JGE (Jurnal Geofisika Eksplorasi)
Vol. 09 No. 01, Maret 2023 (32-42) https://doi.org/10.23960/jge.v9i1.237

IDENTIFICATION OF THE ANCIENT LAKES BASED ON GRAVITY METHODS IN BOROBUDUR TEMPLE

IDENTIFIKASI DANAU PURBA BERDASARKAN METODE GRAVITASI DI CANDI BOROBUDUR

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Received: 2022, September 2nd
Accepted: 2023, January 3rd

Keywords:
Ancient Lake;
Borobudur;
FHD;
Gravity method;
Inverse modelling.

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How to cite this article:

Permana, N.R., Rahman, F., Zani, F.R., Shafa, D., & Fadrian, D.F. (2023). Identification of The Ancient Lakes Based on Gravity Method in Borobudur Temple. *JGE (Jurnal Geofisika Eksplorasi)*, 09(01), 32-42.

Abstract. Indonesia is a country that's well known for its heritages. One of the heritages is Borobudur Temple. Several studies say that the Borobudur was enclosed by a lake. Therefore, this study aims to see the remains of an ancient lake below the surface with gravity method. The process stage begins with obtaining the CBA (Complete Bouger Anomaly) and continues by separating the anomaly with a Bandpass Filter, and followed with 3D inverse modeling and FHD (First Horizontal Derivative) analysis. According to the residual map, there are only minor anomalies in the west, south, and east, ranging in magnitude from -0.539 to (-0.209) mGal. This anomaly is consistent with the location of the ancient lake around Borobudur. In the meantime, the 3D modeling of the FHD study reveals a geologic structure surrounding the Borobudur with an anomaly ranging from 0.00289 to 0.00480 mGal. A deposit layer thought to be an ancient lake is visible between 50 and 525 meters in depth over the east and west sides of the Borobudur temple, and beneath it is visible between 250 and 525 meters. This depth map provides additional evidence that the ancient lake beneath the Borobudur is located between 250 and 525 meters.

Abstrak. *Indonesia is a country that's well known for its heritage. One of the heritages is Borobudur Temple. Several studies say that the A lake enclosed Borobudur. Therefore, this study aims to see the remains of an ancient lake below the surface with the gravity method. The process stage begins with obtaining the CBA (Complete Bouger Anomaly) and continues by separating the anomaly with a Bandpass Filter, followed* *by 3D inverse modeling and FHD (First Horizontal Derivative) analysis. According to the residual map, there are only minor anomalies in the west, south, and east, ranging in magnitude from -0.539 to (-0.209) mGal. This anomaly is consistent with the location of the ancient lake around Borobudur. In the meantime, the 3D modeling of the FHD study reveals a geologic structure surrounding the Borobudur with an anomaly ranging from 0.00289 to 0.00480 mGal. A deposited layer thought to be an ancient lake is visible between 50 and 525 meters in depth over the east and west sides of the Borobudur temple, and beneath it is visible between 250 and 525 meters. This depth map provides evidence that the ancient lake beneath the Borobudur is between 250 and 525 meters.*

1. INTRODUCTION

Borobudur Temple is one of the Buddhist temples in Indonesia which was built in the 8th century and has become a world heritage (UNESCO, 1991). The Borobudur area has enormous potential to be used as field studies, both in terms of geography, socio-cultural aspects of the community and the physical aspects of the temple. Judging from the geographical aspect, the Borobudur temple was built on Borobudur Hill, Magelang Regency, Central Java.

Borobudur Temple is thought to have been built on the hills of Mount Gandul – Sipodang which is the peak of a tertiary-aged volcanic rock type in the Kulonprogo Dome or the broken Menoreh Mountains (Murwanto et al., 2014). During the Quaternary period, several young volcanoes appeared around the part that was broken, including Mount Sumbung, Mount Merbabu and Mount Merapi. Then the broken part formed a basin between the Menoreh Mountain and the volcano known as the Ancient Borobudur Lake. Borobudur Ancient Lake is a landscape around the Borobudur temple complex which has been lost due to silting. The siltation was observed based on the material covering ancient lake deposits which were the result of volcanic activity, tectonic activity, movements due to soil and rock masses and human activities (Rosa et al., 2021).

The change in the shape of the lake and the surrounding environment into a plain is a process that takes a very long time. The main factor causing the silting of the lake is the occurrence of a very intense sedimentation process, in this case caused by volcanic activity, especially Mount Merapi (Murwanto & Purwoarminta, 2015). Records of tectonic activity found in the field indicate that the research area is controlled by geological structures. The geological structure changes the morphology and opens the way out for the pool of water in the lake. Tectonic activity also causes landslides in the Menoreh Mountains which are also triggered by rainfall and earth's gravity. The existence of geological structures will help accelerate the occurrence of rock weathering and the potential for landslides to occur (Dhani, 2015b).

Landslides originating from Menoreh are the most likely cause of the damming of the Sileng River. With the catchment area at Borobudur only about 29 square kilometers, the average flow is about 1.5 m^3/s and the 100-year return flood is about 100 m^3/s. The landslides that cover the Sileng River may not be able to collapse with the flow so the lake will remain. The drying of the lake was caused by the deposition of material carried by the flow from the catchment area and volcanic ash from the eruption of Merapi (Dhani, 2015a).

To find out and prove this, the research was conducted using one of the geophysical methods, namely the gravity method. The gravity method is a geophysical method that aims to determine the state of the subsurface structure based on variations in the distribution of rock density below the earth's surface (Teaching et al., 2021). In addition, the gravity method has the capability to identify and determine subsurface fault structures based on variations in the distribution of subsurface density anomaly values (Al-khafaji, 2016).

2. LITERATURE REVIEW

2.1. Regional Geology

Based on Geological Map (**Figure 1**) (Wartano & Sukandarrumidi, 1995), that in the research area there are several types of rocks. On the map described in several colors, among other; cream color as alluvium rock, dark blue color as young Merapi volcano deposit, light blue color as cleft volcanic rock, and maroon color as jonggrangan formation. The Jonggrangan Formation is composed of limestone, coral, and large forams. The Jonggrangan Formation is early Miocene – Middle Miocene.

Some evidence of the existence of ancient lakes around Borobudur is the discovery of black limestone and black silt rocks containing pollen from swamp plant species, scattered swamp gas and fossils (Murwanto & Purwoarminta, 2015). In the Borobudur area, there is the Borobudur Basin which was originally formed during the Pleistocene period, which was followed by a young volcanic incident that was in the middle quarter - recent period (Murwanto & Purwoarminta, 2015).

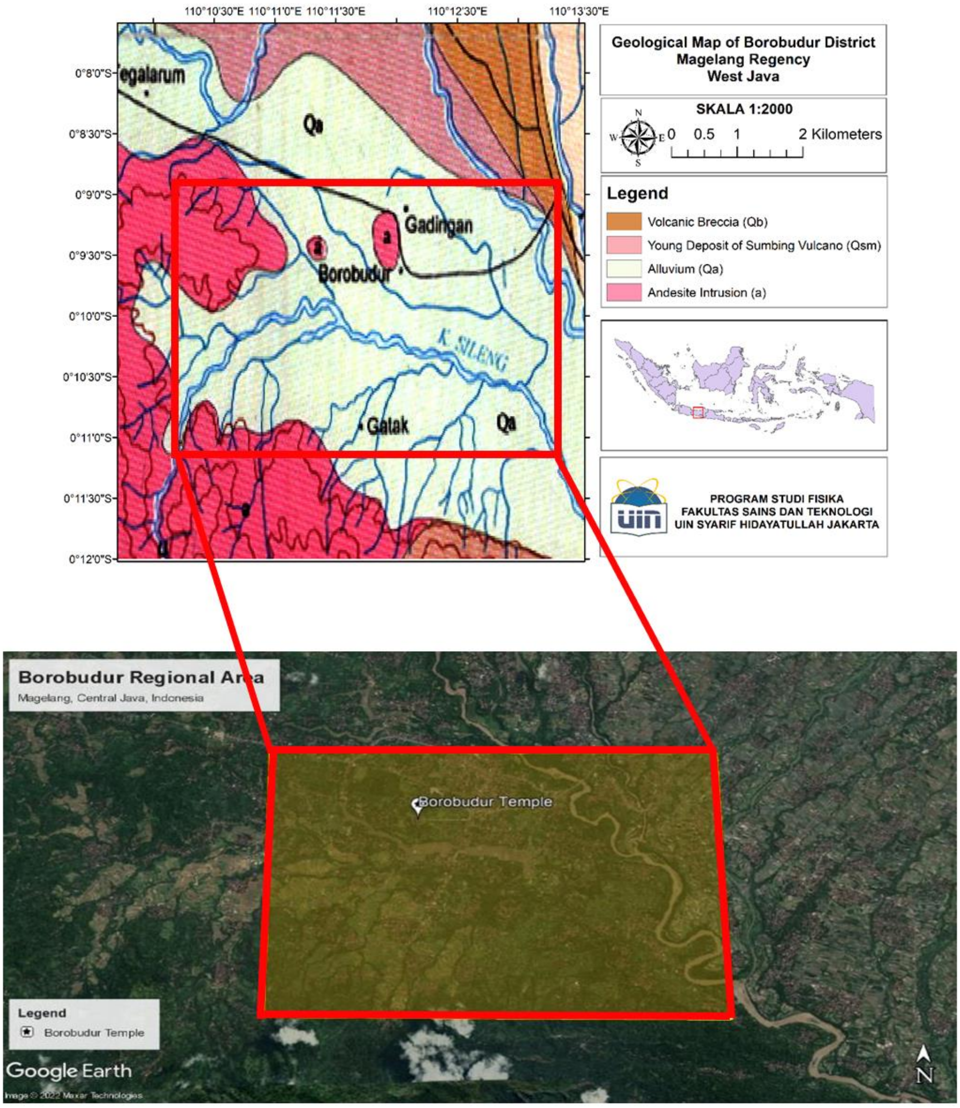

Figure 1. Geological Map of Borobudur District.

2.2. Principle of Gravity Method

The gravity method is a method based on Newton's law which explains the attraction between two objects related to the mass of the two objects. The sound of Newton's law is as follows:

$$\vec{F} = G\ \frac{m_1 m_2}{r^2} \tag{1}$$

Where F is the object's weight in units (N), m_1 is the mass of the first object in units (kg), m_2 is the mass of the second object in units (kg), and r is the distance between the two masses in units (m), and G is gravitational constant with value of 6.67 x 10^{-11} Nm^2kg^{-2}.

Gravitational field measurements result in a Complete Bouguer Anomaly, so to obtain gravitational data it is necessary to make corrections. Such as Bouguer correction and terrain correction. Bouguer's correction is taken into account because there is a pull effect of the mass of rocks located in the stations and datum fields assuming they have infinite radius with a thickness of h (meters) and density of ρ (g/cc) (Nafian et al., 2021). Bouguer correction value can be searched by the equation:

$$BC = 2\pi g\rho h \tag{2}$$

2.3. Inversion Modelling

The inversion method is data processing process or observation of data using techniques math problem solving and statistics to get results in the form of information that can be used to process analysis of the distribution of physical properties below the surface. In the inversion process, the analysis is carried out on the observation data by doing curve fitting between mathematical models and observational data (Melani et al., 2021) .

2.4. First Horizontal Derivative (FHD)

FHD can be in the form of showing the edge of a body from the gravitational anomaly. In other words, FHD can be useful for knowing the horizontal contact contrast limit of the gravity datum obtained from the measurement (Zaenudin & Yulistina, 2018) .

3. METHODS

The location of this study is in the Borobudur area and its surroundings with geographical coordinates between longitude 110.187862 to 110.238157 and latitude -7.633106 to -7.596617. This research was conducted in June 2022. The data used are GGMPlus data obtained from the Bureu Gravimetrique International website, with the amount of data we get is around 289 data (dg, geoid, dem).

Furthermore, the data is carried out Bouguer correction, free air correction, field correction to obtain complete Bouguer anomaly data. The complete Bouguer anomaly data is grid which will then be analyzed for spectrum to determine the estimated depth of the research area using Oasis Montaj software (Abrianto et al., 2021). After performing spectrum analysis, the regional and residual anomalies will then be separated using the Bandpass filter in Oasis Montaj software.

Furthermore, inverse modelling and FHD analysis will be performed (First Horizontal Derivative) to obtain a subsurface structure model. In the modelling process, we look for model parameters that have an appropriate response, also approaching the truth based on observational data. In this study, inverse modelling uses ZondGM3D software to obtain a 3D model of the subsurface structure of the study area. For more details see the flow chart (**Figure 2**).

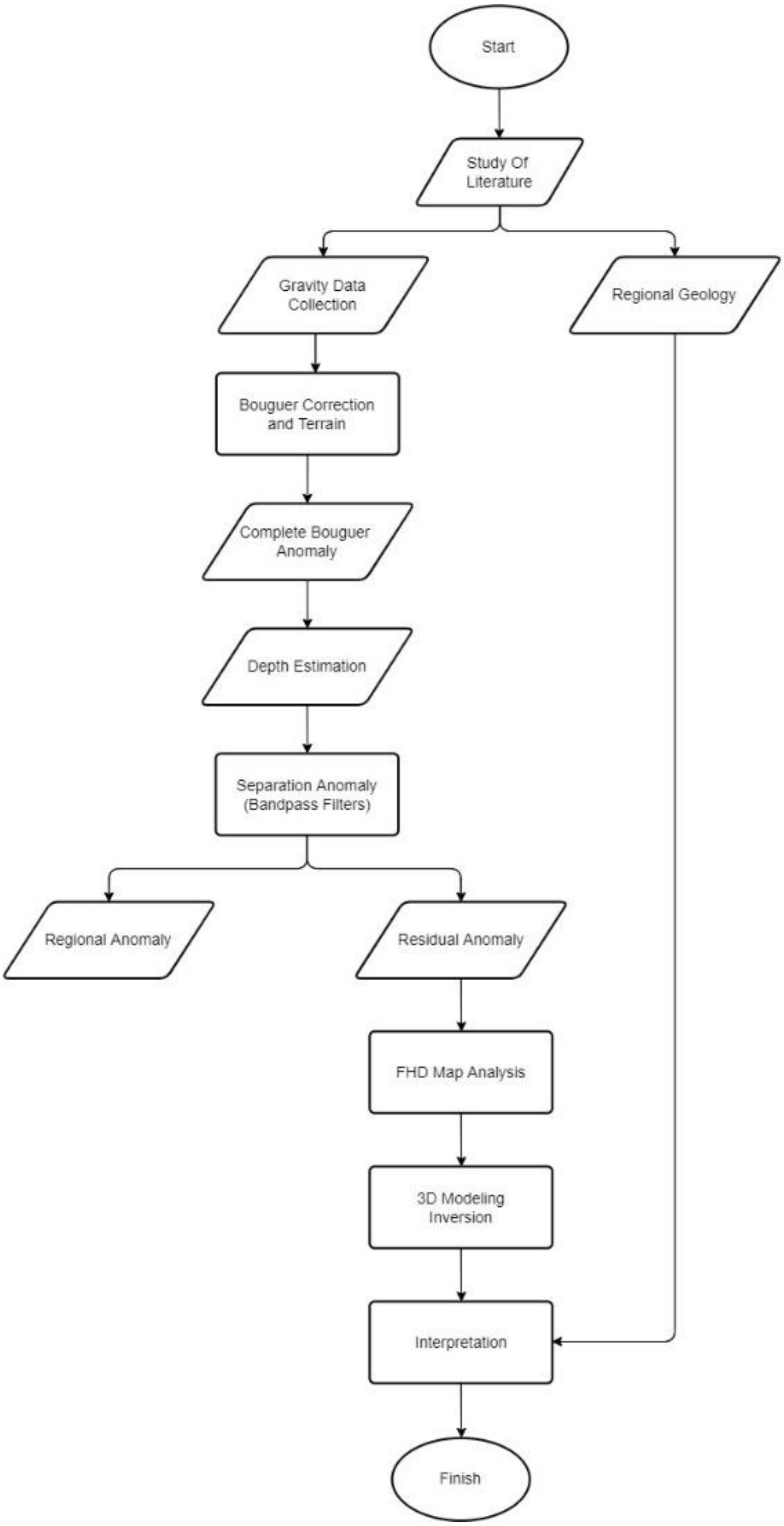

Figure 2. Research Workflow.

4. RESULTS AND DISCUSSION

4.1. Complete Bouguer Anomaly Analysis

In the final result of processing the gravity data in the form of a CBA map, it can be seen in the CBA figure (**Figure 3**) where the gravitational anomaly on the CBA map has anomaly values of around 94.8 – 106.1 mGal where the low anomaly has a value ranging from 94.8 – 97.6 mGal which is in the northeast of the study area where the low anomaly is associated with The Alluvial Formation (Qa) which is made up of silt, sand and gravel (Bianco et al., 2019), where this formation is spread around the Borobudur temple, the moderate anomaly has a value ranging from 98 - 100 mGal which is in the middle of the study area and the high anomaly has a value ranging from 100.4 - 106.1 mGal which is in the west the power of the research area associated with volcanic activity igneous rock deposits from the Menoreh Mountains.

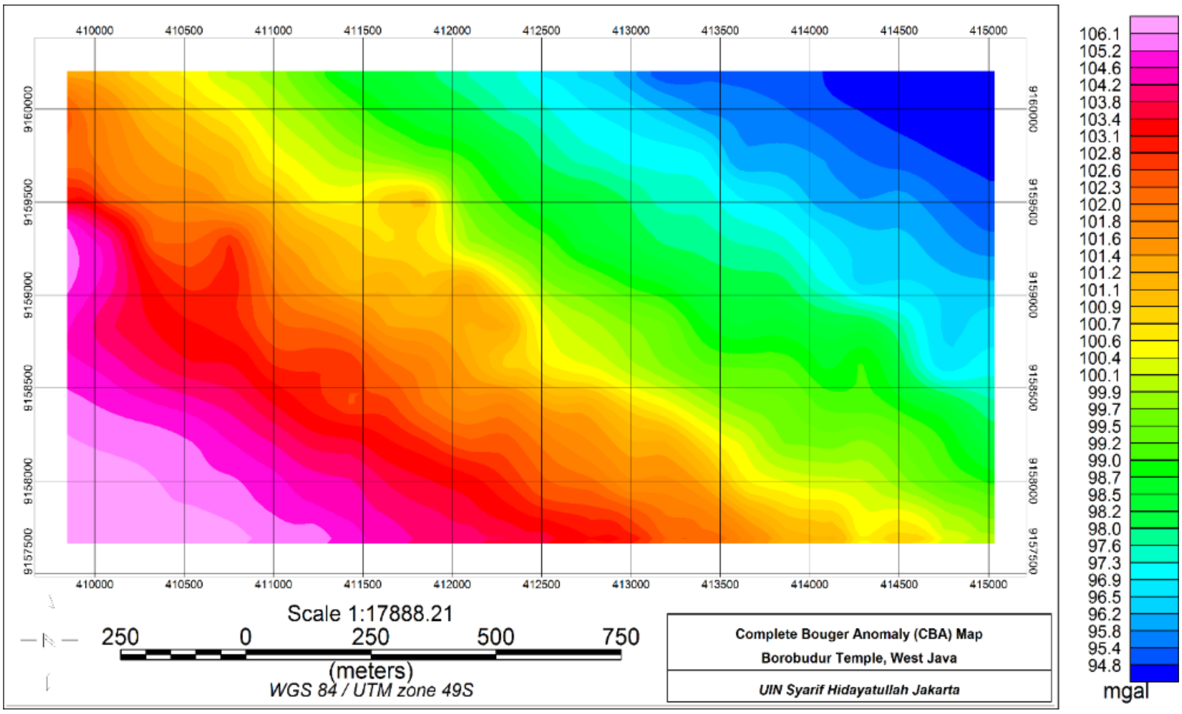

Figure 3. Complete Bouguer Anomaly (CBA) Map.

4.2. Residual Map Analysis

Residual anomaly is an anomaly that arises due to shallow rocks or close to the ground surface, on the residual anomaly map (**Figure 4**) it can be seen that the shape of the regional anomaly map has quite varied contours because shallow rocks have various rock types or rock type heterogeneity, where this is a criterion for residual anomalies where the shallower rocks will become heterogeneous, the residual map below has anomaly values ranging from -0.539 – 0.627 mGal.

High distribution anomalies are almost found in the entire study area but low anomalies are at the bottom of the Borobudur temple and in the eastern part of the study area with anomaly values ranging from 0.004 – 0.627 mGal and low anomalies are found in the west, south and east which are associated with the alleged presence of sedimentation and igneous rock of volcanic activity during the mountainous era which is thought to be an ancient lake under the Borobudur temple with a normal value ranging from -0.539 – (-0.209) mGal, it can be seen that the residual map is correlated with the approximate distribution map of ancient lakes.

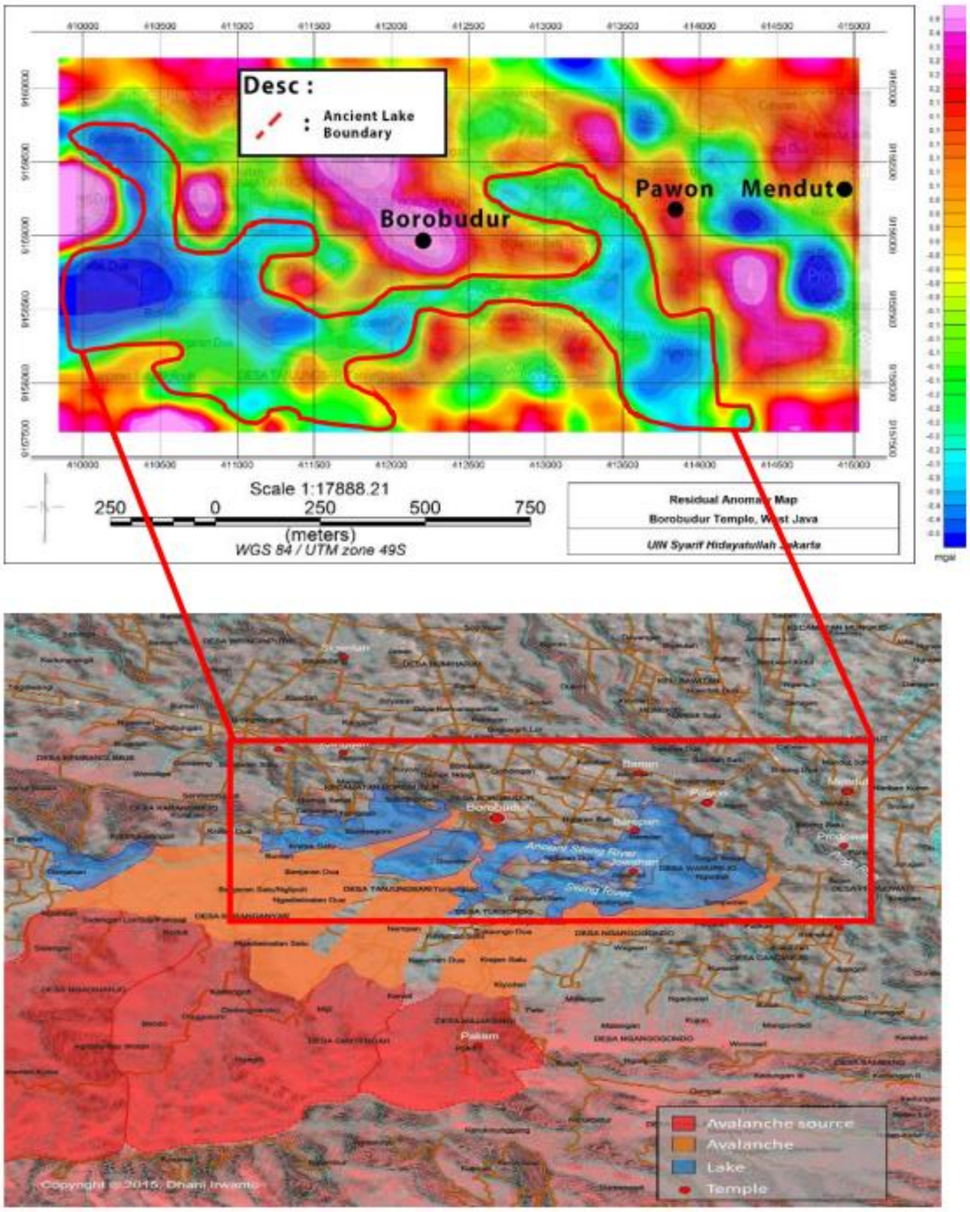

Figure 4. Residual Anomaly Map.

4.3. Geological Structure Identification

The identification of this geological structure aims to validate the existence records of tectonic activity around the Borobudur temple which according to information, this tectonic activity resulted in landslides in the Menoreh Mountain which were also triggered by rainfall and earth's gravity. The existence of geological structures will help accelerate the occurrence of rock weathering and the potential for landslides to occur. The landslides that cover the Sileng River may not be able to collapse with the flow so the lake will remain. The drying of the lake was caused by the deposition of material carried by the flow from the catchment area and volcanic ash from the eruption of Merapi.

Identification of this structure is done using the First Horizontal Derivative (FHD) filter, where this filter serves to see the existence of structures below the surface by looking at the highest anomaly in the filter results, as shown in the FHD image (**Figure 5)** around the Borobudur temple there is a geological structure with anomaly values of approximately 0.00289 – 0.00480 mGal.

4.4. 3D Inverse Modelling

This 3D modeling objective is to see the distribution of the ancient lake that is below the surface of the Borobudur. In 3D Figure below (**Figure 6**), you can see many slicing namely A – A', B – B', C – C' D – D', and E – E' that runs north-south. The results of the subsurface model show two rock compositions that are thought to be thin igneous rocks which are thought to be the result of volcanic activity as a layer of top-soil with depths ranging from surface to 100 m with contrast values. the density is around 0.02 – 0.05 mGal, then there is an alluvium layer which is thought to be an ancient ancient lake with a depth of 50 – 1100 m with a density contrast value of about -0.05 – (-0.02) mGal.

The depth on the 3D model corresponds to the depth map. This starts from 50 – 525 m, the alluvial layer which is thought to be an ancient lake is spread over the east, west and south of Borobudur temple, and at a depth of 250 – 525 m. The alluvial layer which is thought to be an ancient lake is seen just below Borobudur Temple, depth map This adds to the belief that it is suspected that the ancient lake under Borobudur Temple has a depth of 250–525 m. For more details, the depth map image can be seen below (**Figure 7**).

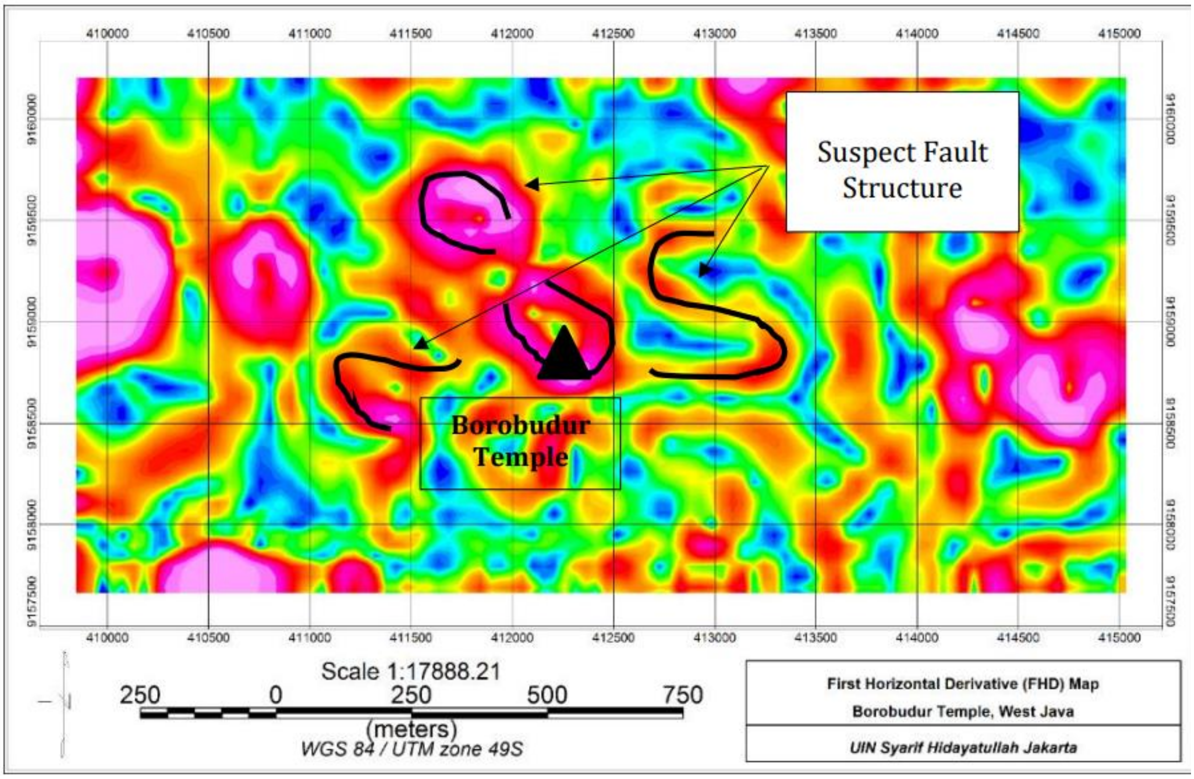

Figure 5. First Horizontal Derivative Map.

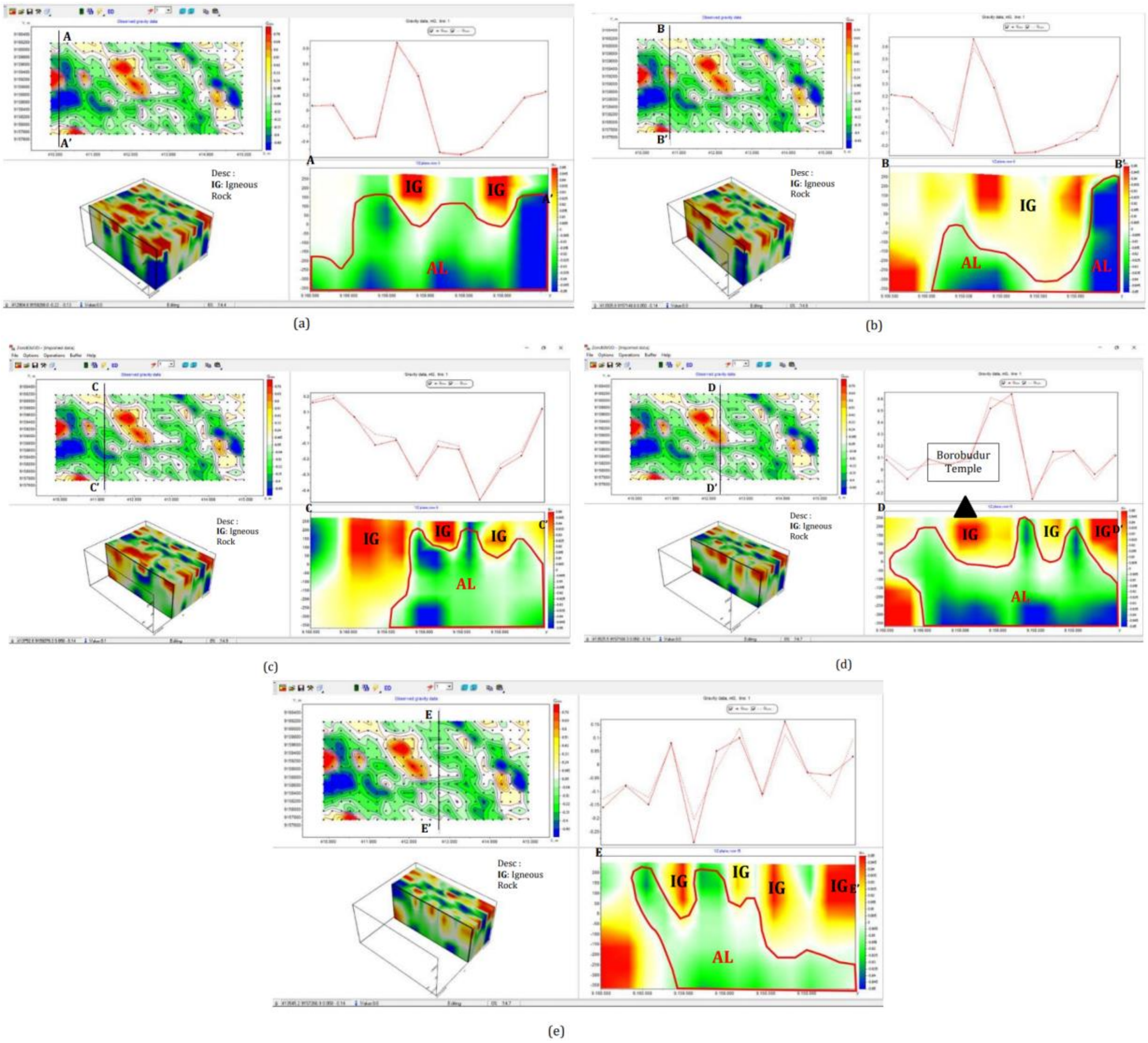

Figure 6. 3D Inverse Modelling (a) A - A', (b) B - B', (c) C – C', (d) D – D', (e) E - E'.

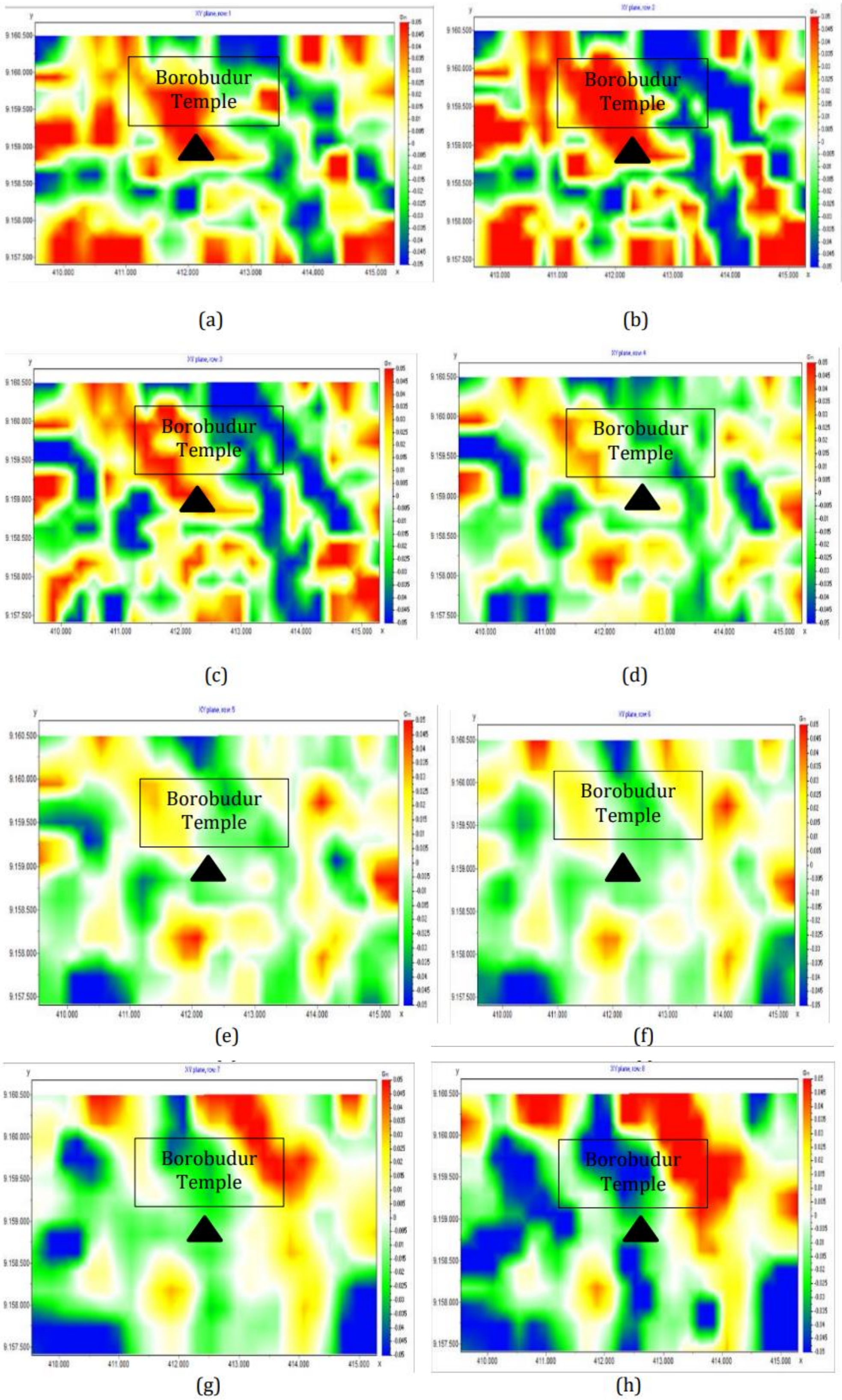

Figure 7. Depth Map Anomaly (a) Surface, (b) 75 m, (c) 150 m, (d) 225 m, (e) 300 m, (f) 375 m, (g) 400 m, (h) 525 m.

5. CONCLUSION

Based on the results of research conducted with the gravity method in the Borobudur Temple Area, Central Java, it can be concluded that:

a. According to the results of the Residual Anomaly Map, it can be seen that the distribution of the ancient lakes around the Borobudur temple has low anomalies located in the west, south and east with anomaly values ranging from -0.539 – (-0.209) mGal, it can be seen that the residual map is correlated with the distribution map of ancient lakes.
b. Based on geological structure Identification using the First Horizontal Derivative (FHD) filter, there is a geological structure around the Borobudur temple with an anomaly value of around 0.00289 – 0.0480 mGal.
c. In 3D modelling and the depth map are correlated with estimates of ancient lakes around the Borobudur temple with a depth of 50 – 525 m alluvial layers with a density contrast value of around -0.05 – (-0.02) mGal which is suspected to be an ancient lake spread over the east, west and south of Borobudur temple, and at a depth of 250 – 525 m an alluvial layer with a density contrast value of around -0.05 – (-0.02) mGal which is forgotten as an ancient lake is seen under the Borobudur temple.

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