UTILIZATION OF MAGNETIC ANOMALY DATA TO LOCALIZE GROUNDWATER FRACTURES IN VOLCANIC ROCK COMPLEXES IN THE SITU TIRTA MARTA AREA, PURBALINGGA REGENCY, CENTRAL JAVA, INDONESIA

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Abstract. Magnetic surveying is one of the geophysical exploration techniques which can be applied to investigate subsurface conditions including groundwater by utilizing the magnetic susceptibility properties of rocks. The study purposes to localize groundwater fractures in the volcanic rock complexes of the Situ Tirta Marta Kutasari area of Purbalingga Regency based on magnetic anomaly data analysis. The research area is an area below the groundwater recharge area for the Purwokerto-Purbalingga Groundwater Basin located on the slopes of Slamet Volcano. The study began with the acquisition of total magnetic intensity data at 256 predetermined location points. The spatial distance between data points was made closer (i.e. 100 m) with a regular pattern forming a grid. The processing of total magnetic intensity data was carried out in several stages including some corrections and reductions so that local magnetic anomalies data were obtained with values ranging from -1408.16 - 775.95 nT. Furthermore, the local magnetic anomalies data were reduced to the pole so that the values obtained range from -2022.48 - 1522.89 nT. First Horizontal Derivative (FHD) analysis of local magnetic anomalies data that have been reduced to the pole shows a maximum horizontal gradient patterns interpreted as the boundaries of lithological contacts in the form of fractures within or between volcanic rock complexes. The fractures in the volcanic rocks are estimated to be groundwater flow paths originating from the recharge area to the discharge area, including the groundwater manifestation area in the Situ Marta complex, Purbalingga Regency.

Keywords: magnetic anomaly data, groundwater fractures, volcanic rock complex, first horizontal derivative, Purbalingga

A. Introduction

A groundwater basin is an area bounded by hydrogeological boundaries, all hydrogeological events or processes such as recharge, drainage, and discharge of groundwater can take place in the area [1]. Based on these criteria, a groundwater basin must have a recharge area and discharge area in one groundwater formation system. The recharge area is a conservation area; where in that area groundwater is not to be utilized on a large scale [2]. Meanwhile, in the discharge area, groundwater can be exploited while still considering environmental factors [3]. Generally, the rock formations that fill the discharge area are of the alluvial type with large porosity and permeability so that they are easy to occupy and allow groundwater to flow [4]. One of the groundwater basins in Central Java Province that has the potential to be developed into a water source for agricultural irrigation is the Purwokerto-

Purbalingga Groundwater Basin. This groundwater basin stretches from Banyumas Regency to Banjarnegara Regency with an area of around 1,318.2 km^2 [5] as seen in Figure 1.

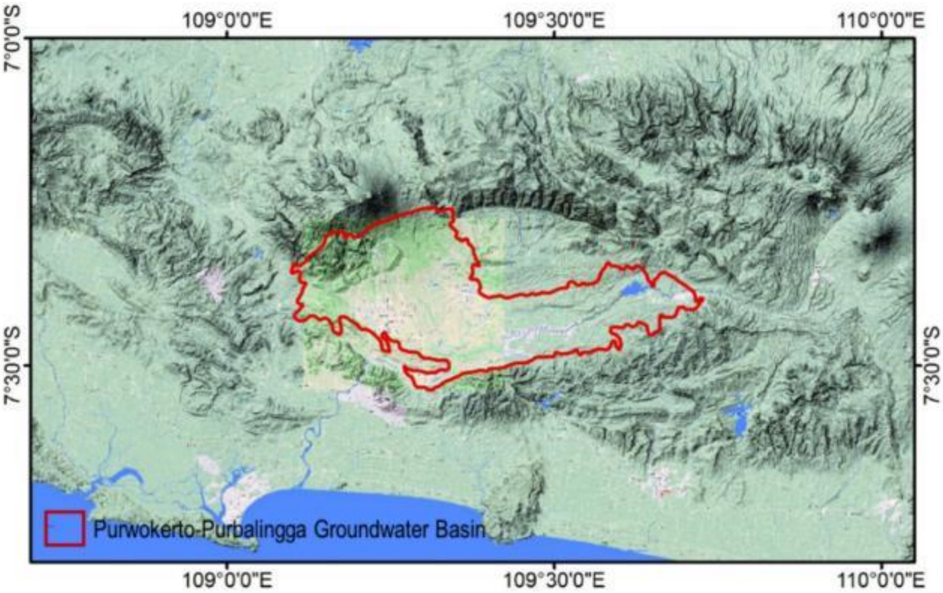

Figure 1. Location map of the Purwokerto-Purbalingga Groundwater Basin [6].

The Purwokerto-Purbalingga Groundwater Basin has a recharge area in the south slope area of Slamet Volcano, Central Java [7]. The characteristics of recharge area need to be known as an effort to preserve groundwater in the Purwokerto-Purbalingga Groundwater Basin area. Excessive use of groundwater in recharge areas can disrupt the availability of groundwater in discharge areas [8]. Knowledge of the characteristics of recharge area can help estimate the groundwater reserves contained therein. This area is composed of massive lava rock with many fractures and vesicular lava rock which has many cavities [9]. Cracks and cavities in volcanic rock complexes can act as potential groundwater aquifers. Groundwater exploration is generally carried out using geoelectric methods [10]. However, this method is often insensitive and experiences problems with current injection when applied to hard and massive volcanic rock complexes. Therefore, the use of other geophysical exploration methods needs to be considered. One geophysical exploration method that is suitable to be applied in areas like this is magnetic method [11]. The application of magnetic methods with higher spatial resolution [12] can be used as a solution for groundwater exploration in volcanic rock complexes, including in the recharge area of Purwokerto-Purbalingga Groundwater Basin.

Magnetic anomaly data filtering techniques allow researchers to map and localize local faults in volcanic rock complexes [13]. These local faults are areas of lithological boundaries between rock blocks. These boundary areas are cracks and fractures that can be filled by water to a certain depth [14] and form aquifers in volcanic rock complexes. The magnetic surveys have high sensitivity to volcanic rocks, because generally these rocks contain many metalic minerals which have relatively large magnetic susceptibility values [15]. Magnetic susceptibility is a proportionality value which shows the level of magnetism of a material in response to the magnetic field that induces it. Magnetic susceptibility can be used as a parameter to identify subsurface rock types through numerical modeling [16]. Meanwhile to identify the distribution of local faults containing groundwater in volcanic rock complexes, the First Horizontal Derivative (FHD) filter can be applied [17]. This filter can be applied to identify lithological contact boundaries between rock blocks in an area. The filtering results are useful for assisting modeling and interpretation of groundwater aquifers in volcanic rock complexes; as an effort to develop groundwater-based irrigation programs.

Magnetic anomaly data have disadvantages such as complexity when carrying out qualitative interpretations caused by the dipole nature of the magnetic field. The dipole nature of the magnetic field means that magnetic anomaly contours have many interpretations, making data interpretation difficult, especially for research areas located in low magnetic latitude areas such as Indonesia. Therefore, further processing of magnetic anomaly data is needed to reduce the dipole effect on magnetic anomaly data, thereby simplifying the process of modeling and interpreting magnetic anomaly data. One method which can be used for this aim is Reduction to The Pole (RTP) method for magnetic anomaly data [18]. The RTP filter is needed to eliminate the influence of the inclination angle of the Earth's magnetic field, because the inclination vector of the induction magnetic field and the external magnetic field has produced a dipole pattern on the magnetic data. Magnetic anomalies data that have been reduced to the poles can have high or low values, according to the magnetic material distribution burried in the subsurface [19]. Magnetic anomalies which are reduced to the poles provide information about the existence of the subsurface anomalous objects [20], as shown in Figure 2. The RTP function is affected by the value of the inclination and declination angles based on equation [21]:

$$A_{pole}(s,\theta) = \frac{1}{(j\,cos\,I\,sin(\delta+\theta)-\gamma)(j\,cos\,I_0\,sin(\delta_0+\theta)-\gamma_0)} \tag{1}$$

δ_0 is the angle of declination and I_0 is the angle of inclination of the magnetization vector, while δ is the angle of declination and I is the angle of inclination of the Earth's magnetic field vector.

Although the magnetic anomaly contour map that has been reduced to the pole is relatively clearer in showing the location of the target anomalous source in the subsurface, but to clarify the boundaries of the lithological contact of the anomalous source, it is necessary to conduct a First Horizontal Derivative (FHD) analysis of the local magnetic anomaly data. The maximum value of horizontal gradient (steepest curve) of the magnetic anomaly data that has been reduced to the pole that originates from an anomalous object in the subsurface will tend to be located at the boundary or edge of the subsurface object. Hence, the maximum horizontal gradient will be localized directly at the edge of the object as shown in Figure 2. The working principle of the maximum horizontal gradient is to localize the steepest change in the magnetization of an object in the lateral direction based on the magnetic anomaly data reduced to the pole. First horizontal derivative or gradient tends to occupy narrow ridges above sudden changes in magnetization or density. The horizontal gradient value of the magnetic anomaly data that has been reduced to the pole can be expressed as follows [21]:

$$h(x,y) = \left[\left(\frac{\partial H_z(x,y)}{\partial x}\right)^2 + \left(\frac{\partial H_z(x,y)}{\partial y}\right)^2\right] \tag{2}$$

where ∂H_z is the magnetic anomaly data that has been reduced to the poles [21].

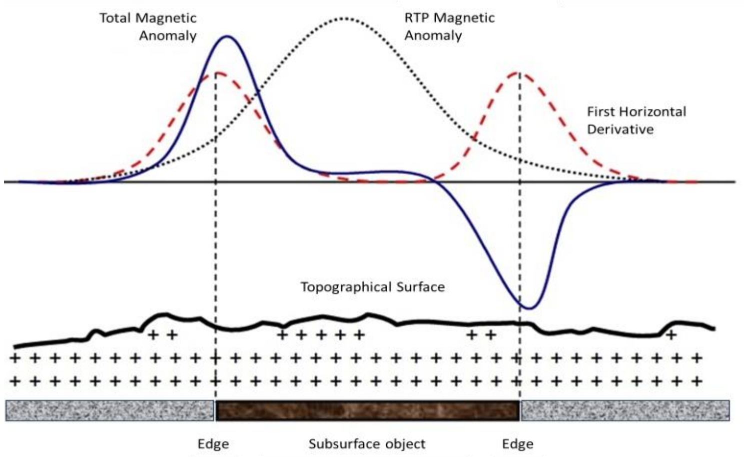

Figure 2. Illustration of the reduction process to the poles of the total magnetic anomalies data and the results of calculating their horizontal gradients [21].

B. Methods

1. Location and Time

The location for magnetic field data acquisition is the Southeastern Slopes of the Slamet Volcano which is the recharge area of the Purwokerto-Purbalingga Groundwater Basin. The area is located in Karangcegak Village, Kutasari District, Purbalingga Regency, Central Java, Indonesia with an area of approximately 1.5 km x 1.5 km as shown in Figure 3. Meanwhile, magnetic data processing and interpretation are carried out at the Electronics, Instrumentation, and Geophysics Laboratory, Faculty of Mathematics and Natural Sciences, Jenderal Soedirman University. The research was carried out for six months, i.e. March – August 2024.

Figure 3. The research area location map; Situ Tirta Marta, Karangcegak Village, Kutasari District, Purbalingga Regency, Indonesia.

2. Research Equipments

The research equipment used in the field is Proton Precession Magnetometers (PPM) model GSM-19T produced by GEM with a sensitivity of 0.05 nT which is used for total magnetic field data acquisition at survey points in the field. Other research equipment is the Global Positioning System (GPS) produced by Garmin's GPS-V Mapping to map magnetic data points and a compass to direct the PPM sensor towards the north of the Earth's magnetic field. Meanwhile, the equipment used in the laboratory is a geological map, laptop, Google Earth and Surfer application, as well as several other software and application programs to support the processing of magnetic anomaly data [9].

3. Research Procedure

The data obtained from the acquisition in the field is the total magnetic field intensity data which are distributed on the topographic surface. In order to obtain total magnetic anomalies data, the data are corrected, including diurnal and IGRF corrections. The IGRF value refers to the value of the Earth's main magnetic field strength [22]. After applying the all corrections, total magnetic anomalies data are obtained. These data are spread on the topographical surface, that are function of longitude (x), latitude (y), and altitude (h). Therefore the magnetic anomalies data must be reduded to horizontal surface; in this research using the Taylor series approach [21], which can be written as equation:

$$\Delta H(x,y,h_0)^{[i+1]} = \Delta H(x,y,h) - \sum_{n=0}^{\infty} \frac{(h-h_0)^n}{n!} \frac{\partial^n}{\partial z^n} \Delta H(x,y,h_0)^{[i]} \quad (3)$$

where $\Delta H(x,y,h)$ is anomalies data that are still spread on the topographic surface, $\Delta H(x,y,h_0)$ is anomalies data that have been distributed on a horizontal surface, h is the altitude of each data, and h_0 is the average topography elevation. After the magnetic anomalies data are distributed on a horizontal surface (through an iterative process in the equation above), these data are separated from the regional magnetic anomalies data, so the local magnetic anomalies data can be obtained with the equation [23]:

$$\Delta H(x,y,h_0)_{Local} = \Delta H(x,y,h_0) - \Delta H(x',y',h_0+\Delta h) \quad (4)$$

$\Delta H(x',y',h_0+\Delta h)$ are regional magnetic anomalies data, which are obtained through an upward continuation process using the equation [21]:

$$\Delta H(x',y',h_0+\Delta h) = \frac{\Delta h}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{\Delta B(x,y,h_0)}{\sqrt{((x'-x)^2+(y'-y)^2+\Delta h^2)^{3/2}}} dxdy \quad (5)$$

In Equation (4), the first term on the right side represents the total magnetic anomalies data on a horizontal surface (h_0), whereas the second term represents the regional magnetic anomalies data resulting from upward continuation at elevation of Δh. Furthermore, the local magnetic anomalies data obtained represent local geological conditions or subsurface rocks [23]. Local magnetic anomalies data are then reduced to the pole and analyzed for horizontal gradients. Based on the analysis results of horizontal gradient contour map, many local faults (including fractures in volcanic rocks) can be easily estimated in their distribution on the surface.

C. Results And Discussion

1. Results of Processing Data

The magnetic field data obtained in the field is the total magnetic field intensity data spread over the topographical surface of the study area. After diurnal and IGRF corrections were applied, the total magnetic anomalies data are obtained with values ranging from -1214.20 – 970.25 nT. As explained in Research Method, the anomalies data are reduced to a horizontal surface using the Taylor series. The surface chosen is the average elevation of the research area (i.e. 267.74 m), so that the iteration process in Equation (3) quickly reaches convergence [21]. The total magnetic anomalies data which have been spread on a horizontal surface, are then separated from regional anomalies data [24]. The separation has been carried out using the upward continuation technique as shown in Equation (5). The upward continuation result which shows a regional anomalous pattern is obtained at an altitude of 2000 m above the reference spheroid. The resulting contour map pattern tends to be fixed and smooth with very small value intervals [9], with values ranging from 193.805 – 194.440 nT. Furthermore, the regional anomalies data were corrected using Equation (4), so that the local magnetic anomalies data are obtained with a value range of -1408.16 – 775.95 nT. The total, regional, and local magnetic anomalies contour maps are shown in Figure 4.

Based on Figure 4, the research area is dominated by positive anomalies closures in the north and negative anomalies in the south. The two closures are paired in the center of the research area, i.e. around the Situ Tirta Marta area. In general, the closure of the total magnetic anomaly contour map is similar to the local magnetic anomaly contour map. This fact indicates that the influence of local magnetic anomalous sources in the research area is relatively more dominant than regional anomalous sources [25]. The sources of local magnetic anomalies are thought to originate from subsurface rock structures dominated by andesite lava rock which has many cracks and fractures, so that it is easily filled by groundwater [26]. The lava deposits spread from the top of Slamet volcano to the research area which is located on the southeast slope. The existence of cracks or fractures in the rocks is thought to be caused by the release of volcanic gases from the liquid lava after reaching the topographical surface. As magma rises to the surface, the pressure on it decreases. When this happens gasses which dissolved in the magma are able to come out of solution, forming gas bubbles (cavities) inside it [26]. The volcanic rocks magnetization with lots of cavities and fractures will tend to be small. This is reflected in the negative value of the local magnetic anomaly [9].

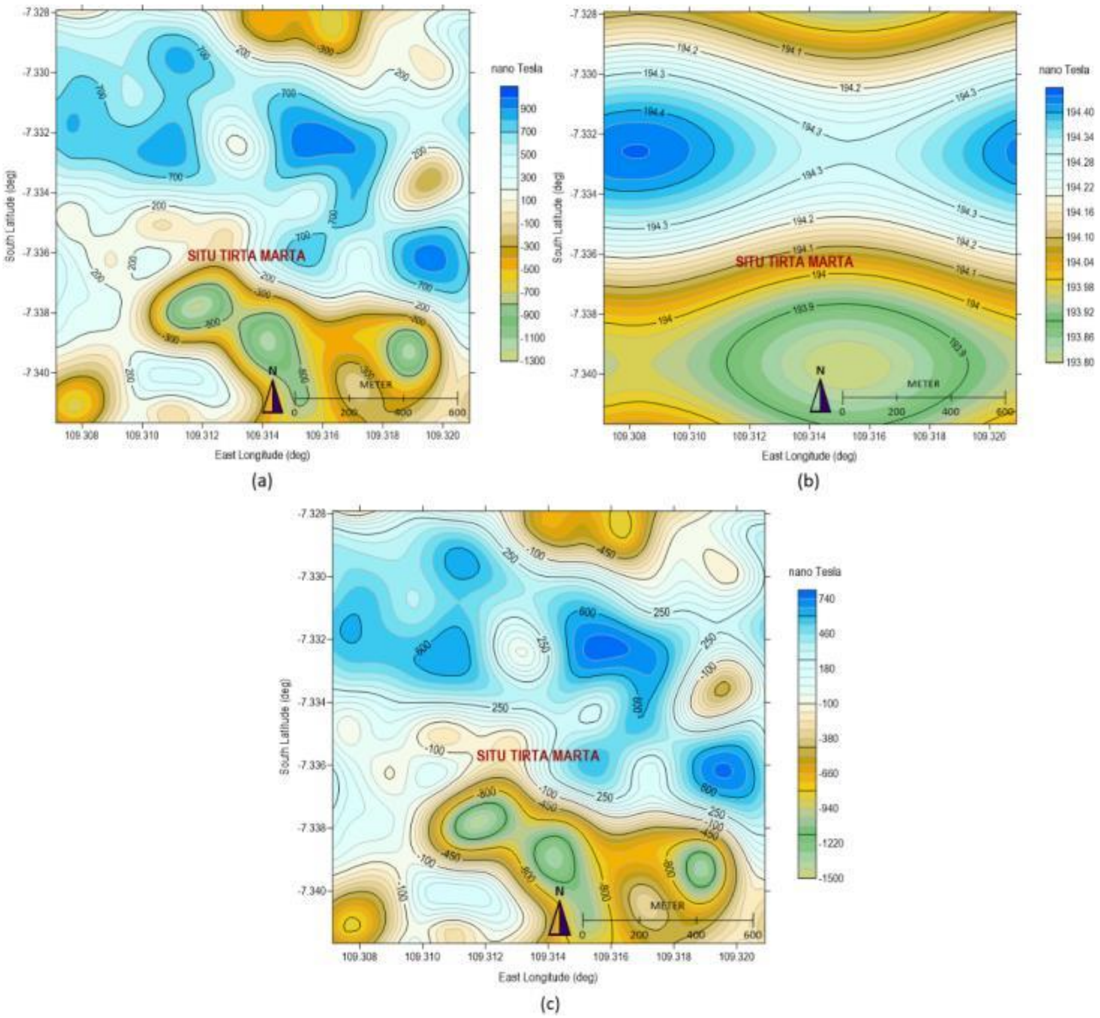

Figure 4. The (a) total, (b) regional, and (c) local magnetic anomalies contour maps of research area; Situ Tirta Marta Complex, Kutasari District, Purbalingga Regency.

2. Results of Reduction to the Poles and Analysis to Horizontal Gradient

Local magnetic anomaly contours generally have complicated closure patterns. Changes in anomaly shape, reduction in overall amplitude, and changes in contour texture make geological interpretation of magnetic data in low latitude area difficult [27]. One solution is to apply reduction to the poles. The reduction to the poles is carried out to change the magnetization direction of the Earth′s main magnetic field that was originally influenced by the declination and inclination angles to be directed vertically like at the north pole. Hence, this process is conducted by changing the inclination of -31.1805° and declination of 0.5839° to 90° and 0° as Equation (1). The reduction to the pole changes the magnetic field asymmetry pattern to a symmetrical pattern. This symmetry pattern can be used as an indication of the presence of bodies or anomaly sources, such as gravity field anomaly data. Therefore, the position of the anomaly sources can be estimated to be right under the curve peak or the anomalous closures center as shown in Figure 1. This filter makes it possible to correlate the magnetic anomalies with other types of geophysical anomalies and geological information, as well as aids their interpretation. Then, the local magnetic anomalies data reduced to the pole have values ranging from -2022.49 – 1522.89 nT, where the values are relatively larger after being reduced to the pole.

The local magnetic anomalous contour map better reflects the spatial distribution of shallow subsurface magnetic anomalous sources, but often the position of the anomalous source does not match the closure on the contour map, making it difficult to identify the geological structure of the research area [27]. Filtering techniques are often used to adjust the position of the anomalous source to match the anomaly closure shown on the contour map, where in this research the reduction to the pole technique has been used for this purpose. Apart from that, filtering is also used to enhance certain features, such as the edges of anomaly source objects, where in this study the First Horizontal Derivative (FHD) filtering technique has been applied. This filtering technique and its equations have been explained and written in the Introduction section. When this filter is applied in a two-dimensional (2D) interpretation, this horizontal gradient tends to occupy a narrow ridge above a sudden change in magnetization [21]. This can be utilized to localize the lithological boundaries of anomalous objects to surrounding objects or rocks by looking at sudden changes in the object's magnetization in the lateral direction. The local magnetic anomaly contour map which has been reduced to the poles and the results of horizontal gradient calculations on the anomalies data are shown in Figure 5.

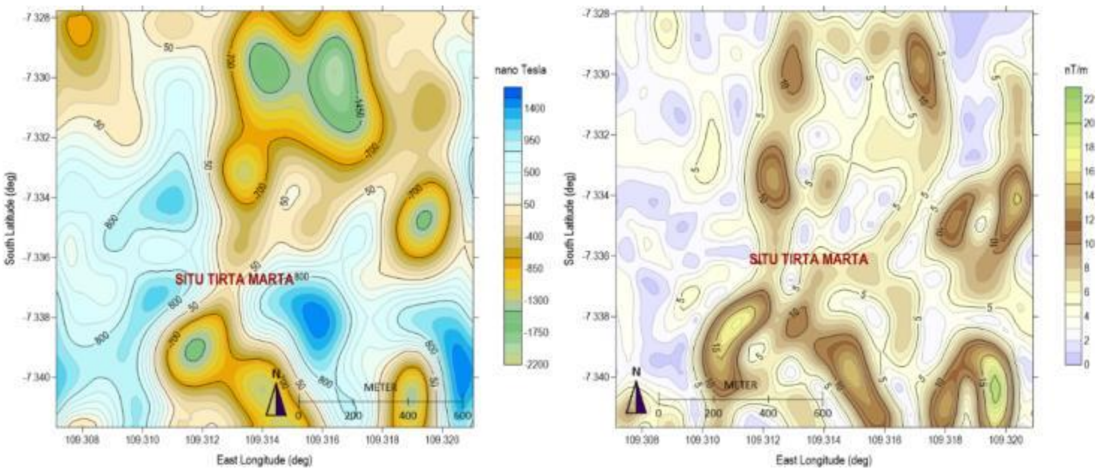

Figure 5. The contour map of local magnetic anomalies reduced to the poles (left) and the results of calculating their horizontal gradients (right).

3. Analysis and Discussion

Regionally, Situ Tirta Marta is located in the southeastern part of the Lower Slopes of the Slamet Volcano which is Quaternary in age. The morphology of the research area forms undulated plains [28]. One of the controlling factors for the emergence of springs at Situ Tirta Marta is the slope of the land. The pool's water source comes from shallow groundwater that flows through volcanic rock fractures from a higher recharge area. Situ Tirta Marta, which is located on a relatively lower slope, will be the destination for groundwater entering from the surrounding area which is more higher. The Situ Tirta Marta complex is shaped like a basin surrounded by small hills. The lithology of the research area consists of volcanic rocks that can be divided into massive lava with many fractures and vesicular lava with many cavities. The lithological conditions allow groundwater to flow from the recharge area on the upper slopes through cracks and cavities. Apart from that, the geological conditions of Situ Tirta Marta, which is located on the border between the Slamet Volcanic Lava Formation and the Laharic Deposits also support the emergence of water that crosses the boundary between the layers of the rock formation [26].

Field observations by Iswahyudi et.al., [26] showed that groundwater from the Situ Tirta Marta spring came out of a rock crack at the foot of the hills extending relatively north-south. The spring came out along the foot of the hill with a length of about 200 m. In addition, there are several spring points that form a straightness. The existence of several springs is estimated to come from the geological structure, in the form of cracks or fractures around the location. This geological structure is a weak zone that allows groundwater from the subsurface to reach the surface or near the surface. The existence of a geological structure is also indicated by the large discharge of water coming out of the Situ Tirta Marta spring. Fractured rocks present complex and heterogeneous hydrogeological environments with irregular distribution of groundwater flow pathways. This is in accordance with the information seen on the FHD contour map, where there are several peaks of horizontal gradient of the RTP local magnetic anomalies data that trend relatively north-south as shown in Figure 6. The position of the maximum horizontal gradient marked with red lines can be interpreted as cracks or fractures in or between volcanic rocks containing groundwater with the flow direction as show by the arrows [29,30]. Volcanic aquifers can be developed into potential groundwater sources for urban and rural areas.

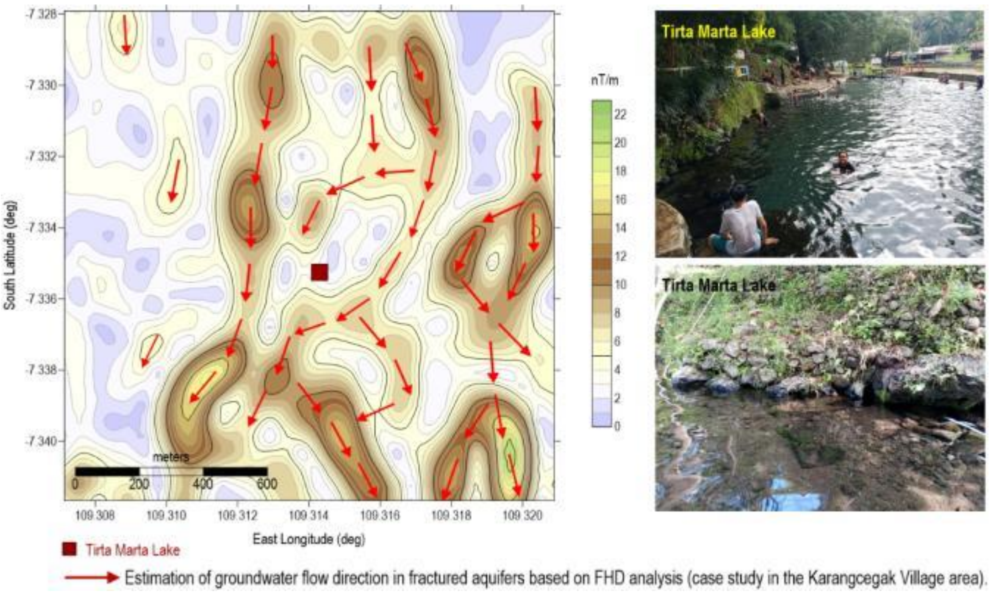

Figure 6. FHD contour map with distribution of lines showing the location of maximum horizontal gradients interpreted as cracks within or between volcanic rocks.

Analysis of several maximum horizontal gradients of the RTP local magnetic anomalies data was carried out along the AB and CD trajectories. Each peak indicates the presence of fractures or cracks within or between volcanic rocks. High maximum horizontal gradient values indicate wide or near-surface fractures, and vice versa [30]. The many fractures in volcanic rocks in the research area will be a path for groundwater to flow from the recharge area on the Upper Slopes of the Slamet Volcano to the discharge area in the Purwokerto-Purbalingga Groundwater Basin area. The amount of groundwater flow in the fractured rocks is controlled by some factors, such as: the size and depth of the fracture opening, the distance of the fracture, the interconnection of the fractures, and the amount of rainwater entering the cracks of the rocks and soil in the recharge area. In the recharge areas, generally water supply occurs through surface water infiltration from rainfall, which then enters rivers, wetlands, and open spaces [31]. Figure 6 above indicates groundwater flow through fractured rocks in a volcanic environment with a North-South orientation. These fracture paths are estimated to occur in subsurface rocks which connect to the Situ Tirta Marta area. Generally hard rock environments (including volcanic rocks) consist of three rock layers, i.e. weathering at the top, fractures in the middle, and massive in the inside [32]. According to information from the community, Situ Tirta Marta has seven springs with large discharges [33]. In fact, the volume of groundwater entering Situ Tirta Marta is very large and clean [26], so this area has developed into a geo-tourism area. Apart from being a tourist location, Situ Tirta Marta has also been utilized by the Regional Drinking Water Company in Purbalingga Regency to meet the freshwater needs of the surrounding community. However, with the abundance of freshwater in this area, efforts to develop sustainable groundwater-based irrigation need to be followed up.

D. Conclusion

Utilization of magnetic anomaly data to localize groundwater fractures has been carried out in the volcanic rock complexes of the Situ Tirta Marta area Karangcegak Village, Kutasari District, Purbalingga Regency, Central Java, Indonesia. The research area is located in the southeastern part of the Slamet Volcano Slopes. Total magnetic intensity data was obtained through data acquisition in the field using a Proton Precession Magnetometer. The data is spread regularly over a spatial distance of around 100 m at 256 location points on the topographic surface. Total magnetic field intensity data processing has been carried out through several stages of correction and reduction, resulting in the local magnetic anomalies data with values ranging from -1408.16 - 775.95 nT. In order to localize the anomalous sources, the local magnetic anomalies data were reduced to the pole to obtain values ranging from -2022.48 – 1522.89 nT. The results of the First Horizontal Derivative (FHD) analysis of local magnetic anomalies data that have been reduced to the pole show several maximum horizontal gradient patterns. These patterns are interpreted as lithological contact boundaries in the form of cracks and fractures within or between volcanic rock complexes. The fractures in this volcanic rock complexes are estimated to be filled by groundwater flowing in a relatively north-south direction, extending from the recharge area on the upper slopes of Mount Slamet to the discharge area from the Purwokerto-Purbalingga Groundwater Basin.

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F. References

[1]. Demiroğlu, M. 2017. Identifying The Groundwater Basin Boundaries Using Environmental Isotopes: a Case Study. Applied Water Science. 7:1161–1167. Available at: https://doi.org/10.1007/s13201-016-0516-y.

[2]. Regulation of the Minister of Energy and Mineral Resources of the Republic of Indonesia No. 31 of 2018 concerning Guidelines for Determining Groundwater Conservation Zones.

[3]. Anonymous, 2017. Geology and Hydrogeology Module; Ground Water Planning Training. Water Resources and Construction Education and Training Center. Ministry of Public Works and Public Housing (PUPR) of the Republic of Indonesia.

[4]. Kaser, D. & Hunkeler, D. 2015. Contribution of Alluvial Groundwater to the Outflow of Mountainous Catchments. Water Resources Research. 52(2): 680-697. Available at: https://doi.org/10.1002/2014WR016730.

[5]. Decree of the President of Republic of Indonesia No. 26/2011 about Determination of Groundwater Basins.

[6]. Sehah, Aziz, A. N., Raharjo, S. A., Buliyanti, S. C., Mubarak, F., Wicaksono, G. F., & Asahi, W. 2024. Study of the Potential of the Purwokerto-Purbalingga Groundwater Basin as a Source of Irrigation Using Gravimetric Satellite Data. Water Conservation & Management. 8(2): 94-103. Available at: http://doi.org/10.26480/wcm.02.2024.94.103.

[7]. Ramadhan, F., 2020. Geology and Purwokerto-Purbalingga Groundwater Basin Modeling. Bachelor's Thesis at Department of Geological Engineering. Faculty of Engineering. Jenderal Soedirman University Purwokerto. pp. 68-70.

[8]. Dao, P. U., Heuzard, A. G., Le, T. X. H., Zhao, J., Yin, R., Shang, C., Fan, C. 2024. The Impacts of Climate Change on Groundwater Quality: A Review. Science of the Total Environment. 912(169241). Available: https://doi.org/10.1016/j.scitotenv.2023.169241.

[9]. Sehah, Raharjo, S. A., Prabowo, U. N. & Sutanto, D. S. 2021. Interpretation of Magnetic Anomaly Data in the Andesitic Rock Prospect Area of Kutasari Subregency, Purbalingga Regency, Central Java, Indonesia. Indonesian Journal on Geoscience. 8(3): 345-357. Available at: https://doi.org/10.17014/ijog.8.3.345-357.

[10]. Sulaiman, N., Ariffin, N. A., Sulaiman, M. S., Sulaiman, N., & Jamil, R. M, 2022. Groundwater Exploration Using Electrical Resistivity Imaging (ERI) at Kemahang, Tanah Merah, Kelantan. 4th International Conference on Tropical Resources and Sustainable Sciences 2022. IOP Conf. Series: Earth and Environmental Science, 1102 (**2022**) 012027. Available at: http://doi.org/10.1088/1755-1315/1102/1/012027.

[11]. Santosa, B. J., Mashuri, Salim, R., & Armi, R. 2012. Interpretation of Magnetic Method for Determining Subsurface Structures around Kelud Volcano, Kediri Regency. Jurnal Penelitian Fisika dan Aplikasinya. 2(1): 7-14. https://doi.org/10.26740/jpfa.v2n1.p7-14.

[12]. Ritis, R. D. & Chiappini, M. 2023. High-resolution magnetic anomaly map of the La Fossa Caldera system of Vulcano Island and Lipari Island (Aeolian Archipelago, Southern Italy. Journal of Volcanology and Geothermal Research. 438:107823. Available at: https://doi.org/10.1016/j.jvolgeores.2023.107823.

[13]. Rosid, M. S., & Siregar, H. 2016. Determining Fault Structure Using First Horizontal Derivative (FHD) and Horizontal Vertical Diagonal Maxima (HVDM) Method: A Comparative Study. International Symposium on Current Progress in Mathematics and

Sciences 2016 (ISCPMS 2016). AIP Conf. Proc. 1862, 030171-1–030171-8. Available at: https://doi.org/10.1063/1.4991275.

[14]. Husaeni, A., Listiawan, Y., Arfiansyah, K. F. & Iskandarsyah, T. Y. W. M. 2021. Rock Characteristics As the Basis of Aquifer Determination in Cianjur Sub-Watershed, Cugenang District, Cianjur Regency, West Java Province. Journal of Geological Sciences and Applied Geology. 5(1): 15-21. https://doi.org/10.24198/gsag.v5i1.34872.

[15]. Dobeneck, T. V., Müller, M., Bosbach, B. & Klügel, A. 2021. Ground Magnetic Surveying and Susceptibility Mapping Across Weathered Basalt Dikes Reveal Soil Creep and Pedoturbation. Frontiers in Earth Science. 8:592986. Available at: https://doi.org/10.3389/feart.2020.592986.

[16]. Hidayati, N., Arman, Y. & Zulfian. 2022. Identification of Subsurface Structures of Geothermal Areas using Magnetic Methods in the Southern Tarutung Area and Surrounding Areas, North Sumatra Province. Prisma Fisika. 10(2): 206-213. Available at: https://dx.doi.org/10.26418/pf.v10i2.55463.

[17]. Septyasari, U., Niasari, S. W. & Maghfira, P. D. 2018. Subsurface Structure Identification Uses Derivative Analyses of the Magnetic Data in Candi Umbul-Telomoyo Geothermal Prospect Area. The International Conference on Theoretical and Applied Physics. IOP Conf. Series: Journal of Physics: Conf. Series 1011 (2018) 012038. Available at: https://dx.doi.org/1088/1742-6596/1011/1/012038.

[18]. Ansari, A.H. & Alamdar, K. 2014. Reduction to the Pole of Magnetic Anomalies Using Analytic Signal. World Applied Sciences Journal. 7(4): 405 – 409.

[19]. Hiskiawan, P. 2016. Effect of Upward Continuation Contour Patterns on Geomagnetic Data of Interpretation of Reduction to the Poles. *Saintifika*, 18(1): 18-26. Available at: https://dx.doi.org/10.15294/jf.v5i2.7421.

[20]. Ravat, D. 2007. Reduction to The Pole. In book: Encyclopedia of Solid Earth Geophysics. D. Gubbins and E. Herrero-Bervera (editors). Springer. pp. 856 – 857.

[21]. Blakely R. J. 1995. Potential Theory in Gravity and Magnetic Applications. Cambridge University Press. USA. 464pp.

[22]. Meteorology, Climatology, and Geophysics Agency. 2024. Earth Magnetic Calculator. https://www.bmkg.go.id/geophysics-potential/kalkulator-magnet-bumi.bmkg. [Accessed 1 September 2024].

[23]. Sehah, Raharjo, S. A. & Risyad, A. 2020. A Geophysical Survey with Magnetic Method for Interpretation of Iron Ore Deposits in the Eastern Nusawungu Coastal, Cilacap Regency Central Java Indonesia. Journal of Geoscience Engineering, Environment and Technology. 5(1): 47-55. Available at: https://doi.org/10.25299/jgeet.2020.5.1.2934.

[24]. Guo, L., Meng, X., Chen, Z., Li, S., & Zheng, Y. 2013. Preferential Filtering for Gravity Anomaly Sparation. *Computers and Geosciences*, 51: 247-254. Available at: https://doi.org/10.1016/j.cageo.2012.09.012.

[25]. Meyer, R., & de Groot, L. V. 2024. Local Magnetic Anomalies Explain Bias in Paleo-magnetic Data: Consequences for Sampling. Geochemistry, Geophysics, Geosystems. 25. Available at: https://doi.org/10.1029/2023GC011319.

[26]. Iswahyudi, S., Jati, I. P., & Setijadi, R. 2018. Preliminary Study of the Geology of Tirta Marta Lake, Purbalingga, Central Java. Jurnal Ilmiah Dinamika Rekayasa. 14(2): 86-91. Available at: http://dx.doi.org/10.20884/1.dr.2018.14.2.189.

[27]. Stewart, I.C.F. 2019. A Simple Approximation for Low-Latitude Magnetic Reduction-to-the-Pole. Journal of Applied Geophysics (El-Sevier). 166: 57-67, Available at: https://doi.org/10.1016/j.jappgeo.2019.04.021.

[28]. Djuri, M., Samodra, H., & Gafoer, S. 1996. Geological Map of Quadrangles of Purwokerto and Tegal, Jawa, Scale 1:100,000. Geological Research and Development Center. Bandung.

[29]. Alamdar, K., Ansari, A. H., & Ghorbani, A. 2009. Edge Detection of Magnetic Body Using Horizontal Gradient of Pseudogravity Anomaly. Geophysical Research. 11: EGU2009-4082. Available at: https://dorl.net/dor/20.1001.1.2538371.1390.37.1.1.2.

[30]. Oni, A. G., Eniola, P. J., Olorunfemi, M. O., Okunubi, M. O. & Osotuyi, G. A. 2020. The Magnetic Method as a Tool in Groundwater investigation in a Basement Complex Terrain: Modomo Southwest Nigeria as A Case Study. Applied Water Science. 10:190. Available at: https://doi.org/10.1007/s13201-020-01279-z.

[31]. Bela, K. R., Seran, E. N. B., Naikofi, M. I., R. & Da Costa, D. G. N. 2019. Relationship Between Built-up Land Cover Patterns and Rainwater Infiltration Rates. Jurnal Rekayasa Konstruksi Mekanika Sipil. 2(2): 109-120. https://doi.org/10.54367/jrkms.v2i2.524.

[32]. Zhou, C. B., Chen, Y. F., Hu, R., & Yang, Z. 2023. Groundwater Flow Through Fractured Rocks and Seepage Control in Geotechnical Engineering: Theories and Practices. Journal of Rock Mechanics and Geotechnical Engineering. 15(1): 1-36. Available at: https://doi.org/10.1016/j.jrmge.2022.10.001.

[33]. Wicaksono, M., 2018. The Freshness of Tirta Marta Lake. Kompas Media Nusantara. https://www.kompas.id/baca/nusantara/2018/04/29/segarnya-telaga-tirta-marta. [Accessed 1 September 2024].