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Interpretation of Magnetic Anomaly Data in the Andesitic Rock Prospect Area of Kutasari Subregency, Purbalingga Regency, Central Java, Indonesia

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Abstract - Interpretation of magnetic anomaly data has been carried out in the andesitic rock prospect area, Kutasari Subregency, Purbalingga Regency, Central Java, Indonesia. Geographically, this area is located within 109.2788° - 109.3072°E and 7.3032° - 7.3319°S. The study has been done in April – September 2019 with the purpose to map the distribution of andesitic rocks based on the local magnetic anomaly data. The data that are acquired in this study have the values ranging between -1,238.13 - 1,892.40 nT. The results of qualitative interpretation on the local magnetic anomaly data having been reduced to the pole show the distribution of strong anomalous sources in the northwest area interpreted as massive andesitic rocks. Whereas the results of quantitative interpretation through 2D-forward modeling on the local magnetic anomaly data show six anomalous bodies, with magnetic susceptibility values ranging from 0.0025 to 0.0350 cgs and depths range between 7.16 - 505.97 m. The highest magnetic susceptibility is 0.0350 cgs interpreted as a massive andesite intrusion forming a very dense dike; whereas the lowest magnetic susceptibility is 0.0025 cgs interpreted as undifferentiated igneous rocks, volcanic breccias, lava, and tuff. Based on the study results, the correlation between the results of qualitative and quantitative interpretations occurs.

Keywords: interpretation, magnetic anomaly data, andesitic rocks, magnetic susceptibility, Kutasari

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Introduction

Andesitic rock is one of the natural resources that are often found in nature, especially around volcanoes. Andesites can be formed due to very high volcanic activities, and they are often found in lava flows produced from stratovolcanoes such as Slamet Volcano. This rock has very strong resistance to weather and durable (Hardiyono, 2013). The results of technical testing show that the andesite rocks have an average unconfined compression strength (UCS) of 410.93 kg/cm^2, crushed resistance of 22.6%, and absorption of about 1.82%, so that it can be used as a building foundation and aggregate of building materials (Hardiyono, 2013). This rock is widely used to build various infrastructures such as roadways, bridges, irrigations, airstrips, ports, apartments, buildings, *etc*. Generally, the andesitic rock used for infrastructure is already in the form of aggregates from mining. This andesitic rock is also used for interior and exterior decoration, as well as classic and modern interior accessories (Prasadewo *et al*., 2016).

One region in Central Java which has a high potential of andesites is Kutasari Subregency, in Purbalingga Regency, especially Candiwulan, Karangcegak, Cendana, Bumisari, Candinata, and Karangjengkol Villages (Ariyanto, 2014). Those villages are located on the lower slopes of the southeastern Slamet Volcano, within the coordinates of 7°14′30″ S and 109°12′30″ E with a peak height of about 3,248 m (Pratomo and Hendrasto, 2012). The people around the area mine the andesite rocks with traditional technique in a massive scale, since it has high selling price. Andesite mining is always found in the lower slopes of the Slamet Volcano, especially in outcrop areas that occur in several locations (Figure 1**)**. However, random and seemingly illegal andesite mining activities resulted in several negative impacts such as collapsed cliffs, environmental damage, landslides, and others (Saputra and Heriyadi, 2019).

Geologically, the studied area and its surrounding areas are composed of various rock formations such as Alluvium (Qa), Laharic Deposits of Slamet Volcano (Qls), Andesitic Lava of Slamet Volcano (Qvls), Clay Member of the Ligung Formation (Qtlc), Kalibiuk Formation (Tpb), Tapak Formation (Tpt), Kumbang Formation (Tmpk), and Halang Formation (Tmph). The order of described rock formations, from young to old, is shown in Figure 2. The stratigraphic sequence closest to the researched area comprises Laharic Deposits of Slamet Volcano (Qls), Andesitic Lava Deposits of Slamet Volcano (Qvls), and Undifferentiated Igneous Rocks of Slamet Volcano (Qvs) (Djuri *et al*., 1996). The laharic deposits of Slamet Volcano consist of andesitic - basaltic lava with igneous rock boulders of 10 - 50 cm in diameter, produced from the eruption of the Old Slamet Volcano. These igneous rocks outcrop to the south of the studied area. The vesicular andesitic lava of the Slamet Volcano occurs on the eastern slopes of the Slamet Volcano, including the studied area and its surrounding areas, while the undifferentiated igneous rocks of Slamet Volcano comprise volcanic breccia, lava, and tuff forming plain and hills. These outcrops are found in the western part of the studied area.

Based on the geological map, the andesitic lavas, the objective of this study, outcrop on the

Figure 1. Several outcrops of andesites in the Candiwulan and Karangcegak Villages, Kutasari Subregency, Regency of Purbalingga, Central Java, Indonesia (source: personal documentation).

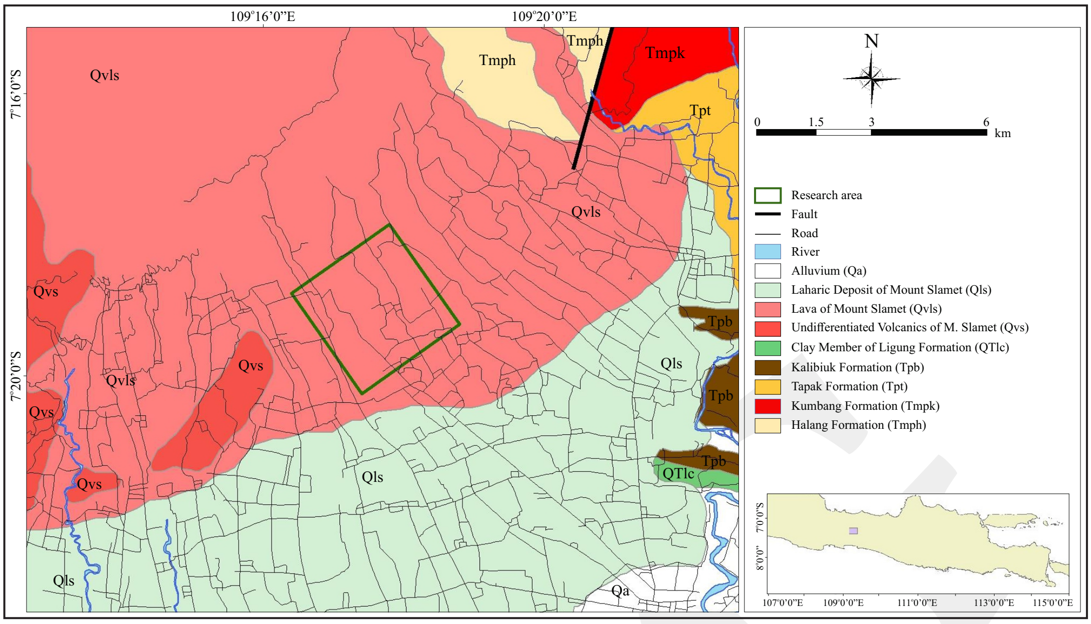

Figure 2. Geological map of the researched area (green lined rectangular). Surficially, the studied area is dominated by andesitic lava (Djuri *et al*., 1996).

uppermost stratigraphic layer in the studied area. Those lavas spread from the top of Slamet Volcano to the studied area which is located on the southeastern slope. The andesitic lavas consist of fractured massive and vesicular lavas. The massive lava is dark grey, with layering structure, having many cracks, sometimes forming a flow structure and aphanitic. However, several different phases of the lava flow formation occur to form different layers, besides the cracks. Whilst, the vesicular lava is dark grey with structure containing many holes, or regularly has small cavities. The existence of holes or cavities in the rocks is thought to be caused by the release of volcanic gases from the liquid lava after reaching the surface. As magma rises to the surface, the pressure on it decreases.

Resistivity observation has been conducted in the northwestern village of Candiwulan (Sehah *et al*., 2018) showing lithological structure in accordance with geological information. Andesitic lava is interpreted to occur at a depth of 0 - 0.24 m with a resistivity value of 366.12 Ωm, and a depth of 5.33 - 74.13 m with a resistivity value of 379.48 Ωm. Whereas very dense and massive andesitic lava boulder with resistivity values of 1223.54 Ωm is interpreted to be found at depths of 2.04 - 5.33 m. Undifferentiated volcanic rocks of Slamet Volcano consisting of lava, breccia, and tuff are estimated to be found at a depth of 74.13 - 84.43 m with resistivity values of 58.82 Ωm, a depths of 84.43 - 100.58 m with resistivity values of 33.21 Ωm, and a depths of 100.58 - 105.61 m with resistivity of 98.85 Ωm. The difference in resistivity values for the same rock formation is estimated due to differences in rock composition or rock physical condition (Hersir and Arnason, 2009), whereas andesitic lava intrusion is interpreted to be found at depths of 105.61 - 152.45 m with resistivity value of 330.19 Ωm (Sehah *et al*., 2018).

METHODS

One of the geophysical surveys which can be applied for mapping of the andesite distribution in the studied area is magnetic survey (Stella and David, 2015). Since the magnetic properties of andesite are large, the magnetic survey can be applied to localize large magnetic anomalous areas that are thought to be related to the presence of igneous rocks, *i.e.* andesitic rocks (Keane and Gilstrap, 2012; Joshua *et al*., 2017; Lino *et al*., 2018). In this study, the survey uses magnetic susceptibility as a tool to identify the types of subsurface rocks and geological structures (Oladejo *et al.*, 2019; Syukri *et al.*, 2018). The magnetic susceptibility value is also used as a basis for modeling and interpretation of magnetic anomalous sources in the subsurface (Dai, 2014; Li and Fu, 2018). Andesites have a value of magnetic susceptibility of 0.0025 - 0.0100 cgs (Zamora *et al.*, 2015), so that it is thought to contain several ferromagnetic minerals.

Magnetic survey for interpretation of the andesitic rock distribution in Kutasari Subregency, Purbalingga Regency, Central Java Indonesia, took place in April - September 2019. The studied area consists of several villages, namely Cendana, Candiwulan, Karangcegak, Candinata, and Karangjengkol Villages. The magnetic station points on the location map of the studied area can be seen in Figure 3. Magnetic data acquisition and geographical position measurement have been done together covering the studied area with the position of 109.2788° - 109.3072° E and 7.3032° - 7.3319° S. The processing, modeling, and interpretation of magnetic data have been done at the Geophysical Laboratory, Faculty of Mathematics and Natural Sciences, Jenderal Soedirman University, Purwokerto, Central Java, Indonesia.

The research began with the acquisition of magnetic data in the field, so that the total magnetic field strength data could be obtained. After several corrections and reductions applied, the local magnetic anomaly data can be acquired. The corrections applied are daily correction and IGRF correction (Telford *et al.*, 1990), whereas the reductions applied are reduction to the horizontal surface and reduction of regional magnetic effect (Blakely, 1995). The local magnetic anomaly data are magnetic anomaly data which is the target of this study, that represent the shallow geological conditions or subsurface rocks (Li and Oldenburg, 1998; Stella and David, 2015). The acquired local magnetic anomaly data is mapped and then interpreted, qualitatively and quantitatively. Qualitative interpretation is conducted on the local magnetic anomaly map that has been reduced to the pole (Blakely, 1995), with the aim to map the andesitic rock distribution in the studied area. Quantitative interpretation is conducted to acquire the anomalous object model interpreted as andesitic rocks based on the results of 2D-forward modeling on the local magnetic anomaly data (Bernard *et al.*, 2014).

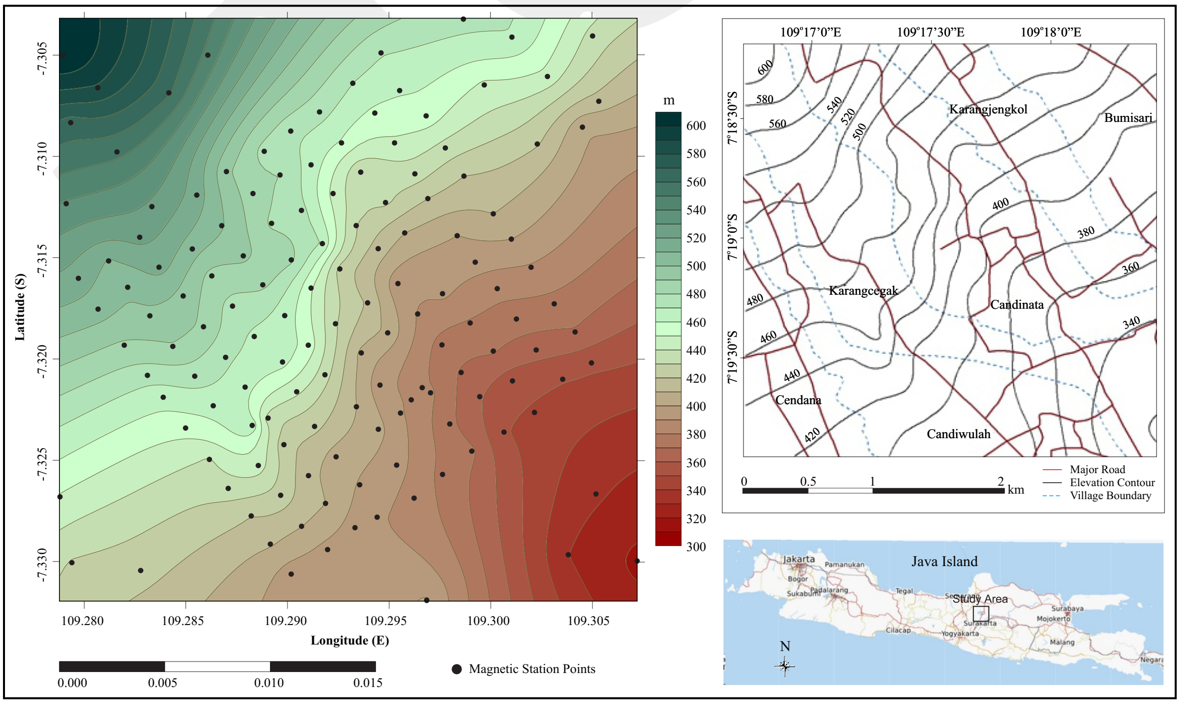

Figure 3. Topography and location maps of the studied area, Kutasari Subregency, Purbalingga Regency, Central Java, Indonesia.

RESULTS

Magnetic Data Processing

Magnetic data acquisition has been carried out at all station points as shown in Figure 3, where the results acquired are magnetic field strength data ranging from 43,467.99 - 46,888.65 nT. As magnetic data processing, daily and IGRF corrections are applied to remove the contribution of external magnetic field and main magnetic field of the earth to acquire magnetic anomaly data (Sehah *et al.*, 2017). Magnetic anomaly data acquired from this calculation have values varying from -1,376.79 - 2,037.26 nT. Furthermore, magnetic anomaly data are reduced to the horizontal surface using the Taylor Series approach (Blakely, 1995), where the horizontal surface is taken at an average topographic height of 438.04 m. After the magnetic anomaly data are distributed on the horizontal surface, then regional anomalies are removed (Ganiyu *et al.*, 2013) to obtain the local magnetic anomaly data (Ilapadila, 2019). Removal of regional magnetic effects are done by using upward continuation techniques which function as low pass filters (Telford *et al.*, 1990; Guo *et al.*, 2013), so anomalous contour pattern which has a relatively fixed trend is obtained. Based on the result of this calculation, the local magnetic anomaly data are acquired with values ranging of -1,238.13 - 1,892.40 nT. Furthermore, the local magnetic anomalous map of the studied area is presented in Figure 4.

Qualitative Interpretation

The local magnetic anomalous map shows the presence of high and low anomalous closures that are very strong in the northwest area. The presence of massive andesitic rocks associated with large magnetic dipole pairs is thought to be localized around that area (Yolanda *et al.*, 2018). Based on the geological information that the dominant rocks in the studied area are andesitic lava of Slamet Volcano (Qvls), the strong magnetic anomaly pairs will indicate strong subsurface anomalous sources, such as massive andesitic rocks. However, the local magnetic anomalous map in Figure 5 shows the complexity of the closures, which can complicate the modeling and interpret processes of the anomalous sources. One technique to reduce the complexity in the modeling and interpreting on the local magnetic anomaly data is to apply reduction to the pole

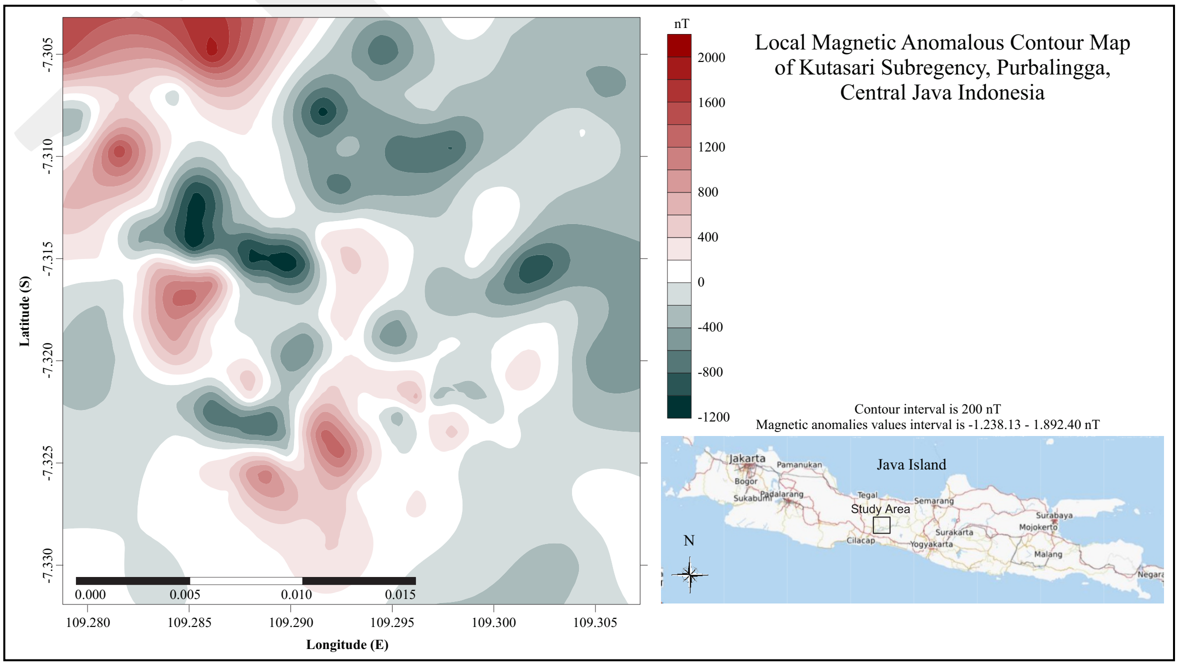

Figure 4. Local magnetic anomalous contour map of the studied area, where these data are distributed on the average topographic height of 438.04 m.

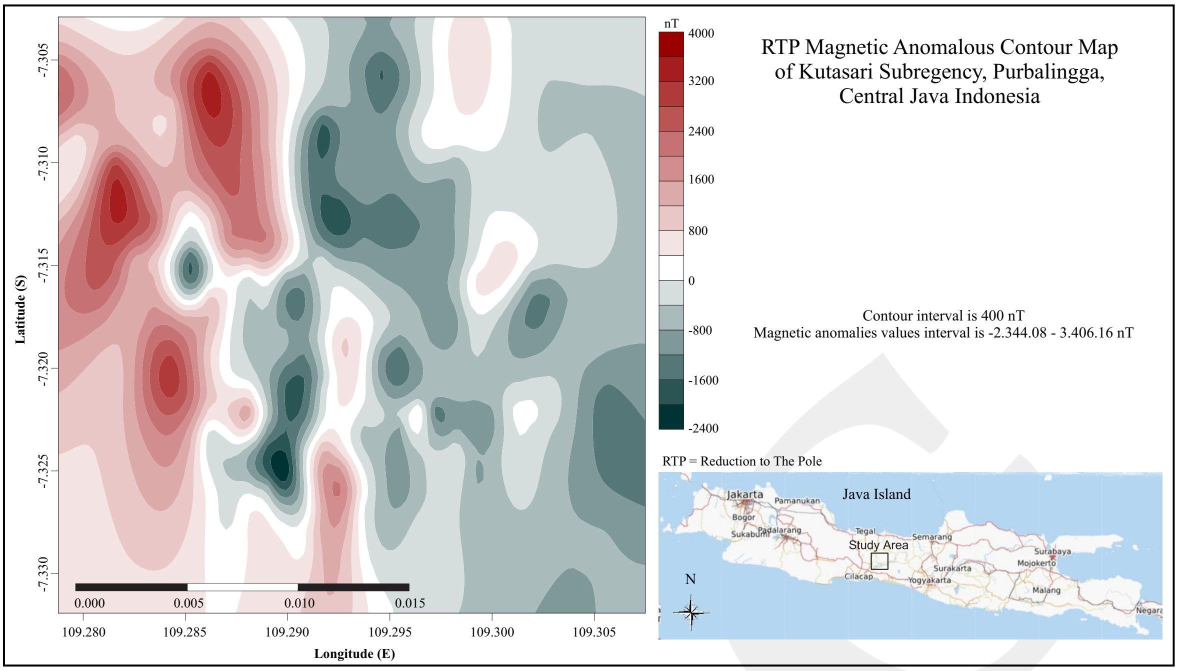

Figure 5. Local magnetic anomalous contour map of the studied area, which has been reduced to the pole.

(RTP). The magnetic anomaly data which have been reduced to the poles show a closure in the form of a monopole, and have a symmetrical pattern where the magnetic anomalous curve is in the form of a half wave. The anomalous object is just below the curve which has the highest amplitude, similar to the gravity anomalous curve (Limbong *et al.*, 2018). This magnetic data filter is needed to eliminate the influence of the magnetic inclination angle. Moreover, the field data are generally still in asymmetric form (Hiskiawan, 2016). The magnetic anomalous contour map of the studied area acquired from RTP calculation is shown in Figure 5 with values ranging from -2,344.08 - 3,406.16 nT. This contour map looks simpler and more informative than the local magnetic anomalous map, as presented in Figure 4.

The magnetic anomaly resulting from the RTP can be of high or low value according to the distribution and quantity of magnetic materials or minerals beneath the earth surface. The more magnetic minerals in the rock, the higher magnetic anomaly response will be. Conversely, if the magnetic minerals in the rock are few, the magnetic anomalies response will also lower (Masyithah *et al.*, 2018). Based on the magnetic susceptibility value, andesitic rock is a rock type with large magnetic properties. The magnetic susceptibility values of andesites have the value ranging of 0.00147 - 0.04900 SI (Li and Fu, 2018), where 1 cgs unit= 4π SI unit. The chemical composition of andesites is 55 - 65% SiO_2 with intermediate values in Fe, Mg, Ca, Na, and K (Nelson, 2011). This indicates that andesitic rocks respond strongly to the magnetic anomalous pattern as shown in Figure 6. Based on this, the massive andesites are interpreted to be located in the magnetic anomalous closure area of RTP, in the northwest of the studied area (red contour). The magnetic anomalous closure centres in this area have the values of 3,395.44, 3,396.77, and 3,406.16 nT, whilst the other areas are interpreted to be dominated by vesicular andesitic lava with structures forming many regular holes or small cavities (Iswahyudi *et al.*, 2018).

Quantitative Interpretation

Interval of local magnetic anomaly data has relatively large values, as exhibited in Figure 5. This, presumably, originates from massive igneous intrusions which might occur in the

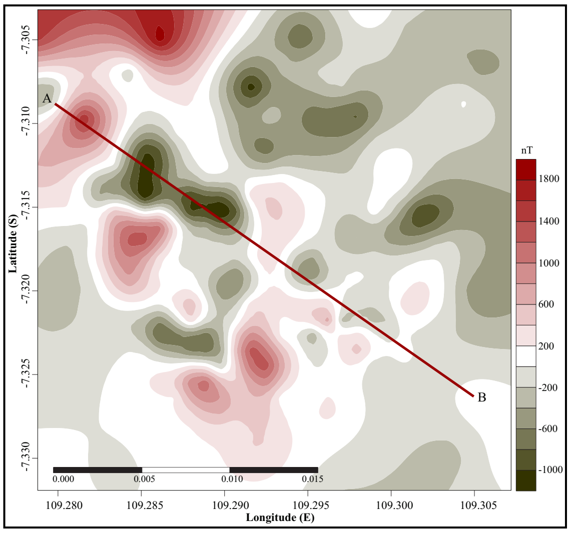

Figure 6. AB trajectory on the local magnetic anomalous map for modeling of the subsurface anomalous bodies.

studied area, especially in the northwestern part. To interpret the type of the subsurface rocks of the studied area, the modeling of the anomalous objects in the subsurface has been done in two dimensions (2D). The modeling begins by making a trajectory on the local magnetic anomalous map through several closures that show dipole pairs (Lino *et al*., 2018). These zones are estimated to be potential magnetic anomalous sources. The 2D-forward modeling is done to the local magnetic anomaly data extracted from AB trajectory (Figure 7). The magnetic anomaly data extracted are referred to as the observed anomaly data. The modeling has been conducted using Mag2DC for Windows (freeware version) by matching the calculated anomaly curve versus the observed anomaly curve (Al-Mufarji *et al.*, 2018). After both curves have matched, then six anomalous bodies assumed as the subsurface rocks are acquired (Figure 8). Whereas the parameters for modeling are presented in Table 1. In this modeling, the average rocks of the studied area are interpreted as andesitic lava with a magnetic susceptibility value of 0.0180 cgs, in accordance with developing geological information.

Lithologically, each anomalous object is interpreted based on the geological information to identify rock types. The average rock in the studied area is interpreted as andesitic lava layers of Slamet Volcano which have cavities with the average magnetic susceptibility value is estimated about 0.0180 cgs units. The magnetic susceptibility values of andesites are between 0.00147 - 0.04900 SI (Li and Fu, 2018), where 1 cgs unit= 4π SI unit. The average magnetic susceptibility value in the studied area is relatively

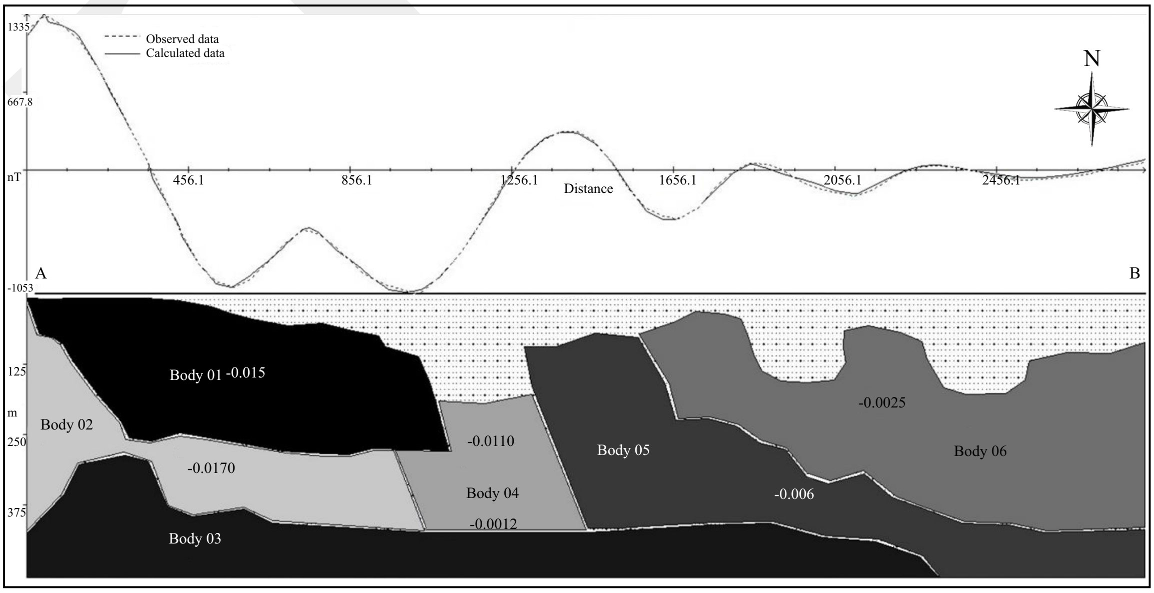

Figure 7. Results of 2D-forward modeling of the local magnetic anomaly data along AB trajectory, equipped with magnetic susceptibility contrast value of each anomalous body (modeling was conducted using Mag2DC for Windows 2.11 - freeware version).

Table 1. Parameter for 2D-Forward Modeling of the Local Magnetic Anomaly Data Along AB Trajectory

Parameter	Value	Parameter	Value
IGRF Value	44754.80	AB Trajectory Length	2768.50 m
Inclination Angle	-31.32°	Depth of Model	500.00 m
Declination Angle	0.72°	Anomalous Value Range	-1053.5 - 1313.3 nT
Profile Bearing	0.00°	Quantity of Anomalous Bodies	6 bodies
Reference Height	0.00 m	Magnetic Susceptibility Contrast	-0.0155 - 0.0170 cgs units
Strike Length	100.00 m	Anomalous Bodies Depth	7.16 - 505.97 m

closer to the maximum value of the magnetic susceptibility range, because this area has the very high andesitic lava dominance. The results of the interpretation are information of subsurface rock types and its formation equipped with magnetic susceptibility contrast value ($\Delta\chi$) for each rock. The magnetic susceptibility contrast value is the difference between the magnetic susceptibility value of each rock to the average magnetic susceptibility value of the rocks in the studied area. Generally, the results of the quantitative interpretations as shown in Table 2 are in accordance with the results of the qualitative interpretations as shown in the local magnetic anomalous map that has been reduced to the pole. In addition, the interpretation results are also in accordance with the geological information of the studied area.

DISCUSSION

Geological Map of Purwokerto-Tegal Sheet (Djuri *et al*., 1996) shows that stratigraphically the types of rock occupying the top part of the researched area are andesitic lava. In Figure 8, this is indicated by an empty zone above the model of anomalous bodies. Underlying the andesitic lava is the undifferentiated volcanics consisting of volcanic breccias, lava, and tuff, distributed to form plains and hills (Djuri *et al*., 1996). In the local scale, the geological map does not give any information on which areas the higher potential of andesitic rocks occur. While the local magnetic anomalous map that has been reduced to the pole can be used as the information source to interpret areas which have higher potential of andesites, based on the anomalous closure. Reduction to the pole (RTP) is used to localize the area with maximum or minimum anomalies directly above the object body causing the anomaly, so the magnetic dipole appearance becomes a monopole where the object position is just below the main closure.

RTP transforms an observed magnetic anomaly into an anomaly under vertical magnetization to facilitate the interpretation of the magnetic anomalies (Zhang *et al*., 2018). Qualitatively, the main closure of the high RTP magnetic anomaly shows a very large distribution of subsurface rocks magnetization, so these rocks are also estimated to have a very large magnetic susceptibility value. The RTP filter is suitable to be applied because generally all igneous rocks, including the andesitic lava, have large magnetic susceptibility (Putri, 2010). The RTP of local magnetic anomalous map acquired shows the dominance of high anomalous closures in the northwest area, interpreted as the very dense massive andesitic rocks. Whereas other areas are dominated by several low anomalous closures in-

Table 2. Results of Lithological Interpretation of the Subsurface Anomalous Bodies from the 2D-Forward Modeling Along AB Track on the Local Magnetic Anomalous Map.

No.	Model	$\Delta\chi$ (cgs unit)	χ (cgs unit)	Depth (m)	Lithological Interpretation Results
1	Body 01	-0.0155	0.0025	7.16 - 286.57	Undifferentiated Slamet Volcano volcanics: volcanic breccias, lava, and tuff (Qvs)
2	Body 02	0.0170	0.0350	19.10 - 422.39	Massive andesitic lava intrusion of Slamet Volcano forming dikes and sills (Qvls)
3	Body 03	-0.0120	0.0060	288.06 - 505.97	Undifferentiated Slamet Volcano volcanics: volcanic breccias, lava, and tuff (Qvs)
4	Body 04	0.0110	0.0290	191.64 - 420.89	Massive andesitic lavas of Slamet Volcano forming flow structure (Qvls)
5	Body 05	-0.0064	0.0116	94.03 - 505.97	Vesicular andesitic rocks having many regular holes or small cavities (Qvs)
6	Body 06	0.0025	0.0205	31.34 - 422.39	Vesicular andesitic rocks containing many regular and more dense holes or small cavities (Qvs)

terpreted as the vesicular andesitic rocks estimated to have been weathered or being weathered. This indicates that the magnitude of rock magnetization corresponds to its density (Dimitriu *et al*., 2016). Several of these andesities appear on the surface in the form of outcrops.

Based on the results of 2D-forward modeling of the local magnetic anomaly data along AB trajectory (Figure 7), body 01 with magnetic susceptibility value of 0.0025 cgs and body 03 with magnetic susceptibility value of 0.0060 cgs are interpreted as undifferentiated Slamet volcanic rocks comprising volcanic breccias, lava, and tuff. This interpretation is in accordance with the lithological stratigraphy of the studied area, where this rock is overlain by the andesitic lava (Djuri *et al*., 1996) occupying the empty zone, as shown in Figure 7. This rock formation is intruded by andesitic dike and sill (body 02). This andesites form body which is very massive and dense in the subsurface with magnetic susceptibility value of 0.0350 cgs. The geological conditions of the volcanic region in the Slamet Volcano area allow the existence of shallow or deep intrusions (Iswahyudi *et al*., 2018). The body 04 with magnetic susceptibility values of 0.029 cgs is interpreted as the massive andesitic lava of Slamet Volcano forming a flow structure. Based on the results of the study, there are several different phases of lava flow formation that form different layers besides cracks (Iswahyudi *et al*., 2018). Whilst the body 05 and body 06 with magnetic susceptibility of 0.0116 cgs and 0.0205 cgs are interpreted as vesicular andesitic lava with structure forming many regular holes or small cavities. The existence of the holes or small cavities was due to volcanic gases released from liquid lava after reaching the surface (Iswahyudi *et al*., 2018). This rock is interpreted to undergo a weathering process, due to interactions with the environment near the surface (Dare and Abayomi, 2015).

The results of qualitative interpretation indicate that andesitic rocks are spread evenly in the studied area. This is observed on the local magnetic anomalous contour map which has been reduced to the pole, where the red anomalous closure (high anomaly) indicates the presence of massive andesitic rocks, while the green anomalous closure (low anomaly) indicates the presence of vesicular andesitic rocks. Both types of rocks also exist in the form of outcrops in several locations, as can be seen in the right part of

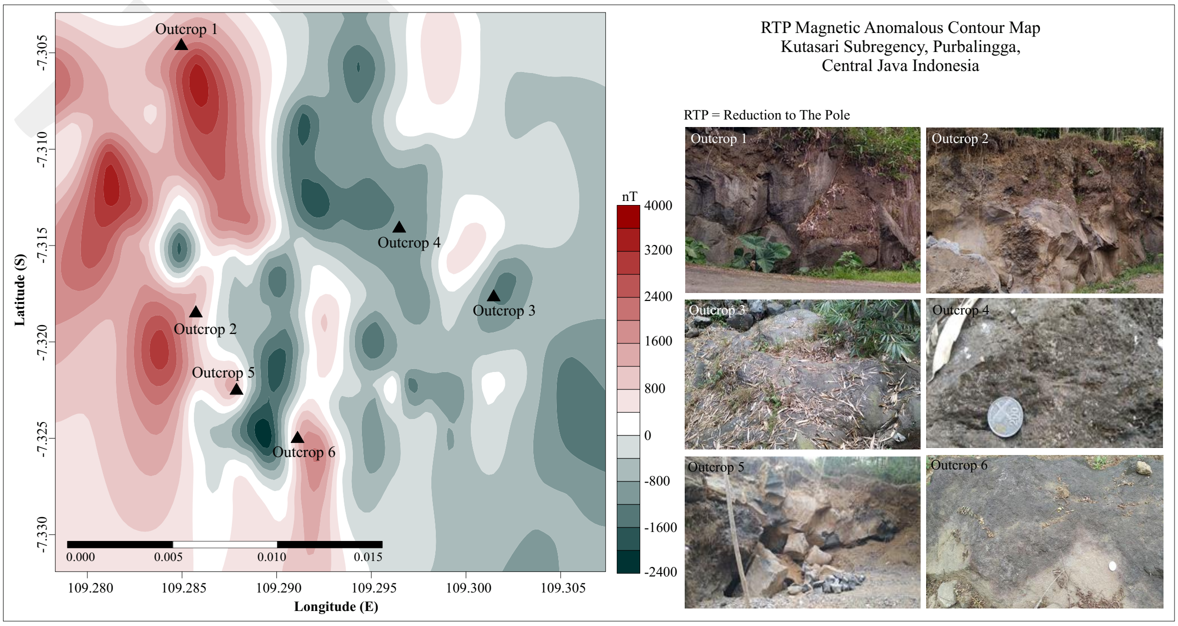

Figure 8. Massive andesitic lava rocks of the Slamet Volcano (outcrops 1, 2, 5, and 6) appearring on the surface and vesicular andesitic lavas with structure forming many holes or small regular cavities (outcrops 3 and 4), that are often found in the studied area.

Figure 8. Generally, these areas are the location of andesitic rock mining activities, especially in the massive andesitic outcrop area. While quantitative interpretation done through 2D-forward modeling of local magnetic anomaly data produces anomalous objects which are interpreted as subsurface rocks and geological structures as shown in Figure 8. The results of qualitative interpretation have a strong correlation with the results of quantitative interpretation, where both interpretation results show the existence of high magnetic anomalous sources in the northwest of the studied area which are interpreted as massive andesitic lava intrusion.

CONCLUSIONS

The magnetic data processing results are the local magnetic anomaly data ranging from 1,238.13 - 1,892.40 nT. The local magnetic anomalous contour map shows the location of anomalous distribution in the northwest areas which is marked by high anomaly contrast values. Qualitative interpretation is done on the local magnetic anomalous contour map which is reduced to the pole; where the result is the RTP anomalous map with values ranging from 2,344.08 - 3,406.16 nT. This anomalous map shows that high anomalous closures dominate the northwest area presumed to originate from massive and very dense andesitic lava intrusion. Whereas other areas are dominated by low anomalous closures which are thought to originate from vesicular andesitic rocks which have many small holes or cavities that are thought to have weathered or are being weathered.

Quantitative interpretation using 2D-forward modeling of the local magnetic anomaly data along the AB trajectory with length of 2,892.79 m resulted in six anomalous bodies interpreted as subsurface rocks in the studied area. Two objects are interpreted as the massive and dense andesitic lava intrusion forming dike and sill, and the massive andesitic lava forming a flow structure, with magnetic susceptibilities values of 0.0350 cgs and 0.0290 cgs. Two other bodies found near the surface are interpreted as vesicular andesites with magnetic susceptibilities values of 0.0116 cgs and 0.0205 cgs. The undifferentiated Slamet volcanics comprise volcanic breccias, lava, and tuff underlying the andesitic lava with magnetic susceptibilities values of 0.0025 cgs and 0.0060 cgs. This interpretation is in accordance with the lithological stratigraphy of the studied area. The results of qualitative interpretation have a strong correlation with the results of quantitative interpretation. Both interpretation results indicate the existence of high magnetic anomalous sources in the northwest of the studied area which are interpreted as massive andesite lava intrusion.

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