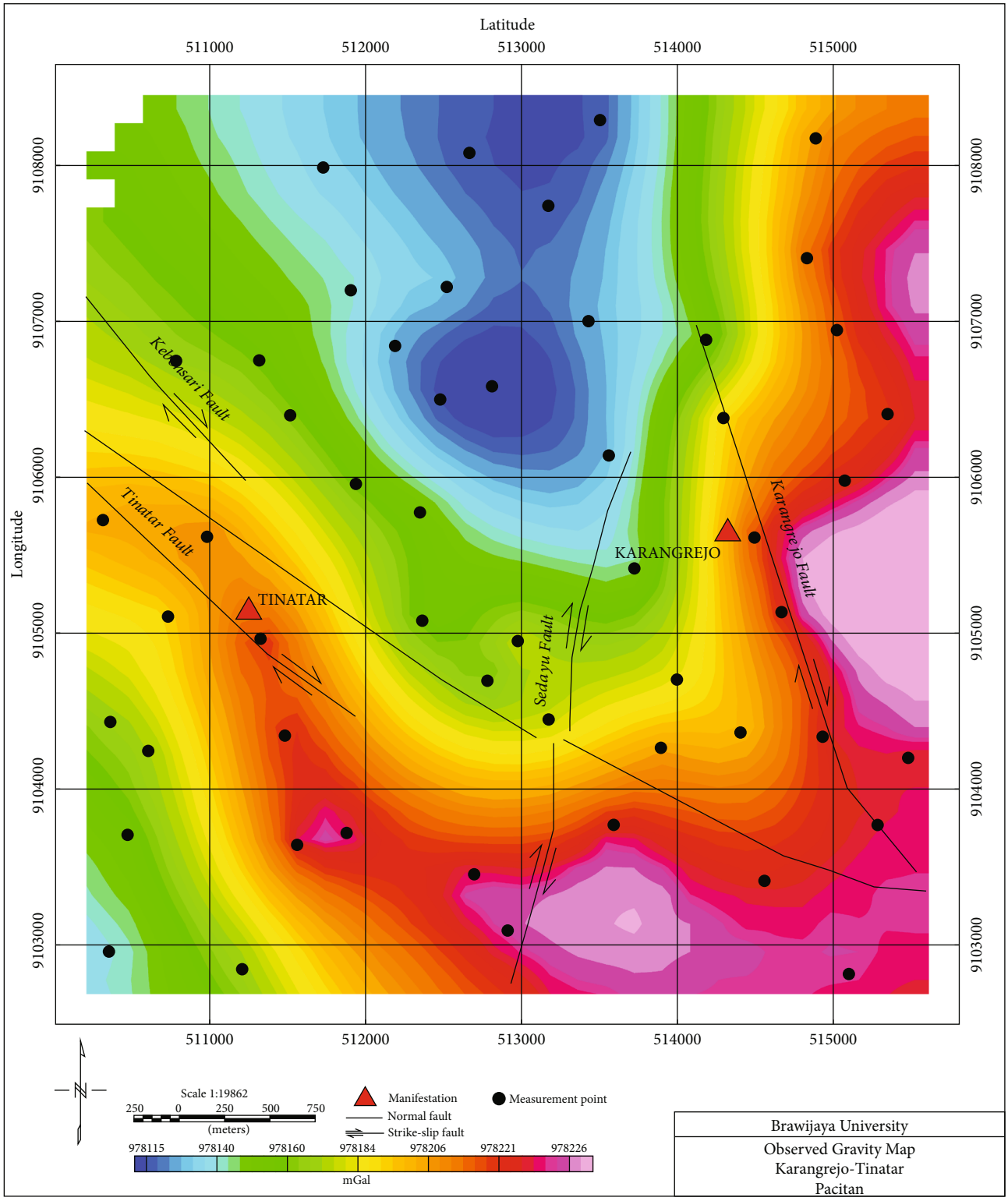
CBA value, it is necessary to determine the Bouguer density which is the average density that represents the mass below the surface of the study area. The method used to determine Bouguer density is the F-H method [18–20]. the Bouguer correction minus terrain correction (BC − TC) as a topography term is plotted against free-air anomaly, and the slope of straight lines is calculated as the Bouguer density which is the average density of the dominant rock in the study area.

By looking at the graph of the results of the calculation of the linear equation (Figure 3), a Bouguer density of 2.63 gr/cm^3 is obtained. This Bouguer density value will be used in further processing, namely, in the Bouguer correction and



(a)

Figure 4: Continued.



(b)

Figure 4: (a) Elevation map of the research area and (b) G_{obs} map of the research area. The fault lines are based on the local geological map by Abdullah et al. [21].

terrain correction stages to obtain complete Bouguer anomaly (CBA) values in the topography that are no longer influenced by the theoretical gravity. The results of the gravity anomaly obtained from data acquisition will be processed and then analyzed to identify subsurface geological structures related to the Karangrejo-Tinatar geothermal system.

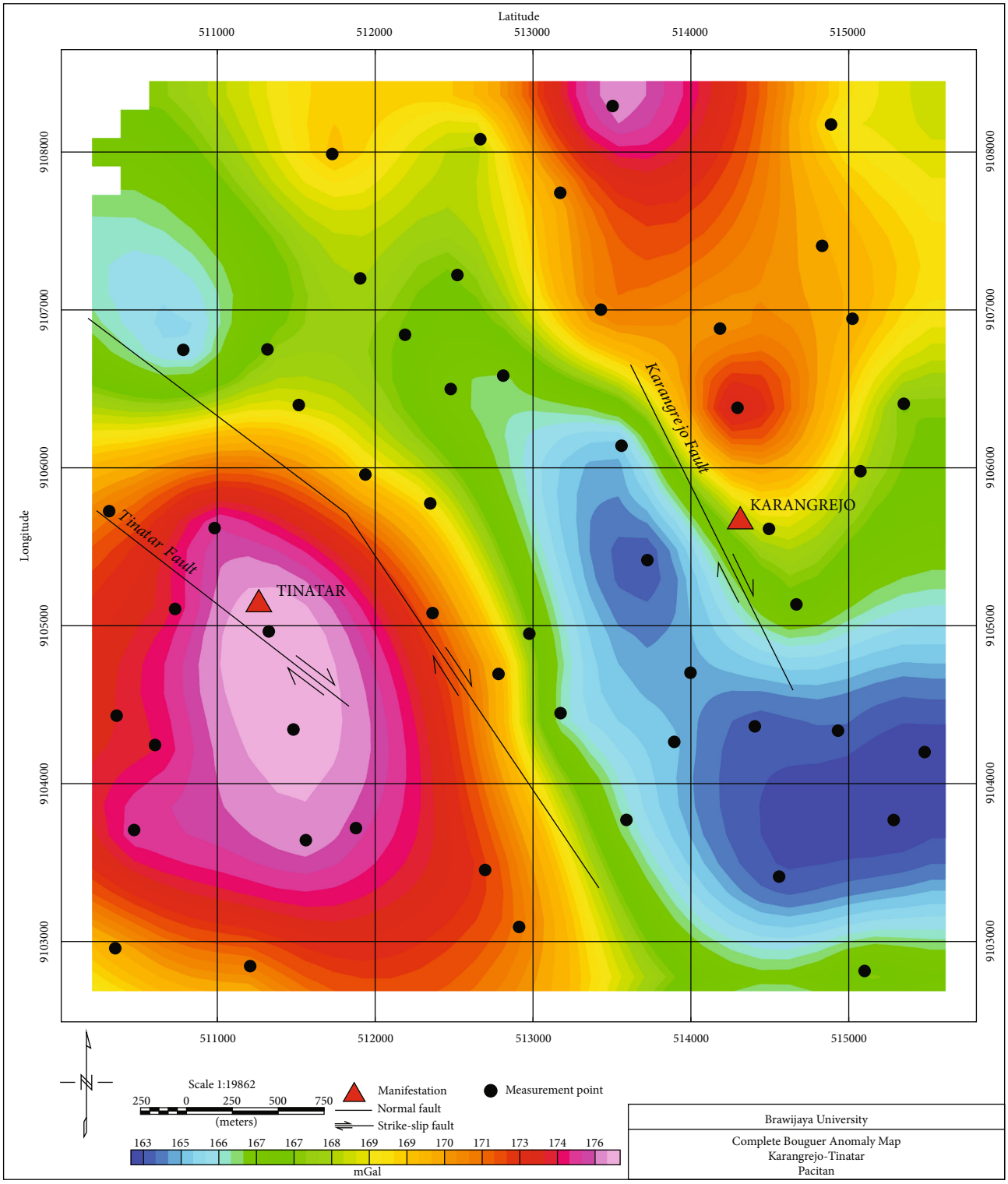


Figure 5: Complete Bouguer anomaly (CBA) map.

3. Results and Discussion

Figure 4(a) shows the elevation contours of the study area. The northern part of the study area has a high elevation with a maximum of 600 meters showing the top of the hill. The lowest elevation of the study area is 20 meters which shows the valley from the hills. Figure 4(b) is a G_{obs} map showing the observed gravity values in the study area. These observed gravity values can be obtained after making corrections to the results of field measurements. Corrections made include tool

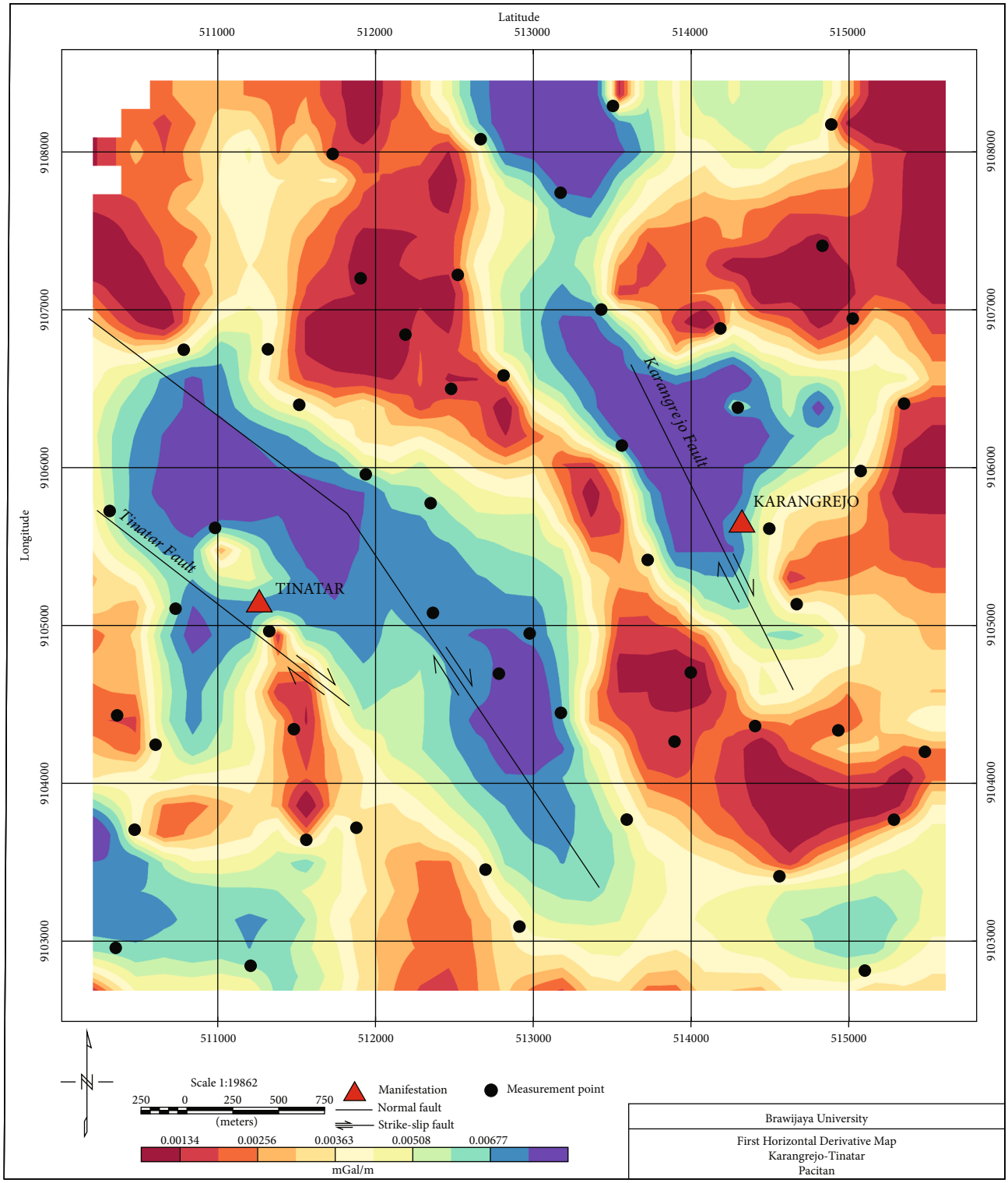


Figure 6: First horizontal derivative (FHD) map.

height correction, tide correction, and drift correction. Observed gravity values range from 977960 mGal to 978085 mGal. Good data can be seen from the G_{obs} pattern, which is inversely related to elevation. The fault lines on the maps are based on a local geological map by Abdullah et al. [21].

Based on the complete Bouguer anomaly map of the topography (Figure 5), the anomaly values in the study area range from 163 mGal to 176 mGal. Low gravity anomaly is located in the southeast of the research area adjacent to the Karangrejo hot spring manifestation. The high gravity

anomalies are in the northeast and southwest, which is adjacent to the manifestation of the Tinatar hot spring.

The northern part of Pacitan Regency has a landscape in the form of elongated hills. These elongated hills are one of the results of very active geological structure activity. It can be seen on the geological map that around the study area, there are many faults with varying ages. These faults were formed at Early Miocene, Middle Miocene, and Plio-Pleistocene, as mentioned by Abdullah et al. [21]. The regional fault that plays a role in the Karangrejo-Tinatar geothermal system is the Grindulu Fault. Purnomo and Pichler [22] classify the geothermal system in Pacitan Regency, more precisely in Karangrejo and Tinatar, into a fault-hosted geothermal system. This fault-hosted geothermal system, as well as the Cikundul, Pakenjeng, and Parangtritis geothermal systems, has a heat source from deep-seated magma of the Tertiary volcanic belt, which remains after volcanism has ceased in the Last Paleogene. Meteoritic water that has seeped and permeated into the Earth's interior is warmed through conduction as it delves to substantial depths and then propelled by convection [23].

Evaluation of the geological structure in the study area begins with estimating the presence of faults from field observations and analysis of gravitational anomalies. The manifestation of hot water is one of the markers of faults in the study area. The manifestation of Karangrejo and Tinatar hot springs in Pacitan is near the river, which is also a marker for the presence of a fault. In addition, on the hills where the manifestation of the Karangrejo hot spring is located, there is a fault escarpment indicating that there is indeed a fault in the area. The pathways for the emergence of the Karangrejo and Tinatar hot springs appear to be two distinct fault lines, namely, the Karangrejo fault and the Tinatar fault. The indication of the faults is strengthened by the color gradation on the CBA map (Figure 5) with the trend of NW-SE near Karangrejo and Tinatar manifestations and the area between. Meanwhile, the strike-slip fault type and the direction of fault movement in Figure 5 are the results of local geology according to Abdullah et al. [21]. In the Karangrejo-Tinatar area, there is indeed a group of faults trending northwest-southeast [21], consisting of several faults, including the Sambi fault (N310°E), Tinatar fault (N310°E), Gembong fault (N310°E), Gedangan fault (N300°E-N315°E), and the Kebondalem fault (N300°E-N315°E). These faults cut the Arjosari Formation and Mandalika Formation rock units.

An analysis using the first horizontal derivative (FHD) was performed to validate the existence of the faults identified in the CBA map analysis. By using this method, the boundary of the anomaly source on the FHD map can show the fault as the maximum value. As a result of the FHD map analysis (Figure 6), three (3) faults were identified, all of which have a NW-SE orientation. The direction and location of these faults are close to the geological structure identified in the local geological map of the Arjosari area in Pacitan [21]. It is believed that this secondary structure was formed due to the influence of the Grindulu regional fault [3], which stretches from east to west of Pacitan Regency.

4. Conclusions

Interpreting the gravity anomalies of the Karangrejo-Tinatar area can be used to understand the geothermal system of these two manifestations and identify the subsurface geological structure. The research results show that the gravity anomaly in the Karangrejo-Tinatar area ranges between 163 mGal and 176 mGal. The analysis of the CBA map, FHD map, and field observations indicated the presence of three (3) faults trending NW-SE. Two of the faults, which are the Karangrejo fault and the Tinatar fault, are suspected to be the flow path for the manifestation of the Karangrejo and Tinatar hot springs.

Data Availability

All gravity data used for analysis in this study were collected primarily by the authors in Pacitan Regency (within the scope described in the main text) on 2-9 August 2022. The data in this study can be accessed via the first author upon reasonable request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Acknowledgments

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