Was the Pesawaran Swarm Induced by Magmatic Fluids? Insight from Magnetic Method Analysis

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ABSTRACT

An earthquake swarm in January 2021 triggered research related to adjacent geological structures, mainly inferred Menanga fault having predicted in the previous studies. This study is focused on investigating the fault and volcanic - related activity in terms of magnetic field anomalies due to sensitivity of susceptibility. By measuring 55 points with 500 m intervals, the observed magnetic values are processed to Reduction to Pole (RTP) anomalies and interpreted by adopting the successive decomposition method. This method generates pseudo-depth structures using the subtraction between below and above residual anomalies for each slice. The result indicates that variation of variated rocks is detected by a short-wavelength magnetic anomaly in slice 1, whereas an NW-SE high anomaly at the southern part research area indicates volcanic activity, which may related to magmatic fluid injection. This magmatic fluid injection reactivated the inferred Menanga fault causing the earthquake swarms. The dimming upward of the high anomaly explains the magmatic injection have not been involved toward the surface and remain isolated at depth.

Keywords: Inferred Menanga Fault, Magnetic Anomaly, Pesawaran, magmatic fluid

1. BACKGROUND

The occurrence of an earthquake swarm in Pesawaran, Lampung, for 11 days, 5 – 16 January 2021, encouraged previous research in the epicenter area to study the correlation between the events and nearby inferred geological structures mainly the Menanga fault [1]. An earthquake swarm happened if small earthquakes were repeated without a big main earthquake. This swarm study mentioned that at least 22 earthquakes were recorded by 22 stations of BMKG with 1.7 – 4 M_{Lv} of their magnitude range. By implementing the relocation technique, the epicenters tended to cluster northwest under the inferred Menanga fault line.

Regarding the swarm study in the inferred Menanga fault area, the fault had a dip around 38-45 degrees. Considering that the magnitude range of the events was not high, the fault did not undergo a stick-slip scheme. This study concluded that the fault geometry had a strike toward the northwest and a dip was in north-northeast trending [1].

Even though the existence of inferred Menanga fault is still debated, an earthquake swarm collocated with the indicated area of this fault should be the initial step to investigate its presence by other approaches. Actually, magnetic anomalies have been successfully studied to identify the possible existence of faults due to their susceptibility [2], [3]. Therefore, this research will perform anomalies by magnetic measurements, which may represent inferred Menanga fault and activities around the fault.

2. REGIONAL GEOLOGY

The study area shown by Figure 1 is located in eastern Mount Ratai, Pesawaran Region, Lampung, which lies on extensive young volcanic deposits (Qhv) consisting of tuff, breccia, and Andesitic-basalt lava. Close to Mount Ratai, the inferred Menanga fault is estimated to be in NW-SE orientation, infiltrating the research area, which estimates to be ended before Tarahan formation (Tpot) [4]. Besides, a thrust fault splitting Menanga formation (Km) and Undifferentiated Gunung Kasih Complex (Pzg) is in a non-continuous line of inferred Menanga fault in which Pzg formation is the understructure of Qhv formation composed of schist and gneiss.
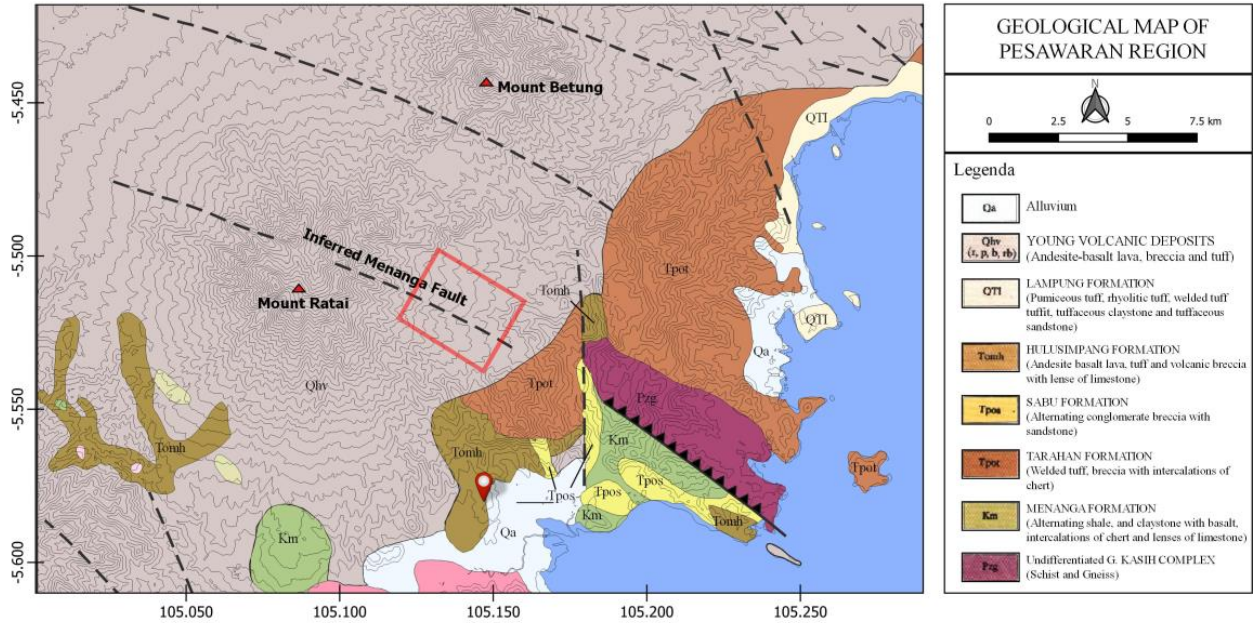
Figure 1. Regional geology and fault locations of Pesawaran region modified from [4]. A red rectangular denotes the study area, whereas red triangles and a red mark represent mounts and hydrothermal manifestation.
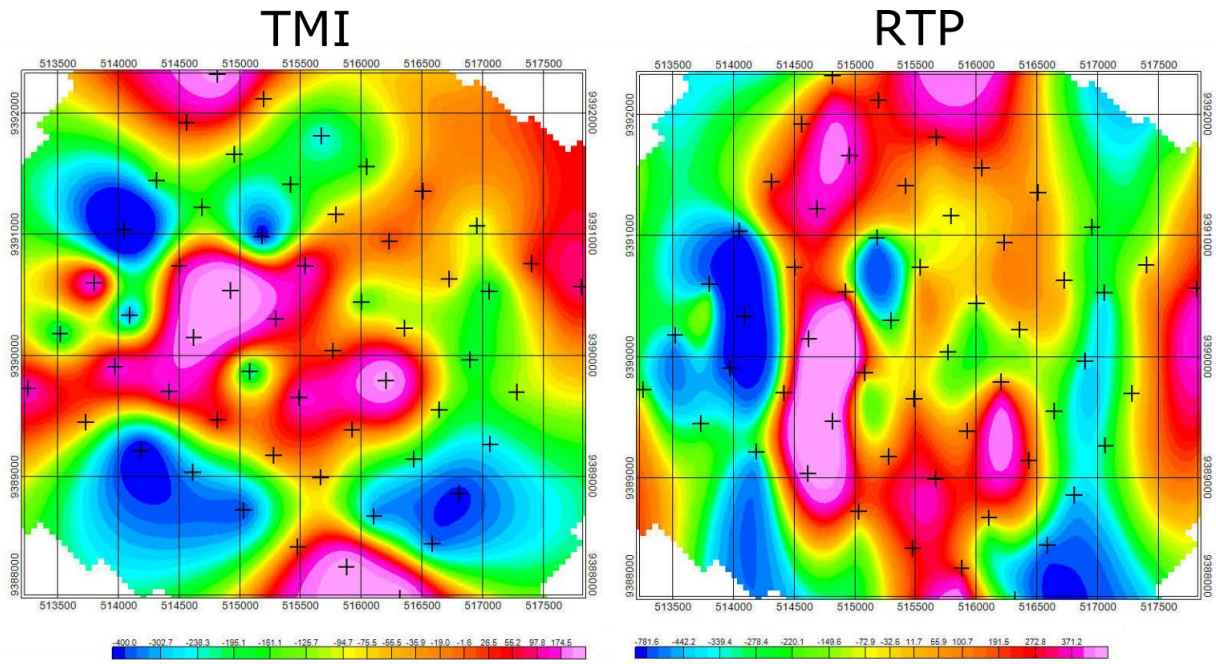

Figure 2. Total magnetic intensity (TMI) and Reduction to Pole (RTP) anomalies in the study area. The plus signs represent the distribution of the observed points. Contour outside the observed points is negligible due to the results of extrapolation.

3. METHOD

3.1. Magnetic Survey and Corrections

A total of 55 points are measured to obtain the magnetic field values covering the area delineated by a red rectangular in Figure 1. Due to an interval of 500 m, this survey occupied around 10.5 km^2 area where distributed 7x8 points illustrated in Figure 2.

The recorded data consists of three measurements of each point becoming averaged magnetic values which are processed into a raw total magnetic intensity (TMI) grid. The process includes diurnal (T_{vh}) and International Geomagnetic Reference Field (T_{IGRF}) corrections following

$$TMI = T_{obs} - T_{vh} - T_{IGRF} \qquad (1)$$

where Tobs is the averaged magnetic values.
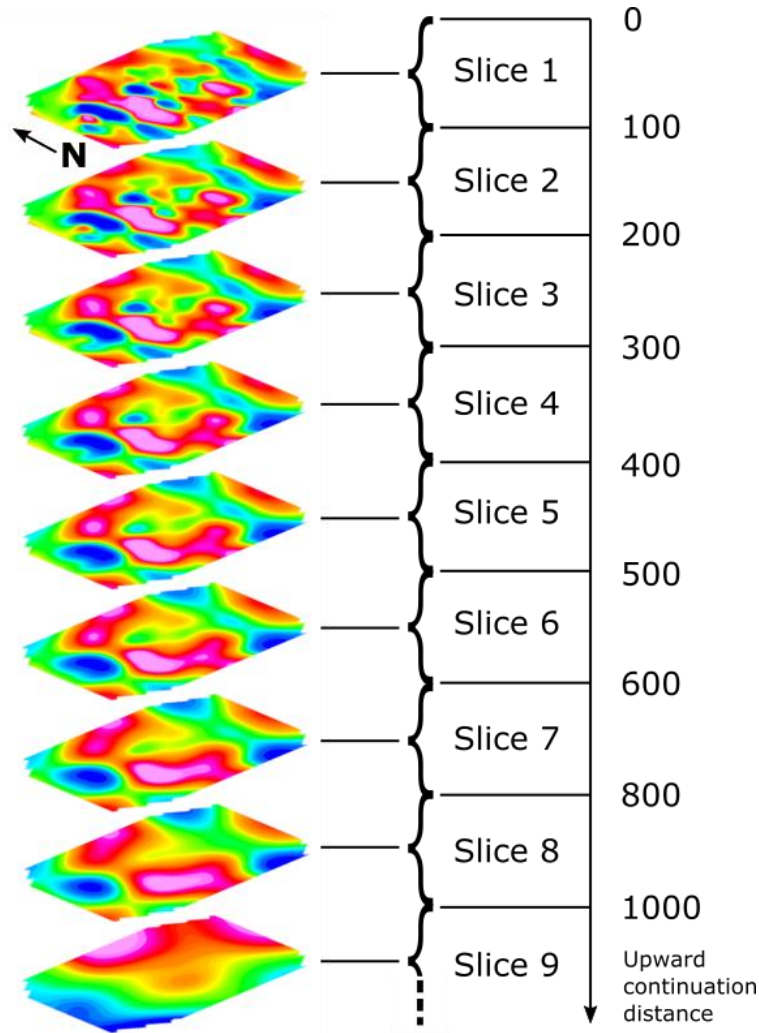
Figure 3. Successive decomposition of RTP anomalies. The slices represent pseudo-depth slice anomalies based on an interval between two upward continuation distances.

Regarding diurnal corrections, periodical magnetic values measured in a local base are used to eliminate external magnetic fields due to time differences and solar radiation effects for each observation day. The correction is obtained by

$$T_{vh} = H_{bi} - H_{b1} \qquad (2)$$

where H_{bi} is a magnetic field value recorded in a local base which has the same time as measured in the field. Moreover, H_{b1} is the base value recorded on the corresponding observation day for the first time. In addition, subtracting the IGRF field from the observed magnetic values aims to vanish a global representation of the Earth's main magnetic field adopting a standard mathematical description.

3.2. Reduction to Pole (RTP) Anomalies

Transforming TMI to RTP anomalies has an objective to facilitate magnetic interpretations where the magnetic field direction has transformed from dipole to monopole, especially in areas with lower latitude [3], [5]. In order to change the direction, the inclination and declination have to be 90 and 0 degrees, respectively, so that the resulting anomalies represent the actual position of concerned mediums. In this study, Figure 2 shows the difference between TMI and RTP anomalies of the observed area.

3.3. Upward Continuation

Extracting regional information in magnetic fields is an advantage of implementing upward continuation because this method eliminates local influences near the surface so that the effect of background magnetic fields is more visible [3]. More visible background magnetic fields can be obtained by inserting higher distance values as the parameter. Moreover, subtracting the RTP data with the result of this method will gain the residual effects of the magnetic field. Theoretically, the brief principle of upward continuation describes potential fields calculated for each point covered in a certain area [5].
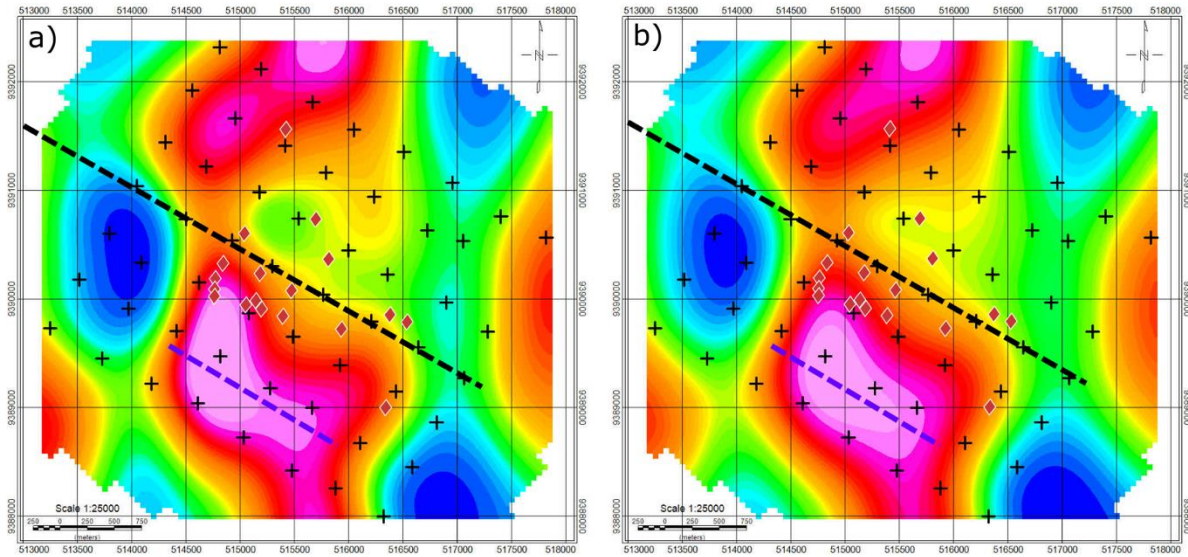
Figure 4. Representatives of the successive decomposition results at slices 7 (a) and 8 (b). There are 2 dashed lines where the black and red colors represent the inferred Menanga fault based on the map in Figure 1 and our propose, respectively. Red points represent the swarm distrbutions based on [1].

3.4. Pseudo-depth Slice Anomalies

Instead of separating a residual and a regional anomaly, this study facilitates the separation of potential field anomalies based on the successive decomposition method. This method calculates several residual and regional pairs where, in this case, the RTP magnetic anomaly obtains several layers by using different distances of upward continuation [6]. Figure 3 shows the successive decomposition of RTP magnetic anomaly, which is initially utilized using gravity anomaly data [7] [8]. The decomposition follows the scheme introduced by [7]. The decomposition is made up of regional and residual pairs by using the upward continuation of 100, 200, 300, 400, 500, 600, 800, and 1000 m of height. This decomposition results in 8 slices of magnetic anomaly, which correspond to the pseudo-depth of each. The slice represents the sum of geological magnetic sources between two successive slices.

4. DISCUSSION

The occurrence of an earthquake swarm in Pesawaran, Lampung, for 11 days, 5 – 16 January 2021, encouraged us to conduct the magnetic survey over the epicenter area of the swarm. From the hypocenter distribution, the Pesawaran swarms are caused by the activity of the Menanga Fault [1]. In nature, swarms are generally related to the fluid activity around the volcanic area [9] [10], geothermal activity [11] and human induced [12]. This approach aims to confirm the mechanism of swarms occurrence, whether it is correlated to the volcanic-fluid activity or purely tectonic fault movement of Menanga.

We collected the data using a 500 m interval in the field, yet we resample the data using a 50 m grid over the research area for the processing. From the pseudo-depth slices, a gradual change formed from short to long-wavelength magnetic RTP anomaly. This corresponds to shallow to the deeper part of magnetic anomaly sources. As we see from slice 1, it shows a short wavelength magnetic anomaly that we suggest as the random distribution of variated rocks that spread near the surface. As the depth goes deeper, from slices 2 to 4, they exhibit an N-S trend high anomaly in the western part of the research area. This N-S trending anomaly also has been seen from slice 1. This high anomaly extends to the east at the northern and southern parts of the research area. The effect of surface magnetic sources is eliminated gradually as the upward continuation is getting higher. It represents by the wavelength anomaly that is getting longer.

From slices 5 and 6, the trend of high anomaly tends to be NW-SE at the southern part and a NE-SW high anomaly at the northern part. Our interest is in the NW-SE high anomaly trending since it is correlated with the existence of inferred Menanga Fault. From slices 7-8 (Figure 4), the pattern is still preserved and the NW-SE high anomaly trending becomes more distinct. The distinction indicates strong magnetic sources. Since the location is in the vicinity of a dormant volcano, which is Mount Ratai, this leads to the idea that the anomaly is related to the activity of volcanic, which is magmatic fluid injection. This idea is based on the 2006 swarms earthquake which is located at the east of Mount Betung, which is located close to Mount Ratai (Figure 1). These swarms are interpreted as the volcanic-tectonic (VT) induced by the magmatic injection and activated a fault at a certain depth [13]. According to

[11] the fluid pressure can destabilize the fractures and cause the rupture according to the Mohr-Coulomb failure criterion. The pressure is able to activate the predominantly shear crack and produces swarms. Since the Pesawaran swarms occurred exactly at the trace of inferred Menanga fault and it is strengthened with a high magnetic anomaly at this area, these facts agree with the idea that the occurrence of the swarm is caused by the magmatic fluid activity that reactivated the Menanga Fault. Since the strong magnetic anomaly occurred at the slice of 7-8 and gradually dimmed upward, it is indicated that the magmatic fluid activities have not been involved toward the surface and remain isolated at depth.

5. CONCLUSIONS

The implementation of successive decomposition method on the magnetic field anomalies in this study indicates an NW-SE high anomaly at below slice 5, which may be related to the magmatic fluid injection. Whereas a short wavelength magnetic anomaly on the slice near the surface represents the random distribution of variated rocks. This magmatic fluid activity reactivated the Menanga fault occurring the Pesawaran swarm. The magmatic fluid activity has not been involved toward the surface and remain isolated at depth indicated by the high anomaly dimming upward.

AUTHORS' CONTRIBUTIONS

Conceptualization, Y.S. and I.N.; Data curation, R.W.; Investigation, Y.S., I.N., and R.W; Methodology, Y.S. and I.N.; Supervision, I.N.; Validation, Y.S. and I.N.; Writing – original draft, Y.S. and I.N.; Writing – review & editing, Y.S. and I.N.

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REFERENCES

[1] I. Nurfitriana, A. Wibowo, R. Rudianto, Reloksi Gempa Bumi Swarm di Pesawaran-Lampung, Januari 2021, *J. Geocelebes*, Apr. 2021, pp. 91–101, doi: 10.20956/geocelebes.v5i1.13328.

[2] S. Rasimeng, Analisis Sesar Gunung Rajabasa Lampung Selatan Sebagai Daerah Prospek Geothermal Berdasarkan Data Anomali Medan Magnet Total, *J Sains MIPA*, vol. 14, no. 1, 2008, p. 6.

[3] I. M. Fathonah, N. B. Wibowo, Y. Sumardi, Identifikasi Jalur Sesar Opak Berdasarkan Analisis Data Anomali Medan Magnet dan Geologi Regional Yogyakarta, *Indones. J. Appl. Phys.*, vol. 4, no. 02, 2017, p. 192, doi: 10.13057/ijap.v4i02.4990.

[4] S. A. Mangga, Amirudin, T. Suwarti, S. Gafoer, and Sidarto, Peta Geologi Lembar Tanjung Karang, Sumatera (skala 1:250.000), Pusat Penelitian dan Pengembangan Geologi, Bandung.

[5] S. Darmawan, H. Danusaputro, T. Yulianto, Interpretasi Data Anomali Medan Magnetik Total Untuk Permodelan Struktur Bawah Permukaan Daerah Manifestasi Mud Vulcano (Studi Kasus Bledug Kuwu Grobogan), *J. Geofis.*, vol. 13, pp. 7–15, 2012.

[6] E. Ibrahim, M. Arfaoui, S. Mogren, S. Qaysi, A. Lashin, H. Alfaifi, Disposition of magmatic eruptions and fault distribution in northwestern Saudi Arabia using pseudo-depth slice magnetic anomaly, *J. Geophys. Eng.*, vol. 18, no. 4, pp. 463–481, Aug. 2021, doi: 10.1093/jge/gxab028.

[7] M. Arfaoui, M.H. Inoubli, A. Amiri, An optimal multiscale approach to interpret gravity data using successive decomposition of the Bouguer anomaly, Contributions to Geophysics and Geodesy, vol. 48, no. 2, 2018, pp. 133–160.

[8] M. Arfaoui, M.H, Inoubli, S. Tlig, R. Alouani, Gravity analysis of salt structures. An example from the El Kef-Ouargha region (northern Tunisia), *Geophysical Prospecting*, vol. 59, 2011, pp. 576–591.

[9] G. Saccorotti, G, Ventura, G. VilardoSeismic swarms related to diffusive processes: The case of Somma-Vesuvius volcano, Italy", *Geophysics* 67, 2022, pp. 199–203, https://doi.org/ 10.1190/ 1.1451551.

[10] D.P. Hill, A model for earthquake swarms", *J. Geophys. Res*. vol. 82, 1347–1352, 1977. https://doi.org/10.1029/JB082i008p01347

[11] V. Vavryčuk, P. Hrubcová, Seismological evidence of fault weakening due to erosion by fluids from observations of intraplate earthquake swarms, *J. Geophys. Res. Solid Earth*, vol. 122, 2017, pp. 3701–3718. https://doi.org/ 10.1002/2017JB013958

[12] T.S. Eyre, M. Zecevic, R.O. Salvage, D.W. Eaton, A long-lived swarm of hydraulic fracturing-induced seismicity provides evidence for aseismic slip, *Bull.* Seismol. Soc.Am. vol. 110, 2020, pp. 2205–2215. https://doi.org/10.1785/0120200107.

[13] B. Mulyatno, Analisis Geofisika Gempa Swarm Kemiling", *Prosiding Hasil-hasil Penelitian dan PKM UNILA*, ISBN:979-15525-0-5, 2006.