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Mineral Perspectivity Mapping in the Montana Region Based on a Combination of Variations in Gravity, Magnetic, and Geochemical Data Using Likelihood Ratio and Fuzzy Logic Methods

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Abstrak: Montana merupakan Provinsi di Amerika Serikat yang dijuluki "Negara Harta Karun" karena memiliki komoditas logam yang beragam sehingga pemetaan prospek mineral di Montana sangat menarik. Dibutuhkan pemahaman mineralisasi endapan porfiri di lokasi penelitian untuk mengetahui peran data gravitasi, magnetik, dan geokimia. Pada penelitian ini, integrasi data yang digunakan adalah metode *likelihood ratio* dan *fuzzy logic* untuk mendapatkan peta tubuh bijih, peta tingkat mineralisali, dan peta prospek mineral di lokasi penelitian. Dari variasi data gravitasi dan magnetik, didapatlah peta sebaran tubuh bijih. Dari data geokimia Au, Ag, Cu, As, Pb, dan Zn, didapatlah peta tingkat mineralisasi di daerah penelitian. Peta potensi tubuh bijih dan peta tingkat mineralisasi dikombinasi lagi untuk mendapatkan peta prospek mineral. kemudian semua hasil peta dari metode *likelihood ratio* dan metode *fuzzy logic* diinterpretasi dan dibandingkan. Dari peta prospek mineral, penulis berhasil memetakan zona mineralisasi untuk memilih penargetan eksplorasi dengan luas total area mineralisasi yang didapat sebesar 8223 km^2 dengan area terluas 2868 km^2 pada area tipe batuan plutonik yang litologinya granitik.

Kata kunci: Fuzzy, Gravitasi, Likelihood, Magnetik, Mineral.

*Abstract***:** *Montana is a province in the United States which is nicknamed the "Country of Treasures" because it has a variety of metal commodities so mapping the mineral prospects in Montana is very interesting. It is necessary to understand the mineralization of porphyry deposits at the research site to determine the role of gravitational, magnetic, and geochemical data. In this study, the data integration used is the likelihood ratio and fuzzy logic methods to obtain ore body maps, mineralization grade maps, and mineral prospect maps at the research site. From the variation of gravity and magnetic data, a map of the distribution of the ore body is obtained. From the geochemical data of Au, Ag, Cu, As, Pb, and Zn, a map of the mineralization level in the study area was obtained. The ore body potential map and mineralization level map are combined again to get a mineral prospect map. then all map results from the likelihood ratio method and the fuzzy logic method are interpreted and compared. From the mineral prospect map, the authors succeeded in mapping the mineralized zone to select exploration targets with a total area of mineralization obtained of 8223* km^2 *with the widest area of 2868* km^2 *in plutonic rock types with granitic lithology.*

Keywords: Fuzzy, Gravity, Likelihood, Magnetic, Mineral.

1 INTRODUCTION

Montana is a province in the United States that is dubbed the "Country of Treasures" because it has a wealth of metal commodities such as base metals, precious metals, iron and ferrous alloys, and several other metals (Gammons et al., 2020). With information like this, the authors are interested in conducting research related to Mineral Perspectivity Mapping (MPM) in this area. According to Yousefi et al. (2021), the most common problem of MPM is that it has not been able to handle complex geological processes (multiscale ore formation) so GIS is sometimes less effective in real-world exploration. Answering the problems above, the author attempts to conduct a large-scale MPM study (1:1729093 (Continental to Regional Scale)).

There have been many studies of MPM with various integration methods to get a good model. However, according to Yousefi et al. (2019), the main cause of the MPM problem is the ineffective use of input data related to the ore formation process, so exploration system information is needed to maximize input data. In this study, Montana is an area with available and complete data that provides aeromagnetic, geochemical, and satellite gravity data. All knowledge-based geophysical and geochemical data can be processed, manipulated, visualized, and integrated with large quantities efficiently to obtain good mineral prospect maps (Nykänen and Salmirinne 2007). The data integration method in this study uses the Fuzzy Logic method (a model with the Knowledge-Driven type) and the Likelihood Ratio (a model with the Empirical-Function type).

In this study, we will conduct MPM research by making geophysical and geochemical data the main focus in seeing the efficiency of input data. The purpose of this study is to how various data can be combined and integrated to obtain a mineral prospect map. Various geophysical data on a large scale are interpreted to identify the ore body. Various geochemical data were interpreted to identify the distribution of mineralization levels in the study area. various data

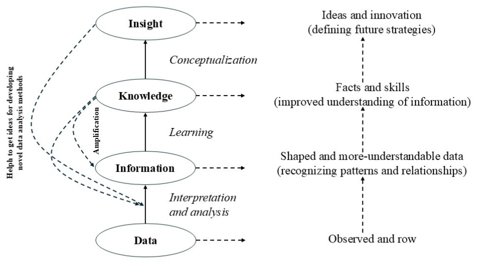

Figure 1. The concepts of data, information, knowledge, and insight and their interrelationships (Yousefi et al., 2021).

are integrated using the fuzzy logic method and likelihood ratio which the result is a mineral prospect map. From the resulting mineral prospect map, the authors hope to be able to identify and know the distribution of ore in Montana and be able to choose targeting criteria that can be mapped.

2 BASIC THEORY

2.1 Mineral Prospect Mapping

Hronsky and Groves (2008) said that the foundation of targeting mineral exploration is how diverse data sets can be combined, integrated, and interrogated correctly, while according to Yousefi et al. (2019) what is needed in MPM is optimal input data and proper integration. better than conceptual mineral deposit models with available data. Starting from the available exploration and geoscientific data, it becomes a checkpoint in gathering information about the process of mineral ore formation. The information obtained can be used to generate knowledge about the constituent processes involved in generating the deposit data system. If the knowledge related to the correlation of each input data with its constituent processes is known, then the data integration is ready to be carried out (Yousefi et al., 2021). A simple explanation can be seen in Figure 1.

The mineral prospect maps that have been obtained from the integration are then interrogated to turn the data into insight so that the results can propose a further framework in which new developments can be expected.

2.2 Overview of the Research Area

Southwest Montana is a fertile but semiarid valley land separated by relatively small but high mountains. Although the geological structure of the study area resulted from severe tectonic collisions, the current skeleton is the result of tectonic extension (Gibson 2009).

In the research area, it can be seen in Figure 2 that there are volcanic, plutonic, and metamorphic rock types exposed on the surface. In the research area, there are plutonic Boulder Batholite, Castlerock, and Little Belt Mountains Plutons (Susan M, Porter, Lonn, & Lopez, 2007). Presence The presence of plutonic rock is very important in mineral exploration because it can function as a source rock for mineral deposits.

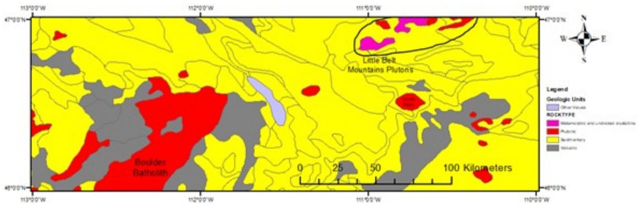

Figure 2. Map of Rock Types in the Research Area.

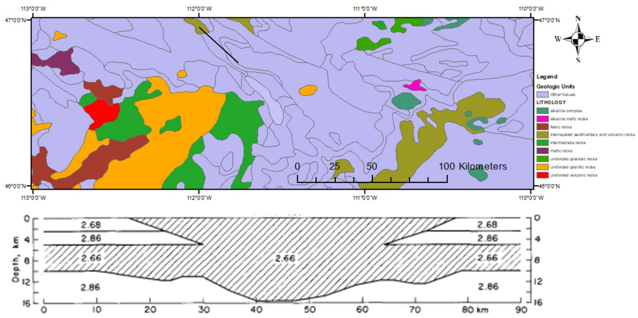

Figure 3. Gravity Modeling Results on the Boulder Batholith intrusion (Biehler and Bonini, 1969).

2.3 Gravity Method

In the search for mineral prospects, the gravity method is useful for investigating body rock or subsurface structures that have associated lateral density variations such as finding ore bodies, intrusions, and faults whose density is different from the surrounding rock (Mussett et al., 2000).

In the study area, the intrusion area with black shading (Figure 3) is a granitic intrusion with a density of 2.66, while the surrounding area is a sedimentary rock with a density of 2.86 (Biehler and Bonini, 1969). this will result in the reading of the gravity value in the study area coinciding with the low anomaly. The gravity data needed in this study are Simple Bouguer Anomaly (SBA) gravity data, regional gravity, and residual gravity.

2.4 Magnetic Method

The purpose of the magnetic method is to show how anomalies relate to the shape, orientation, and latitude of the object of exploration (Mussett et al., 2000). The application of magnetic methods is often used for preliminary surveys in the field of mineral exploration, identifying metallic minerals contained in rocks, and identifying subsurface geological structures (Reynolds, 2011). The magnetic data needed in this study are Reduce to Pole (RTP) magnetic data, regional magnetics, and residual magnetics.

2.5 Geochemical Method

A Geochemical Atlas from the USGS is a collection of graphs, maps, and tables showing the analytical value of chemical elements in flow-sediment and soil samples in the Americas. data were prepared from the National Geochemical Survey (NGS), which consisted of reanalyzed National Uranium Resource Evaluation (NURE) sediment flow and additional soil sample data collected for the NGS (Sutphin, 2005). The purpose of a geochemical concentration map is to present the pattern of elemental occurrence and provide the distribution of elemental concentrations in an area.

2.6 Fuzzy Logic Method

Fuzzy logic is a conceptual method used to map various input spaces into a suitable output space. The value of the proportion in fuzzy logic is the overall value between 0 and 1 (Rojas., 1996).

In mathematical operations, if X is the universe of discourse and its elements are denoted by x, then the fuzzy set A (MA) in X is defined as a set of ordered pairs as written in the equation below.

$$MA = \{x, \mu A(x) | x \in X\} \quad (1)$$

$\mu A(x)$ is called the degree of membership of x in A. The membership function maps each element of X to a membership value between 0 and 1. In the fuzzy concept, it is also known as Logical Operation (Rojas., 1996). The types of fuzzy operations are Fuzzy And, or Product, Sum, and Gamma. The function of the fuzzy operation is to find out how fuzzy inference is connected (Kainz, 2010).

2.7 Likelihood Ratio Method

The strength of the spatial relationship between the occurrence of deposits and their associated factors is expressed in likelihood ratios. The Likelihood ratio is the ratio of the probability of a deposit (%occ) to the probability of the area (%Area) (Lee et al., 2014) The Likelihood ratio is the likelihood ratio (LS) with the equation as written in the following formula:

$$LS_i = \frac{\%occ}{\%area} \quad (2)$$

The more similar the spatial relationship to the occurrence of mine, the higher the ratio, even exceeding 1 (Lee et al., 2014). The likelihood ratios for each range or factor class are summed to calculate the MPI_L (Mineral Potential Index) as written in the following formula:

$$MPI_L = \sum LS \quad (3)$$

where LS = likelihood ratio for the rank or class of each factor, and MPI_L = Mineral Potential Index indicating the mineral potential value.

3 METHODOLOGY

The research flow consists of the preparation stage, data collection, data processing, and the final stage. The research starts from the study of literature and the determination of the research location. The datasets used in this research are satellite gravity, aeromagnetic, and geochemical data. Each data is processed so that it can find out the role of each data in the Exploration Information System and the input data patterns are visible to each other. Each input data weight is calculated based on the Likelihood Ratio method. From the gradient obtained in the Likelihood Ratio, the authors can find out how big the role of the input data is in mapping mineral prospects.

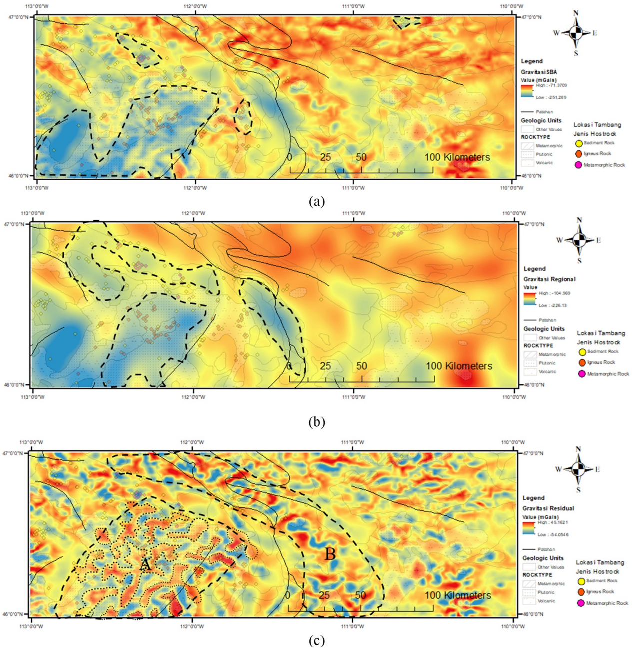

Figure 4. Gravity Map (a) SBA, (b) Regional, (c) Residual.

4 DATA PROCESSING RESULTS

12 input data are used as predictor maps that function to predict mineral potential in all research locations. Each prediction map has its own role in determining the potential value of minerals. 12 maps will be interpreted, combined, and integrated. The interpretation review is assisted by lithological maps, regional structures, and the location of the mine presence in the study area.

4.1 Gravity Method Results

Gravity maps are used to determine the location of the ore body from the density value approach. The SBA map is obtained from Topex data processing which has been corrected by Bouguer correction. Furthermore, the SBA map was filtered to obtain a regional gravity map and residual anomaly. The results of the SBA, regional and residual gravity maps can be seen in Figure 4.

The SBA map and regional gravity show that the granitic intrusion and other intrusion areas are at low gravity values. In Paper Biehler and Bonini (1969) describe the regional area in the low plutonic area due to constant anomalous mass in depth throughout the main part of the intrusion axis, and the density of the environmental area which is Precambrian to cretaceous sedimentary has a higher density than intrusive rock. In Biehler and Bonini (1969) research, the results of gravity modeling in the study area show that sedimentary rocks in the study area have a density of 2.86 and an intrusive rock density of 2.66 (as shown in Figure 3), so that regional gravity readings correlate with low gravity anomaly values (colored blue in Figure 4(b)).This intrusive rock can only be seen from regional gravity, while the residual gravity does not correlate with low anomalies. This shows that these intrusive rocks are on a regional scale. The residual gravity may show the ore body subsystem at a high anomaly (red in Figure 4(c)). The contrast of the red

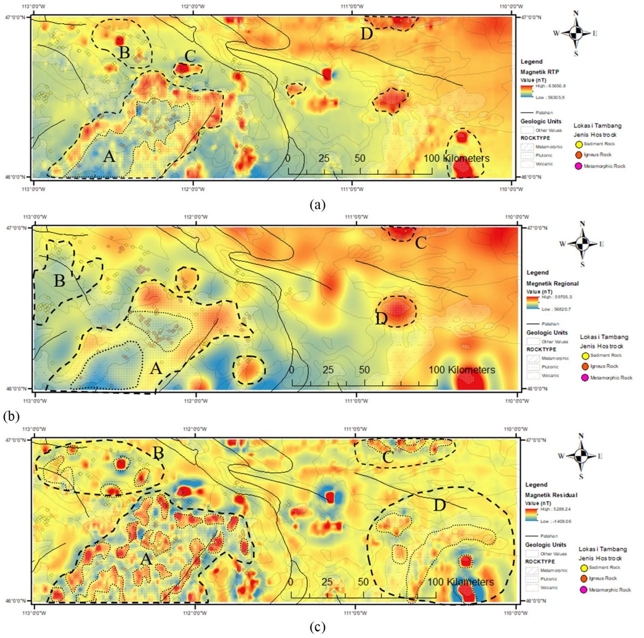

Figure 5. Magnetic Map (a) RTP, (b) Regional, (c) Residual.

and blue colors in zone A in Figure 4(c)) is brighter than the surrounding area, which shows the intrusion boundary on a regional scale. From the gravity map, the residual red color which is correlated with low regional (in blue) can be interpreted as an area of the mineral ore body.

4.2 Magnetic Method Results

Magnetic maps are used to determine the location of the ore body from the approach to the magnetic properties of rocks. The RTP magnetic map is obtained from the RTP filter from the total magnetic map where the magnetic value has been transformed to the poles so that the magnetic anomaly can represent the object. Furthermore, the RTP map was filtered by spectrum analysis by transforming the Fourier RTP data to obtain regional and residual magnetic maps. The results of the RTP, regional and residual magnetic maps can be seen in Figure 5.

All the magnetic maps in Figure 5, show the location of the presence of many mines that are in high anomaly (red color). The residual magnetic map (Figure 5(c)) is highly representative of the ore body sub-systems throughout the study area. In the regional magnetic section of zone C in Figure 5(b), it is seen that the mining location points are correlated with high anomalies (red color), and zone A in Figure 5(b) shows many mining location points correlated with low anomalies (blue). Area A in Figure 5(b) is a plutonic and volcanic area. intrusive rock may be clearly demarcated when viewed from the magnetic map, but in the middle of the intrusion, there is a low anomaly where the mining points in zone A refer to the low anomaly. This may be a consideration for how regional magnetic maps can be connected with mineral potential maps because there are 2 behavioral problems with regional magnetic maps with different interpretations.

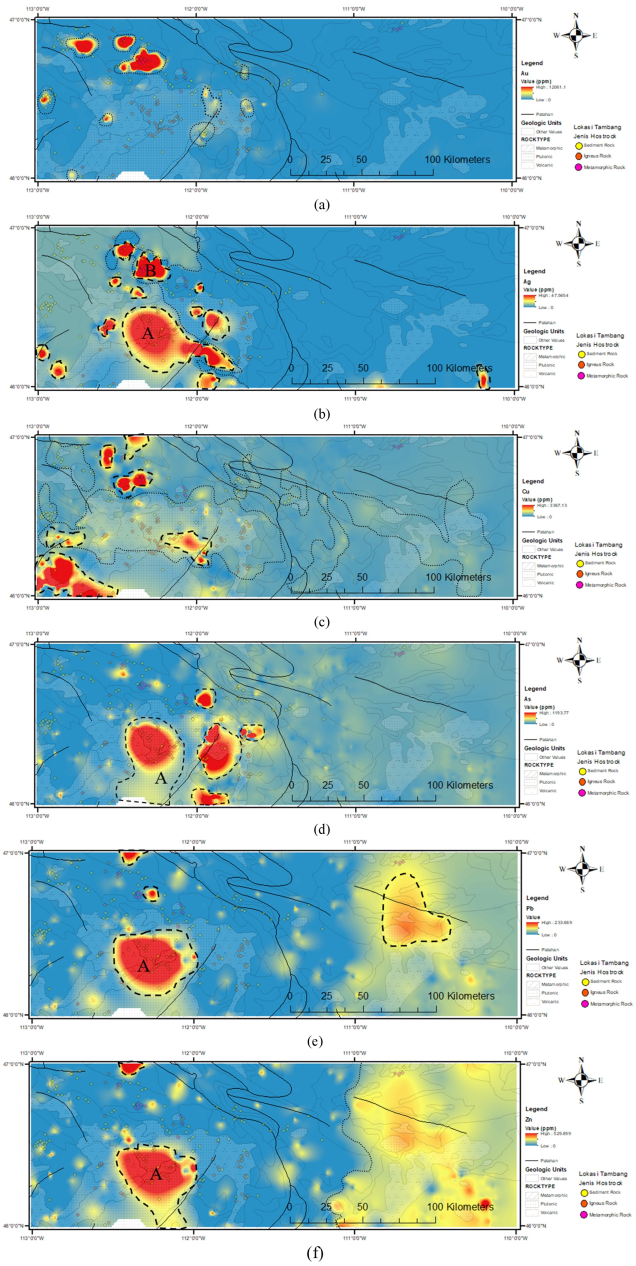

Figure 6. Geochemical Maps (a) Au, (b) Ag, (c) Cu, (d) As, (e) Pb, (f) Zn.

4.3 Geochemical Method Results

The univariate anomaly map of Ag, As, Au, Cu, Pb, and Zn was created by displaying information on geochemical data in the research area which contains information about the coordinates of the rock sample station (Geochemical rock sampling survey) and the element content measured in ppm (parts per million). The data is grid in a geophysical application and interpolated. The result of this interpolation is an anomaly map of the elements Ag, As, Au, Cu, Pb, and Zn with units of ppm (parts per million) which can be seen in Figure 6.

Various geochemical maps were made to identify areas of mineral potential because these elements are commodities from mining in rich Montana. Areas of focus may be dire-

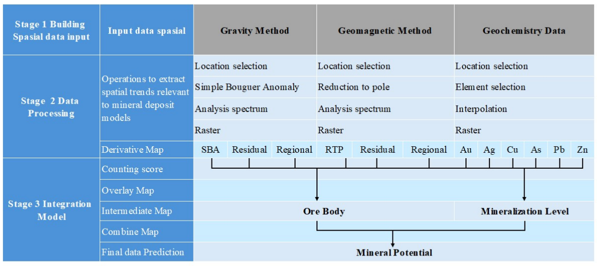

Figure 7. Mineral Prospect Mapping Flow.

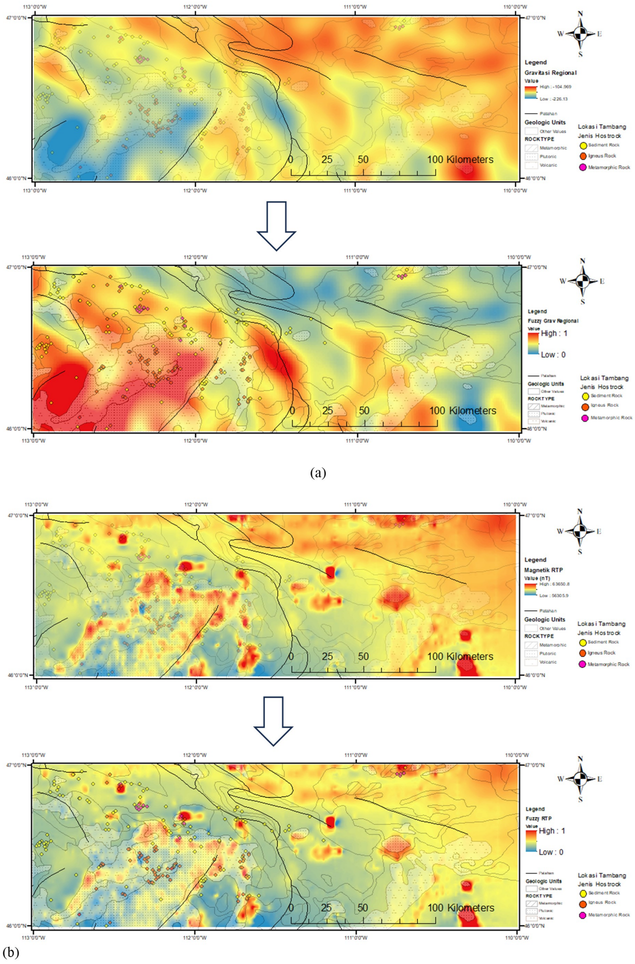

Figure 8. Fuzzy Membership.

cted to plutonic, volcanic, and metamorphic areas. In the granitic plutonic area, Ag, As, Pb and Zn elements show high and wide anomalies in the area (marked zone A on each map). There are no correlated elements in the metamorphic area in the northeast of the map. In the northwestern area of the map, there are many high anomalies. The elements Au, Ag, and Cu show very clear anomalies with high concentrations and correlate with mining points with igneous and metamorphic rocks. Areas of high mineralization when viewed from the distribution of geochemical concentrations may be in the granitic area (Zone A in Figure 6(b)) and the northwest area (Zone B on the Ag concentration map (Figure 6(b)).

4.4 Integration Architecture

12 input data have been prepared and ready to be combined. The gravity method and magnetic method are combined and integrated to obtain the distribution of the ore body. Geochemical methods were used to obtain mineralization level maps. To get a map of mineral prospects, the flow can be seen in Figure 7.

To obtain the mineral potential map, 2 integration methods were applied, namely the likelihood ratio method as an empirical model, and the fuzzy logic method as a knowledge-driven model. Intermediate maps and map results from these two methods are created and obtained which are then ready to be interpreted.

4.5 Likelihood Ratio Calculation

The most important thing in implementing the likelihood ratio method is calculating the ratio of the presence of each class and the ratio of the area of the class. All data divided into 5 classes are labeled 1 to 5. Number 1 indicates the very low class, 2 indicates the low class, number 3 indicates the moderate class, number 4 indicates the high class, and number 5 indicates the very high class. The calculation of the ratio of each class of gravity method can be seen in Table 1.

Table 1 shows that the LS values of SBA, regional gravity, and regional magnetics have the highest LS values in the low class (class number 2), while in the LS calculation the residual gravity, RTP, and residual magnetic data show the highest LS values in the very high class (class number 5). In the LS calculation, the geochemical data in Table 1 shows that the highest values are very high (such as elements Au, Ag, Pb, and Zn) and high (such as Cu and As). All LS from each class has an important role because the LS value is the weight given to each class which is finally used to obtain mineral prospect maps.

4.6 Application of Fuzzy Logic

The first thing to do in the fuzzy logic method is to carry out a membership fuzzy in which each data value is changed from 0 to 1. close to 0. Staining is done where red indicates a high score and blue indicates a low score.

In assigning a score to fuzzy membership, there are low anomalies that are given a high score (Figure 8(a)) such as SBA maps, regional gravity, and regional magnetics. There are also high anomalies that are given high scores (Figure 8(b)) such as residual gravity maps, RTP, residual magnetic, and all geochemical maps. This is considered based on the value of LS which has the highest value in the high or low class and based on research by Biehler and Bonini (1969) which shows the density of intrusive rocks is lower than the surrounding environment.

After all the data is fuzzy membership, the next step is fuzzy membership processed with fuzzy operators into intermediate maps, then fuzzy operations are carried out again to

Table 1. Likelihood Ratio Calculation (LS).

SBA	**Class**	**Area**	**% Area**	**occ**	**% occ**	**LS**
Verry-Low	(-251.9) – (-198.37)	2486	8.07 %	23	10.798 %	1.337994
Low	(-198.37) – (-1775.9)	5794	18.80%	73	34.272%	1.822099
Medium	(-1775.9) – (-156.04)	9100	29.55%	66	30.986%	1.04889
High	(-156.04) – (-136.99)	9101	29.55%	43	20.188%	0.683293
Verry-High	(-136.99) – (-71.37)	4323	14.03%	8	3.756%	0.267628
	Total	**30804**		**231**		
Grav Reg	**Class**	**Area**	**% Area**	**occ**	**% occ**	**LS**
Verry-Low	(-226.13) – (-194.77)	2653	8.62%	30	14.08%	1.634737
Low	(-194.77) – (-174.34)	4908	15.93%	62	29.12%	1.826899
Medium	(-174.34) – (-158.18)	8391	27.24%	86	40.38%	1.482219
High	(-158.18) – (-143.46)	9081	29.48%	33	15.48%	0.525542
Verry-High	(-143.46) – (-104.97)	5770	18.73%	2	0.94%	0.050128
	Total	**30804**		**213**		
Grav Res	**Class**	**Area**	**% Area**	**occ**	**% occ**	**LS**
Verry-Low	(-54.05) – (-17.48)	2156	7%	17	7.98%	1.140322
Low	(-17.48) – (-5.42)	6614	21.47%	42	19.72%	0.918359
Medium	(-5.42) – (3.14)	11103	36.04%	64	30.05%	0.833618
High	(3.14) – (13.26)	8366	27.16%	60	28.17%	1.037196
Verry-High	(13.26) – (45.16)	2565	8.327%	30	14.08%	1.691459
	Total	30804		213		
RTP	**Class**	**Area**	**% Area**	**occ**	**% occ**	**LS**
Verry-Low	(56305.8) – (57630.8)	6938	22.98%	77	36.15%	1.573151
Low	(57630.8) – (57890.0)	10540	34.67%	76	35.68%	1.029156
Medium	(57890.0) – (58206.9)	10648	35.02%	38	17.84%	0.509359
High	(58206.9) – (59272.6)	2100	6.91%	19	8.92%	1.291346
Verry-High	(59272.6) – (63650.7)	127	0.42% 3	1.41%	3.37152	
	Total	**30401**		**213**		
Mag Reg	**Class**	**Area**	**% Area**	**occ**	**% occ**	**LS**
Verry-Low	(56820.6) – (57589.9)	2653	8.62%	30	14.08%	1.634737
Low	(57589.9) – (57827.5)	4908	15.93%	62	29.11%	1.826899
Medium	(57827.5) – (58076.4)	8391	27.24%	86	40.38%	1.482219
High	(58076.4) – (58687.2)	9081	29.48%	33	15.49%	0.525542
Verry-High	(58687.2) – (59705.4)	5770	18.73%	2	0.94%	0.050128
	Total	**30401**		**213**		
Mag Res	**Class**	**Area**	**% Area**	**occ**	**% occ**	**LS**
Verry-Low	(-1408.0) – (-121.320)	2156	7%	17	07.98%	1.140322
Low	(-121.320) – (88.7599)	6614	21.47%	42	91.84%	0.918359
Medium	(88.7599) – (613.960)	11103	36.04%	64	83.36%	0.833618
High	(613.960) – (2347.12)	8366	27.16%	60	03.72%	1.037196
Verry-High	(2347.12) – (5288.24)	2565	08.33%	30	69.15%	1.691459
	Total	**30804**		**213**		
Au	**Class**	**Area**	**% Area**	**occ**	**% occ**	**LS**
Verry-Low	0 – 1	15051	49.65%	74	34.74%	0.6998
Low	1 – 5	7983	26.33%	25	11.74%	0.4457
Medium	5 – 100	6251	20.62%	70	32.86%	1.5938
High	100 – 200	369	01.22%	10	04.69%	3.857
Verry-High	20 – 12620	661	02.18%	34	15.96%	7.3207
	Total	**30315**		**213**		
Ag	**Class**	**Area**	**% Area**	**occ**	**% occ**	**LS**
Verry-Low	0 – 0.2	19821	65.38%	66	33.67%	0.515
Low	0.2 – 1	4205	13.87%	19	09.69%	0.6989
Medium	1 – 3	4018	13.25%	46	23.47%	1.7707
High	3 – 6	1190	03.93%	15	07.65%	1.9469
Verry-High	6 – 50	1081	03.57%	50	25.51%	7.1539
	Total	**30315**		**196**		
Cu	**Class**	**Area**	**% Area**	**occ**	**% occ**	**LS**
Verry-Low	0 – 10	364	01.2%	0	0%	0
Low	10 – 50	22268	73.46%	11	12.36%	0.1683
Medium	50 – 100	50	17.83%	46	51.69%	2.8994
High	100 – 200	1302	04.29%	20	22.47%	5.2322
Verry-High	200 – 3500	977	03.22%	12	13.48%	4.1836
	Total	**30315**		**89**		

Table 2. Likelihood Ratio Calculation (LS) (Continued)

As	**Class**	**Area**	**% Area**	**occ**	**% occ**	**LS**
Verry-Low	0-10	11671	38.5%	10	31.25%	0.8117
Low	10-25	15934	52.56%	0	0%	0
Medium	25-50	1394	04.6%	3	09.38%	2.0388
High	50-100	568	01.87%	11	34.38%	18.346
Verry-High	100-1200	748	02.47%	8	25%	10.132
	Total	**30804**		**32**		
Pb	**Class**	**Area**	**% Area**	**occ**	**% occ**	**LS**
Verry-Low	0-5	14409	47.53%	42	46.67%	0.9818
Low	5-15	3055	10.08%	2	02.22%	0.2205
Medium	15-30	8378	27.64%	2	02.22%	0.0804
High	30-50	2939	09.69%	12	13.33%	0.3753
Verry-High	50-250	1534	05.06%	32	35.56%	7.0265
	Total	**30315**		**90**		
Cu	**Class**	**Area**	**% Area**	**occ**	**% occ**	**LS**
Verry-Low	0-10	12343	40.72%	24	35.29%	0.8668
Low	10-20	2635	08.69%	0	0%	0
Medium	20-50	2447	08.07%	2	02.94%	0.3644
High	50-100	9423	31.08%	12	17.65%	0.5677
Verry-High	100-550	3467	11.44%	30	44.12%	3.8576
	Total	**30315**		**68**		

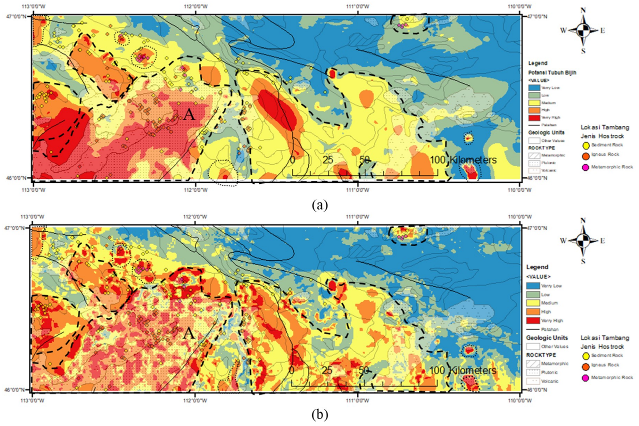

Figure 9. Ore Body Potential Map (a) Fuzzy Logic Results (b) Likelihood Ratio Results.

become mineral prospect maps. The mineral prospect map can then be visualized and divided into 5 classes based on very low, low, medium, high, and very high potential. Then the mineral prospect map can be analyzed further.

5 RESULTS

5.1 Ore Body Map

The input data from the ore body are SBA, regional gravity, residual gravity, RTP, regional magnetic, and residual magnetic. The input data is integrated with the likelihood ratio and fuzzy logic (Fuzzy OR) methods. The results of the rock body distribution map can be seen in Figure 9.

From the ore body map (Figure 9) it can be seen that high anomalies are present on most of the maps. The dominant mining points are in the medium class for the fuzzy logic method, and the high class for the likelihood ratio. The anomalies in these two maps show that they have many similarities but differ in shape. area A is an intrusion area that is characterized by the high anomaly and is a plutonic and volcanic area. The difference in the map generated by the fuzzy logic method looks stronger, which is in area A, the closer to the center of the area, the higher the ore body potential, while the map results from the different likelihood ratio where the ore body potential class is spread randomly and evenly in area A. A clearer difference can be seen from the calculation of the LS value in each class.

Table 3 shows the LS calculation from the ore body potential map. The fuzzy results show that the presence of the mine has the greatest weight in the high class. While the likelihood method shows the ratio of the possibility of a mine being in a very high class. From the fuzzy logic results, it can be concluded that the ore body potential map generated from the fuzzy logic method has been mapped well, although it is relatively not as optimal as the likelihood results.

5.2 Mineralization Level Map

The input data from the mineralized zone are Ag, As, Au, Cu, Pb, and Zn geochemical maps. This input data has been adjusted to the gradient of the LS value. The mineralization level map was obtained from the operator Fuzzy Or geochemical maps of Ag, As, Au, Cu, Pb, and Zn. The results of the overlay can be seen in Figure 10.

From the map of the mineralization level, it can be seen on the map of the mineralization zone from the fuzzy and likelihood ratio that the high anomaly is in area A. The dominant mining points are in the very high, high, and medium classes, although there are some that are in the low anomaly.

The difference in the map generated by the fuzzy logic method in Figure 10(a) looks stronger whereas, in areas A and B, the area of fuzzy logic shows a higher class level. The map results from the likelihood ratio in Figure 10(b) are different, which shows the very high class area is not too large, and the class contour is not so narrow as the

Table 3. LS Value of Mineralization Level

	Class	Area	% Area	occ	%occ	LS
	Verry Low	7187	23.64	3	1.41	0.059577
	Low	6363	20.93	30	14.08	0.672926
Fuzzy	Medium	9384	30.87	83	38.97	1.262404
	High	3863	12.71	58	27.23	2.142948
Potential	Verry High	3604	11.85	39	18.31	1.544501
	Total	**30401**		**213**		
	Class	Area	% Area	occ	%occ	LS
Likelihood	Verry Low	7463	24.55	2	0.94	0.038249
	Low	6166	20.28	25	11.74	0.578688
Potential	Medium	8973	29.52	73	34.27	1.774944
	High	6433	21.16	80	37.56	1.774944
	Verry High	1366	4.49	33	15.49	3.448034
	Total	**30401**		**213**		

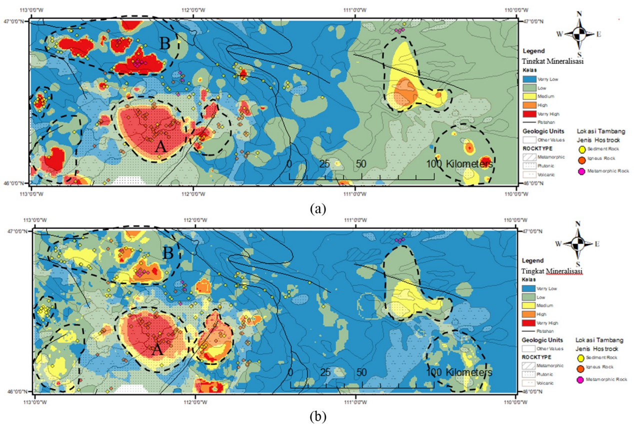

Figure 10. Map of Mineralization Level (a) Results of Fuzzy Logic (b) Results of Likelihood Ratio.

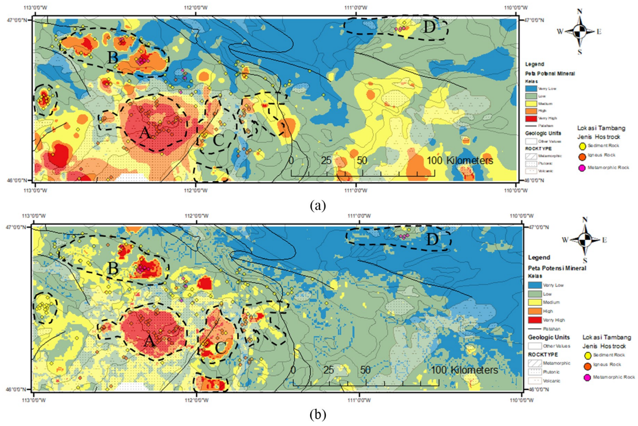

Figure 11. Mineral Potential Map (a) Fuzzy Logic Results (b) Likelihood Ratio Results.

fuzzy logic path. A clearer difference can be seen from the calculation of the LS value in each class.

Table 4 shows the LS calculation from the mineralization level map. From the results of fuzzy logic and likelihood ratio, it shows that the existence of the mine has the greatest weight in the very high class.

5.3 Mineral Potential Map

The 2 intermediate maps are then fuzzily overlaid again with the fuzzy SUM operator and a mineral potential map is obtained from the fuzzy logic method. 2 The input data is also calculated as the likelihood ratio value and added together so that a mineral potential map is obtained from the likelihood ratio method. The map of the results of the two methods can be seen in Figure 11.

Judging from the anomaly in Figure 11, Igneous host rock is dominated by very high potential class as can be seen in areas A, B, and C. Only a small number of mine points correlate with very low class potential areas. The igneous and metamorphic host rock in area B in Figure 11 also shows the presence of mines in the high potential class. From the mineral potential map, it can be seen from the results of the fuzzy and likelihood ratio that the points of the presence of dominant mines are in very high, high, and medium classes, although there are some that are in the low anomaly. The anomalies in these two maps show that they have many similarities but differ in form and class level. More clearly related to the difference in weight for each class can be seen in Table 5.

Table 5 shows the LS calculation from the mineral potential map. From the results of fuzzy logic and likelihood ratio, it shows that the existence of the mine has the greatest weight in the very high class.

5.4 Mineralization Zone

From the mineral potential map, the author made a map of the distribution of mineralization which aims to determine the area of the prospect and the next exploration target. The mineralization area map is obtained from the author's interpretation based on the mineral potential map as a result of the likelihood ratio and fuzzy logic. The author's basis indicates that the area is of medium to very high potential, the presence of intrusion on the geological map as source rock, and the presence of a mine which indicates that the area is an economically mineralized area to explore. A map of the mineralized zone can be seen in Figure 12.

A map of the mineralized area has been created and is shown in orange on the base map (Figure 12). The area of mineralization measured based on the WGS 1984 EASE-Grid 2.0 Global is 8223 km^2 with the widest area of 2868 Km^2 in the mineralized area A in Figure 12. Most of this area has been heavily mined, especially in areas A, B, C,

Table 4. LS Value of Mineralization Level

	Class	Area	% Area	occ	%occ	LS
Fuzzy Potential	Verry Low	11390	37.57	58	2.723	0.72474
	Low	15108	49.83	64	30.05	0.60291
	Medium	996	3.285	2	1	0.28579
	High	665	2.194	7	3.286	2.13857
	Verry High	2156	7.12	82	38.5	5.41306
	Total	**30315**		**213**		
	Class	Area	% Area	occ	%occ	LS
Likelihood Potential	Verry Low	18222	60	59	27.7	0.460823
	Low	8328	27.48	59	27.7	1.008299
	Medium	1926	6.353	18	8.45	1.33013
	High	1098	3.622	45	21.1	5.832949
	Verry High	741	2.444	32	15.05	6.146243
	Total	**30315**		**213**		

Table 5. LS Value of Mineral Potential Map

	Class	Area	% Area	occ	%occ	LS
Fuzzy Potential	Verry Low	6393	37.57	23	10.8	0.51204
	Low	13332	49.83	65	30.05	0.69389
	Medium	5900	3.285	23	10.8	0.55482
	High	3261	2.194	49	23.1	2.13857
	Verry High	21429	7.12	53	24.25	5.27863
	Total	**30315**		**213**		
	Class	Area	% Area	occ	%occ	LS
Likelihood Potential	Verry Low	7201	23.75	2	0.94	0.039529
	Low	16519	54.49	83	38.97	0.715109
	Medium	4756	15.69	51	23.94	1.526182
	High	833	2.75	20	9.34	3.417142
	Verry High	1006	3.32	57	26.76	8.06408
	Total	**30315**		**213**		

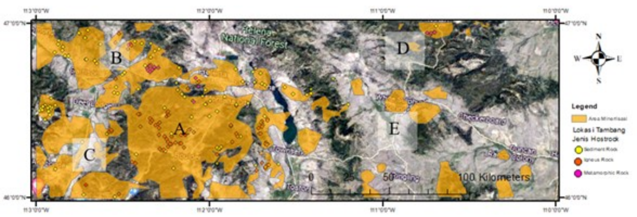

Figure 12. Mineral Potential Map (a) Fuzzy Logic Results (b) Likelihood Ratio Results.

and D in Figure 12 But there are still many areas in other areas such as east of the map or area E that can still be explored.

6 CONCLUSION

In the research area, the relationship between SBA, regional gravity, and regional magnetic to mineral prospect mapping is low anomaly, while the residual gravity relationship to mineral prospect mapping is not very clear, there are high anomaly and low anomaly. The relationship between RTP and residual magnetic to mineral prospect mapping is high anomaly. Geochemical data to show the concentration of an element on the surface, the higher the concentration, the higher the abundance. Variations in magnetic data were used to obtain the distribution of ore bodies, and variations in geochemical methods were used to obtain maps of mineralization levels.

The results of the research succeeded in obtaining a map of mineral prospects from a map of the distribution of rock bodies and a map of the level of mineralization. Anomalies in mineral prospects obtained from fuzzy logic and likelihood ratio methods show that they have many similarities but differ in form and grade level. From the mineral prospect, a map of the mineralized zone was made and succeeded in knowing the area of the prospect for the next exploration target. The area of mineralization is 8223 km^2 with the widest area of 2868 km^2 in plutonic rock types with granitic lithology.

7 SUGGESTION

- Further research with a more detailed scale area (district, prospect, or local scale) in the mineralized zone area to obtain a more detailed deposit existence.
- Perform processing with more detailed data scale data to facilitate data interpretation.
- Mapping mineral prospects at the research site with other integration methods such as Logistic regression, Neural Network, Analytical Hierarchy Process, Weight of Evidence methods, etc.

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