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GRAVITY INTERPRETATION OF MUD VOLCANO BASED ON SATELLITE DATA (STUDY CASE KUWU AND CANGKRING MUD VOLCANO)

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ABSTRACT

A mud volcano is one type of mountain in the world. Mud volcano has specific characteristics. In Java, several mud volcanoes spread from west to east of Java. Bledug Kuwu and Bledug Cangkring are mud volcanoes in Central Java. Research on the Bledug Kuwu and Cangkring mud volcanoes systems still needs to be done. In this preliminary study, the gravitational field analysis of the Kuwu-Cangkring mud volcano system was done using GGmPlus satellite data with a 220 m grid and elevation data using ERTM. Free air anomaly data processing obtained a complete Bouguer anomaly value of 23 to 34 mGal. The separation process of anomalies using the upward continuation method produces a local of -0.5 to 0.5 mGal and a regional of 23 mGal to 34 mGal. The local anomaly value of Bledug Kuwu was -0.275 to - 0.05 mGal and Bledug Cangkring-0.125 to 0.1 mGal. The local anomaly around Bledug Cangkring is higher than Bledug Kuwu, indicating a lower density beneath Bledug Kuwu than in Cangkring.

Keywords: gravity; Kuwu–Cangkring; Mud; Volcano

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INTRODUCTION

A mud volcano is one of the geological phenomena that appear on the surface, which is the release of material from the earth in the form of mud or mire. As volcano materials, mud material moves out and may contain various mineral elements. Some of the minerals contained in the mud material can be useful. There are some unique minerals in the mud material named rare earth metals. Several studies explain that rare earth metals in mud volcano formations can support today's advanced technologies [1-2].

The formation of mud volcanoes is associated with various endogenous events such as earthquakes, subsurface stresses, and strains. Mud volcanoes are built from mud diapirs. Diapir is a rock intrusion due to the difference in pressure and buoyancy. Intrusion is generally vertical, involving relatively mobile low-density rock breaking through higher-density rock, usually through fractures. The process of breaking through the diapir can result in the formation of folds (anticline). Mud volcanoes will extrude liquids such as hydrocarbons and gases. The gases contained are methane, carbon dioxide, and nitrogen. During extrusion, fluid movement from the deeper layer occurs due to pressure from within. The liquid under pressure will push the labile cracks. In principle, the releasing liquid/material is the same as in other volcanic eruptions. The difference occurs in the amount of pressure, temperature, and type of material. The mud volcano's temperature is lower than that of ordinary volcanic material. The material is very soft grains suspended in a liquid [3-8].

Several studies using different methods have been conducted by previous researchers focusing on Bledug Kuwu. Bledug Kuwu is the main focus because of its higher activity, and the Kuwu area is more expansive than Cangkring. Research has been carried out using various geophysical methods such as seismic, geoelectric, magnetotelluric, audio magnetotelluric, gravity, and magnetism. Geological research uses geochemical analysis to obtain data on the mineral composition contained in the Bledug Kuwu mud. Several scientists conducted research using geoelectric, SP, and IP methods, and the results of the electromagnetic method research (geoelectric, IP, and SP) are the basin model and the dome model with the alleged presence of a salt dome [9-12]. The seismic research of Bledug Kuwu yielded information on the suspected presence of a salt dome and channel structure that caused the eruption in Bledug Kuwu. The results of the seismic method are similar to those of the electromagnetic method. Seismic and electromagnetic research in Bledug Cangkring has yet to be carried out. Research on the potential field method found negative anomalies around Bledug Kuwu and suspected faults in the Kuwu area [13-15].] Geological research that observed the presence of anticline found anticline-syncline structures and bedrock models [16-18]. Bledug Kuwu and Bledug Cangkring are known to be close to the active deformation zone. Still, the subsurface structure has not been validated yet, considering that the a0rea is associated with a depression zone containing hydrocarbons.

After 2022, several tectonic activities increased, triggering the activity of Bledug Cangkring, which caused a wider area to be affected by mudflow. The increased activity that caused the mudflow area to expand is of particular concern for economic, social, and mitigation. Bledug Kuwu and Cangkring are located close together, 1.3 km away. Bledug Cangkring’s dimensions are smaller and younger than Kuwu’s. The last activity of Bledug Cangkring was in February 2022 and March 2024. The activity of Bledug Cangkring was lower than that of Bledug Kuwu. Bledug Kuwu has two large and several small craters, and mud continues to erupt. Bledug Cangkring has only one open medium crater whose activity is not visible but suddenly releases large amounts of mud. Because research on the subsurface of Bledug Kuwu and Cangkring has not been carried out, this study aims to analyze the subsurface system of Bledug Kuwu and Cangkring using gravity field data. The initial analysis focused on local and regional anomaly analysis in the Kuwu - Cangkring area using GGmPlus gravity satellite data. GGmPlus satellite data is reliable enough to help obtain an initial result of the research area before applying a more comprehensive study by density analyses and other methods [19-22].

MATERIALS AND METHODS

The basic theory of gravity method is Newton's concept of gravitation. This concept describes the action-reaction between 2 masses at a distance. The further away, the smaller the gravity. The various densities affected the gravitation value. The dimensions, densities, and space of a mass to another mass will affect the value of gravity [23]. Newton's concept of Gravity is Equation (1).

$$\vec{g}_z(\vec{r}) = \frac{\partial U_z(\vec{r})}{\partial Z} = -G \int_V \frac{\rho(\vec{r}_0)(Z_0 - Z) d^3\vec{r}_0}{[(X-X_0)^2 + (Y-Y_0)^2 + (Z-Z_0)^2]^{3/2}} \quad (1)$$

The density variation will determine the anomaly value. Density variations vertically and horizontally will give different anomalous responses on the surface. So that the modeling carried out will give the distribution of the density values below the surface. The complete Bouguer anomaly is gravity observations (g_{obs}) corrected for latitude, density, and topography. The latitude correction is called normal gravity or gravity latitude (g_n). Topographic correction is the correction of the gravity value to the height of an observation point. This correction is called the Free Air Correction (FAC). This correction ignores the mass below the surface. The mass correction is calculated in terms of Bouguer correction (*BC*), curvature correction (*CC),* and terrain correction (*TC*) [21]. The complete Bouguer anomaly calculation is Equation (2).

$$CBA = g_{obs} - (g_n - FAC + BC + CC - TC) \quad (2)$$

The gravity data used in this study was a satellite gravity field and elevation by GGmPlus. The GGmPlus is very useful for preliminary research [22]. GGmPlus data download from Curtin Laboratory. The research area was from 7.105° S to 7.135° S and 111.10° E to 111.135° E. The raw data consists of longitude and latitude coordinates, elevation (h), and gravity disturbance or free air anomaly. The density variation will determine the anomaly value. Density variations will give different anomalous responses on the surface. The complete Bouguer anomaly is gravity disturbance was corrected to latitude position, density value, and topography condition[21]. Topographic correction is the gravity correction to the height and mass of an observation point. GGmPlus data is provided as FAA-corrected data, so no further FAA corrections are required. GGmPlus data is gravity disturbance data equivalent to FAA data. The correction was used in terms of Bouguer correction (*BC*), curvature correction (*CC),* and terrain correction (*TC*). The CC was ignored because the height difference was not too much. The average density value was calculated using the Parasnis method [23]. The average density used in Bouguer and terrain correction. In this research, curvature correction was not used because the elevation difference was only 50 m, and the curvature correction must be applied if the elevation is more than 2900 m.

Bledug Kuwu and Bledug Cangkring are in the Ngawi stratigraphy and geological area. The stratigraphy of the research location refers to the stratigraphy of the Northeast Java Basin from the Rembang Zone and Kendeng Zone (Figure 1). The Bledug Kuwu mud volcano and its surroundings are in the Kendeng Zone. The Kendeng zone consists of the Tawun, Kalibeng, Klitik formations of the Kalibeng, Kerek, Ngrayong, Madura, Wonocolo, Ledok, Mundu, Selorejo and Tambakromo formations [24].

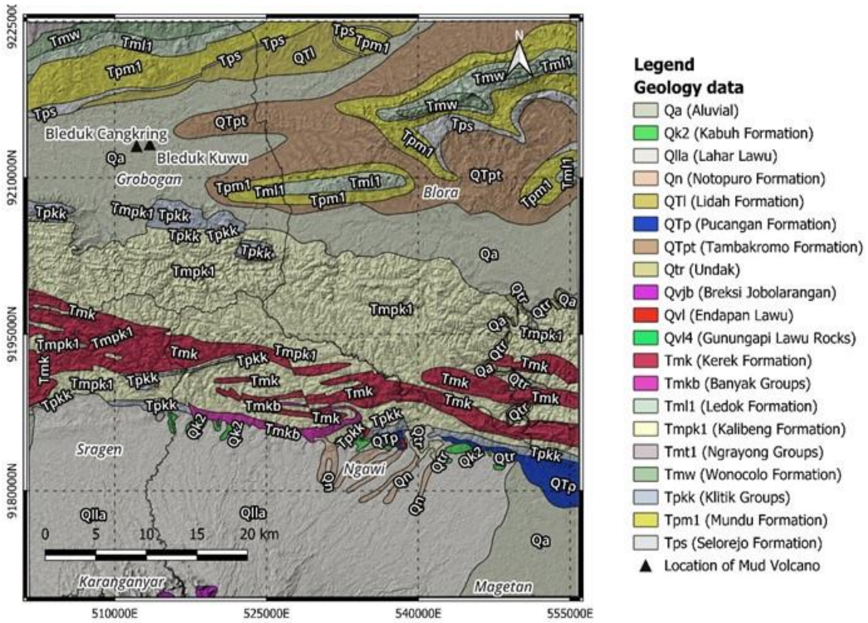

Figure 1. Geological Map of Ngawi

RESULT AND DISCUSSION

The GGmPlus satellite data of the Bledug Kuwu - Cangkring area produces a Free Air Anomaly (FAA) value of 23 mGal to 34 mGal. The FAA contour pattern tends to the northwest. FAA is 26 mGal to 35 mGal in the northwest, and the FAA value decreases in the northeast, southeast, and northwest. Bledug Kuwu - Cangkring has an anomaly area of 29 mGal to 31 mGal. On the FAA contour, no anomalies appeared in the Bledug Kuwu - Cangkring area. Higher FAA values in the west are related to the topography of the research area, which tends to be lower in the west. The eastern side of the research area leads to a higher plain or a hilly area. From a physical concept, it is explained that lowland areas respond more to gravity than hilly or highland areas. The FAA map of the Bledug Kuwu - Cangkring area is mapped as shown in Figure 2.

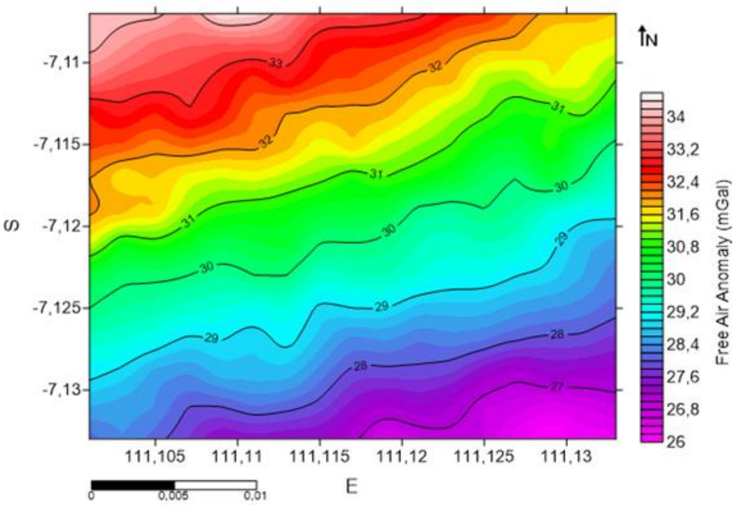

Figure 2. The map of Bledug Kuwu and Cangkring free air anomaly generated by GGmPlus

Bouguer and terrain correction calculations are applied to obtain the complete Bouguer anomaly value. To calculate those two corrections, an average density calculation is required. Calculating average density value can use several methods such as Parasnis and Nettleton.

GGmPlus data is satellite data resulting from mathematical model calculations and terrestrial data owned. The mathematical model uses the average density value of 2.67 g/cc, so the average density value can also be the value of 2.67 g/cc. The local area's average density must be calculated to find the rock density in the research area. The method used in density calculation was the Parasnis. The Parasnis' method calculated the slope of A versus B. The A value was Bouguer correction minus terrain correction (*BC-TC*). In contrast, the B value was gravity observation value minus latitude correction plus its free air anomaly value (gobs – gn – *FAC*). Such gradient value was an average density value in the research area [23].

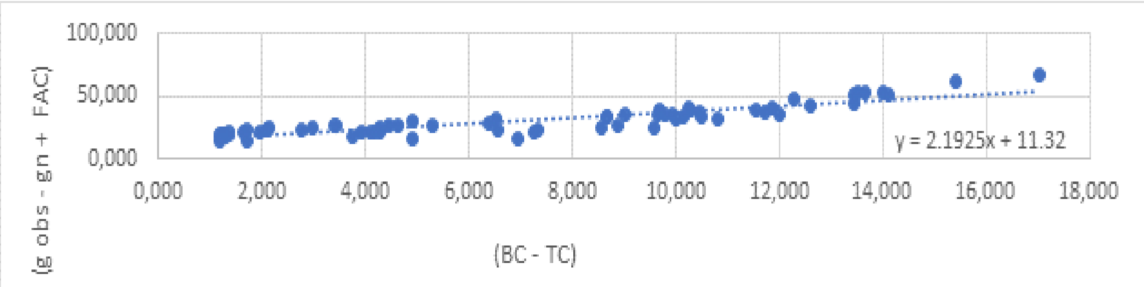

Figure 3. Parasnis method of average density graph

The average density value in this research was 2.1925 g/cc. The graphic in Fig.3 shows the average density gradient. Based on the Ngawi geological map, the rock formation consists of sediment with sand, alluvium, clay, limestone, marl, and coral. Those rocks fill the syncline, and the density of those rocks is 1.92 g/cc to 2.55 g/cc [25]. The Bledug Kuwu – Cangkring rock formation dominates with clay, marl, and limestone [26]. A large amount of clay and gas beneath the surface allows the occurrence of a mud volcano, and the endogenous activities trigger the mud volcano.

Bouguer's correction value is 4.4 mGal to 6.4 mGal. The Bouguer correction of the Bledug Kuwu – Cangkring area is 4.9 mGal to 5 mGal. The Bouguer Correction map is shown in Fig. 4. In theory, the highland area will have a larger correction value than the lowland area as a response to the thickness of the subsurface mass [27]. The Bouguer correction value obtained has not been able to explain how the density variation in the Bledug Kuwu - Cangkring area is.

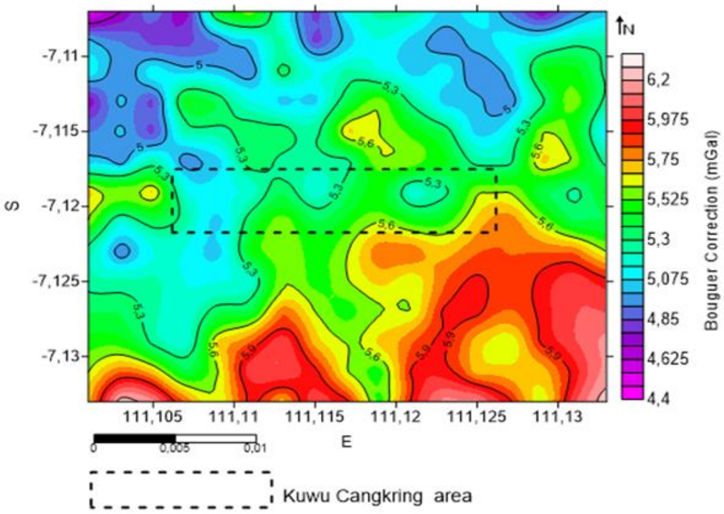

Figure 4. Bouguer correction map on Bledug Kuwu - Cangkring mud volcano

The Bouguer correction map shows that the Kuwu - Cangkring area is in the moderate value of Bouguer correction. In general, the Bouguer correction contour pattern has a contour trend that is almost the same as the FAA contour map. The distribution of the Bouguer correction value is getting more prominent towards the southeast and decreasing towards the northwest. Still, the contour line is wavier/ more undulation in the center area. The Bouguer anomaly's value can be calculated using the Bouguer correction value. The anomaly Bouguer value is 20 mGal to 30 mGal. The contour map of the Bouguer anomaly is smoother than the Bouguer correction map because the contour undulation is reduced. The Bouguer anomaly map has the same trend as the FAA but has more details on the area around Bledug Kuwu – Cangkring. The Bouguer anomaly value is lower than the FAA. Some older gravity research with terrestrial data shows the exact contour of anomaly Bouguer as satellite gravity data so that satellite gravity data can be used for the preliminary study [10,22,28].

The topography of the Bledug Kuwu – Cangkring area is relatively not sharply undulating, so the curvature correction can be ignored. Calculate terrain correction using ERTM data to obtain a terrain correction value of 2.6 mGal to 5 mGal. The terrain value is high in the northeast and northwest, and the value decreases towards the south and southeast. The terrain correction on the Kuwu – Cangkring area is three mGal to 4 mGal. The south and southeast of the Bledug area are higher. Still, the undulation is not much, so the correction is about 2.6 mGal to 3.0 mGal—Bledug Kuwu – Cangkring surrounding with higher terrain correction value. The higher value of terrain correction on the northwest to the northeast area indicates more elevation variation around those areas. The terrain correction distribution is shown in Figure 5.

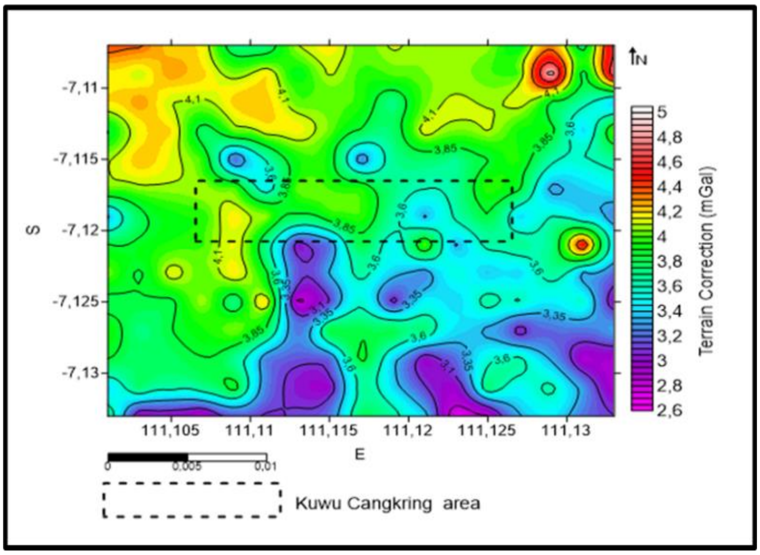

Figure 5. Terrain correction map on Bledug Kuwu – Cangkring mud volcano

The final result of the advanced processing was a complete Bouguer Anomaly/CBA mapped in Fig. 6. The CBA map has almost the same contour lines as the FAA but is wavy (undulation). Bouguer and terrain correction contribute to the wave pattern on the CBA contour line. The distribution of values is still the same as in the FAA, with values that are not much different. The accumulated Bouguer and terrain correction values affect the CBA values but not much. The map coordinates are changed to UTM coordinates in meters to facilitate further processing.

The CBA value was 23.0 mGal to 33.8 mGal. A CBA value consists of low, medium, and high values. A low CBA value from purple to dark blue with a CBA value is 23 mGal to 25 mGal. A low CBA value spread from the southeast to the southwest. A medium CBA value of green to yellow color ranges from 27.0 mGal to 31.0 mGal. The medium CBA spread from the east to the west. A high CBA value from orange to red color ranges from 31.0 mGal to 33.8 mGal. This CBA value spread from the south to the northeast to the northwest. CBA Kuwu - Cangkring area is 27.8 mGal to 30 mGal. Bledug Kuwu's CBA is lower than Bledug Cangkring's, the difference is two mGal. The CBA contour pattern in some areas is close so that it can be predicted as a part of the syncline structure in the study area [16,18,22,26]. The dense contour line has a southwest-northeast direction, and it is located south of Bledug Kuwu and Cangkring.

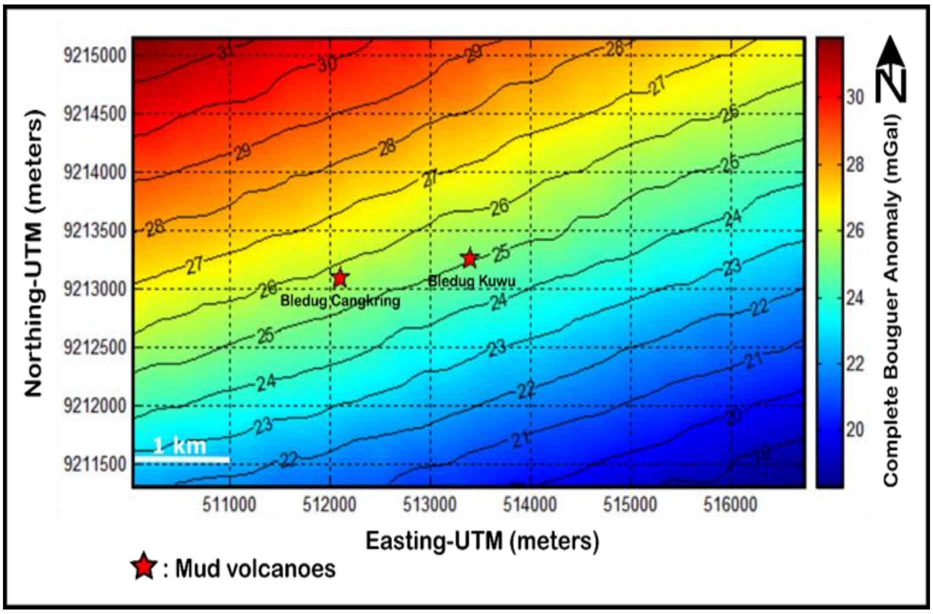

Figure 6. The map of Complete Bouguer Anomaly contour of Bledug Kuwu dan Cangkring

The CBA value has yet to be able to explain the gravity response in Kuwu and Cangkring more clearly. For this reason, an anomaly separation process is needed. CBA is a total response to local and regional anomalies beneath the surface therefore, it must be separated. Many separation processes, such as upward continuation, moving average, polynomial, and wavelet, can be used. This separation process uses a simple method, namely upward continuation. The continuity method can be used for the initial interpretation of a study. Other separation methods, such as inversion modelling, will be used for more detailed separation processes. In this process, the gravity value is calculated at several heights to obtain the consistency of the contour line pattern. The initial process of this method is to get regional anomaly values. The local anomaly is the difference between the CBA and regional values. The results of the separation are mapped as shown in Figure 7 and 8. Figure 7 is a contour map of local anomaly values and Figure 8 is a regional anomaly contour map.

The local anomaly value in the study area is -0.5 mGal to 0.5 mGal, while in the Bledug Kuwu - Cangkring area, it is -0.3 mGal to - 0.1 mGal. The local anomaly value of Bledug Kuwu was -0.275 to - 0.05 mGal and Bledug Cangkring-0.125 to 0.1 mGal. The local anomaly of Cangkring is higher than that of Bledug Kuwu, but the local anomaly around Cangkring is lower than that of Bledug Kuwu. Regional anomalies have contour patterns like the FAA and CBA contours, but the contour patterns are smooth. Regional anomaly value 23 mGal to 34 mGal. The regional anomaly value of the study area is 30 mGal to 34 mGal, located from the northwest to the northeast. The highest value is in the northwest, while the lowest is in the southeast. The low anomaly of 23 mGal to 26 mGal is represented by dark blue to purple colors. The green to yellow color gradation represents the anomaly value of 27 mGal to 29 mGal, representing the moderate anomaly.

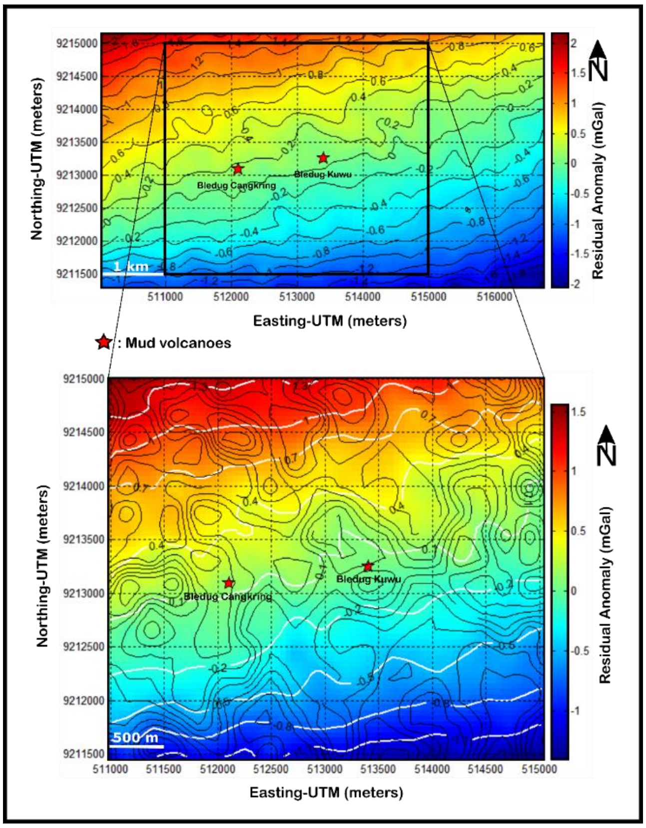

Figure 7. The map of the local and regional contour of Bledug Kuwu dan Cangkring.

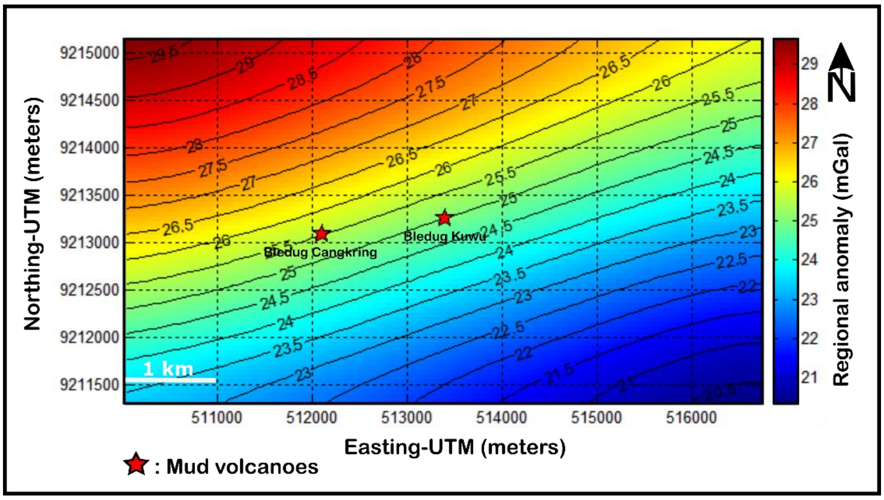

Figure 8. The map of regional anomaly of Bledug k Kuwu dan Cangkring.

The difference in the value of the FAA anomaly to the regional anomaly is only three mGal. This can be explained that there is no considerable subsurface density variation. Although there are mud volcanoes, the regional anomaly manifestations of mud volcanoes are not identified. A mud volcano dimension causes Bledug Kuwu - Cangkring, which are not enormous mud volcanoes; their density is different from that of common volcanic volcanoes. A volcano is built by volcanic rock, which is denser, and also erupts some magma, which has high density [24,28,29]. The volcano will be a huge material on the surface, which adds much gravity response. Much gravity response can be identified in a regional anomaly. In a small response, the local anomaly is usually used to determine the condition beneath the surface. The local anomaly of Kuwu–Cangkring describes the presence of mud volcanoes.

The low anomaly zone is thought to be related to the presence of mud and gas that appears as a mud volcano eruption. Minimum anomalous values are often associated with low-density materials. Seismic research resulted in low seismic propagation in the Bledug Kuwu area, indicating a non-solid phase. The material fluid causes slower seismic wave propagation [13-15]. The results of the resistivity study also produced a pattern of decreasing resistivity values towards the Bledug Kuwu area [11]. The anomalous value in the area around Bledug is higher. A high anomaly indicates the presence of a material with a higher density. Materials containing more water and gas will have lower density values. Materials with higher water content will have higher conductivity values, while denser materials may have higher resistivity.

Some studies suspect the existence of a salt dome in Kuwu. The existence of a salt dome indicates the presence of brine water in the research area [11]. The first step of gravity satellite processing has not been able to describe the presence of a salt dome. Completing the process by inverse density modeling is needed to obtain maximum results describing the salt dome. Previous gravity studies using terrestrial data showed anticline structural patterns. This anticline structure contributed to the formation of Bledug Kuwu and Cangkring.

The local anomaly values in the south and north of Bledug Cangkring are lower than those in Bledug Kuwu. In addition, the low anomaly closure is also wider than the one in Bledug Kuwu. These results may be of concern regarding future mud volcano activity. Complete research and more methods are expected to provide an overview of the activities of Bledug Kuwu and Cangkring in the future. Comprehensive geophysics studies in Lusi, Sidoarjo, Kalang Anyar, and Tawang alun indicate the presence of fault structures associated with mud volcano activity. The research also shows the relationship between mud volcanoes and each other, which are located on the same fault line. Identifying the presence of mud in a hydrocarbon basin is important because it relates to the potential for mud volcanoes. Mud volcanoes in Java, especially Central Java, are mostly associated with syncline-anticline zones and fault zones. A complete gravity analysis is expected to predict the distribution of syncline-anticline that could become new mud volcanoes that could appear around Bledug Kuwu. [4,5,7,9,22].

CONCLUSION

Free air anomaly data processing obtained a complete Bouguer anomaly value of 23 to 34 mGal. The separation process of anomalies using the upward method produces a local of -0.5 to 0.5 mGal and a regional of 23 mGal to 34 mGal. The local anomaly value of Bledug Kuwu was -0.275 to - 0.05 mGal and Bledug Cangkring-0.125 to 0.1 mGal. The local anomaly around Bledug Kuwis is lower than Bledug Cangkring, indicating a lower density beneath Bledug Kuwu than Cangkring.

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