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# Using fuzzy Logic Method and Analytic Hierarchy Process to Mineral Potential Mapping in Janja Exploration Area (South of Nehbandan, Iran)

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## Abstract

This paper describes the application of the knowledge-based fuzzy logic and analytic hierarchy process (AHP) method,integrate various exploratory geo-datasets. This application helps prepare a mineral potential map (MPM) for copper and gold exploration and determine the optimal drilling locations in the Janja exploration area. Accordingly, different exploration layers were derived from geological, geochemical, and geophysical data, including lithology, structural, alteration, copper and gold geochemical anomaly, and magnetometric geophysical layers. After obtaining normalized weights, different fuzzy operators tried combining the weighted evidential layers into potential maps. The exploration layers were prepared and weighted and then combined by fuzzy logic methods and the Analytic Hierarchy Process, finally providing the mineral potential map of the study area. According to the MPM, the high potential zones in terms of mineralization and exploration potential are the area's north and center, corresponding to diorite and granodioritic intrusions. To evaluate the performance and applicability of the approach, the productivity of the 12 drilled boreholes (Cu and Au concentration) are compared to produced MPMs. The verification results showed that AHP and fuzzy logic methods had 62.5% and 54.17% overlap with MPMs, respectively, indicating that the AHP method performed better than fuzzy logic. The prediction based on the AHP method is more accurate and can provide directions for future prospecting. Eventually, optimal drilling locations for future exploration activities were presented.

**Keywords:** *Analytic Hierarchy process, Exploration, Fuzzy logic, Iran, Janja, Potential Mapping.*

## 1. Introduction

One of the most useful tools in mineral exploration is exploratory studies using Geographic Information System (GIS). The use of this science enables the preparation and integration of different information layers in the framework of various models. It also helps organize information related to the exploration of mineral reserves (Bonham-Carter, 1994). In fact, GIS creates a suitable space to access mineral information and data analysis and determine potential exploration areas by creating a suitable database. Simultaneous access to all geological and mineral information of the region in preliminary, detailed, and semi-detailed explorations helps determine the best areas for exploration through an analysis of these data and avoids the waste of time and budget (Bonham-Carter, 1994). Thus, various methods of modeling and integration information layers are used to obtain suitable results when determining potential exploration areas, particularly, appropriate locations for detailed exploration investigations (Malczewski, 1999). Nowadays, geoscience and exploration researchers typically use Geographical Information Systems (GIS) to prepare mineral potential maps (MPM). MPM is a Multi-Criteria Decision Making (MCDM) task that prioritizes mineralized areas from high to low potential through methodologies that deal with data fusion problems. Some of these studies include An et al. (1991), Mukhopadhyay et al. (1996), Carranza and Hale (2001), Carranza (2002), Porwal et al. (2003), Ranjbar and Honarmand (2004), Porwal (2006), Karimi et al. (2008), Carranza (2010), Madani (2011), Pazand et al. (2012), and Abedi et al. (2013). These researchers have used GIS to integrate exploration data and prepare mineral potential maps. The integration of GIS and the analytic hierarchy process (AHP) are a powerful tools to solve the potential mapping problem (Carranza, 2008; Pazand et al., 2011). AHP and fuzzy logic is a decision analysis method that considers both qualitative and quantitative information and combines them by decomposing ill-structured problems into systematic hierarchies to rank alternatives based on a number of criteria (Chen et al., 2008; Srdjevic and Medeiros, 2008; Minatour et al., 2012). In addition to finding the potential of minerals, these two methods can also be used to find underground water and the potential of areas prone to landslides and soil erosion (Al-Sababhah and Al maqablah, 2023; Karimi-Sangchini et al. 2020; Mahfoud et al. 2024). In general, the main steps to prepare a mineral potential map include determining

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mineralization detection factors, preparing information and factor maps, integrating the maps, and evaluating the results (Carter, 1994; Karimi et al., 2008). The high potential of the Au-Cu mineralization and the lack of studies in generating mineral potential maps in this region motivated us to construct geospatial datasets for detailed exploration. This research has weighed the information layers and mineralization evidence while applying the combined method of fuzzy logic and analytic hierarchy process (AHP) to the mineral potential mapping of the Janja exploration area (South of Nehbandan-Sistan and Baluchistan) and determine the optimal drilling locations.

## 2. Geographical Location

The Janja exploration area with an area of 138 km$^2$ is located 70 kilometers south of Nehbandan and 210 kilometers north of Zahedan at the geographical coordinates of 60 °23″ longitude and 31 °7″ latitude. This area includes parts of the geological maps of 1:250000 Zabul (Alavi Naeni et al., 1988) and 1:100000 Khunik (Eftekharnejad et al., 1990) and is located in the structural zone of eastern Iran (Sefidabe Basin) and under the Zabul-Zahedan-Saravan zone, according to the structural zoning map of Iran (Nabavi, 1976; Aghanbati, 2004). The Nehbandan-Zahedan route can be used to access this exploration area (Figure 1).

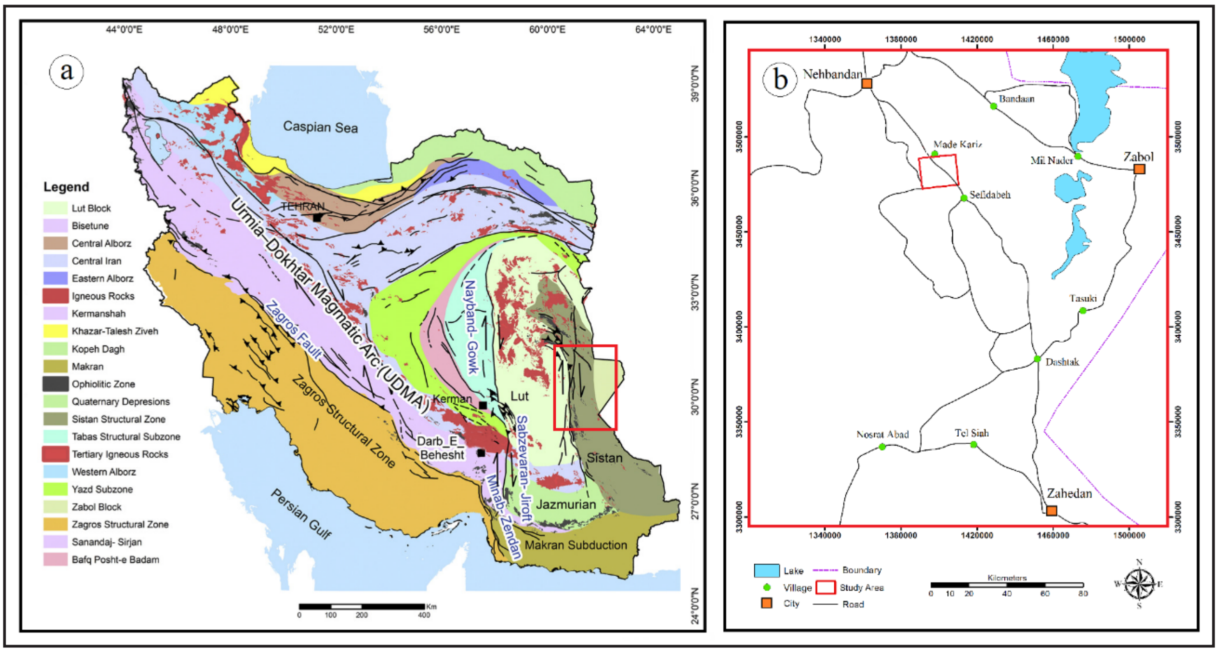

**Figure 1. a**) Geographical location of study area in the geological map of Iran, and **b**) Access routes to study area

## 3. Geological Setting

In general, the rock units of the Janja exploration area include sedimentary rocks of Upper Cretaceous to Paleocene age (turbidites and Sefidabe formation) and semi-deep igneous rocks (Figure 2). The sedimentary rocks of this area include sandstone, calcareous sandstone, shale, siltstone and pyroclastic and turbidite sediments. Semi-deep igneous rocks in this area include diorite to quartz diorite and granodiorite, intruding into the volcanic units and flysch structures (Bazzi et al., 2013). Intrusion of these intrusive bodies into the sedimentary and volcanic units of the flysch facies has led to contact metamorphism and alteration and subsequently the mineralization of copper, gold, and other valuable elements (Rahimi et al., 2022). Hypogene mineralization has occurred mainly in the form of pyrite and a slight amount of chalcopyrite, galena, and sphalerite, while supergene mineralization can also be recognized by iron oxides. Propylitic alteration is the most widespread type of alteration in the area, and Skarn zone is also locally evident in the region. It seems that the alteration and mineralization in this area is related to the intrusion of igneous intrusive bodies, and the creation of contact metamorphism and hydrothermal processes is associated with the porphyry dykes, observed in the region. Based on the mineralized samples taken from this area, the maximum grades are 60.67 ppb, 180.4 ppm, 12285 ppm, 99260 ppm, and 109300 ppm for gold, silver, copper, lead, and zinc, respectively. Based on geological studies and field observations, the mineralization in this area includes hydrothermal polymetallic veins, observed together with silica veins (Elyaspoor, 2010). The main minerals identified in these veins include galena, sphalerite, chalcopyrite, and chalcocite (Bazzi et al., 2009). The length of these mineral veins varies from 100 to 110 meters and often have a vertical dip. The thickness of the veins varies from 10 centimeters to 2 meters, and their trend can be traced up to a maximum of 200 meters. According to the studies carried out in Janja area, polymetallic mineralization of gold, silver, copper, lead, and zinc veins has obviously occurred in this area (Rahimi et al., 2020).

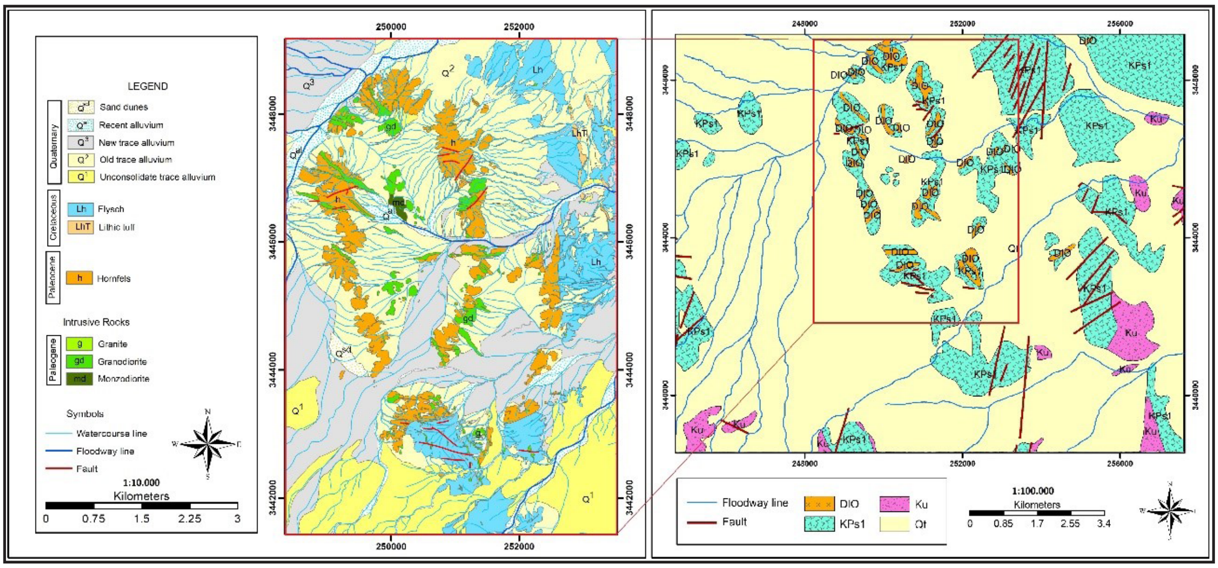

**Figure 2.** Geological map of Janja exploration area (Rahimi et al., 2020)

## 4. Materials and Methods

The current research has used library, field, and laboratory studies to collect basic information. Geological maps, satellite images, digital elevation maps, and related sources were used to extract active faults and accurately identify lithological units. Remote sensing studies, conducted on ASTER sensing images, were used to reveal argillic, propylitic, and phyllic changes, while Landsat 7 images were utilized to highlight iron oxide changes and prepare the alteration map of Janja area. The magnetometry geophysical method was employed to investigate changes in the intensity of the total magnetic field and the potential of the exploration area concerning the presence of mineral deposits. The results of geochemical sampling of 153 stream sediment samples were utilized to prepare geochemical anomaly map of copper and gold in the area, after which data preparation and analysis were conducted by ArcGIS 10.8 software. Different exploration layers were initially prepared by this software, followed by combining these layers with two methods of fuzzy logic and analysis hierarchic process. Finally, the mineral potential map of the area was prepared to determine the optimal drilling locations. Figure 3 summarizes the research methodology.

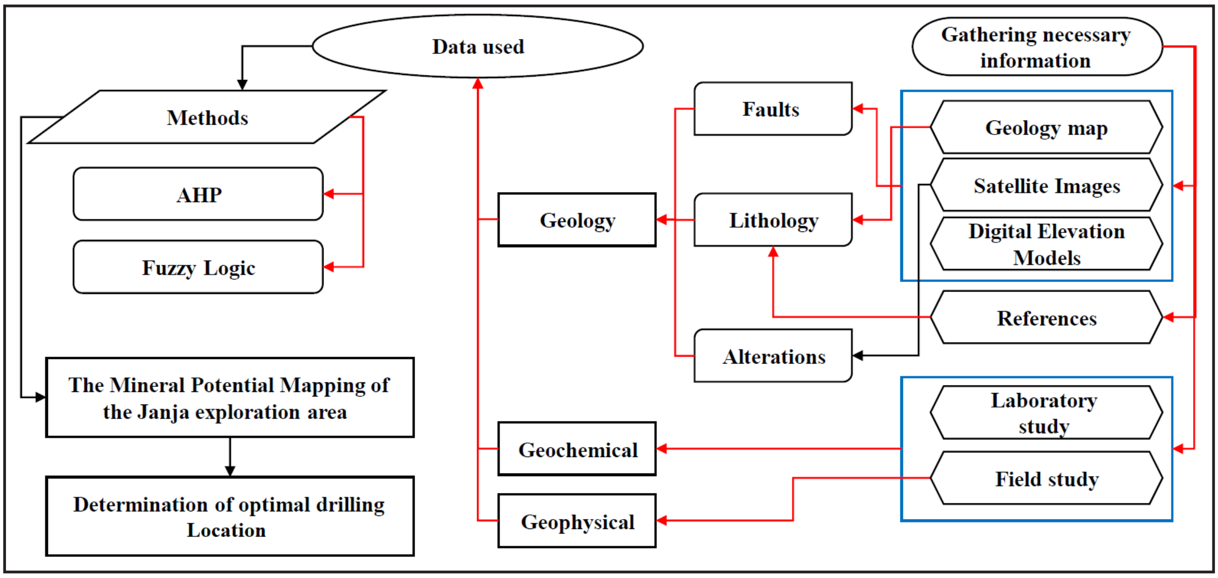

**Figure 3.** Research Methodology

## 5. Preparation of Evidential Layers Characteristics and Classification of Evidential Layers

Exploration layers effective in mineralization were determined at this step according to the geological and exploration features of the study area and using expert knowledge. These exploration layers are separated and extracted from geological maps, satellite, geochemical, geophysical data, and field studies. The prepared information layers included lithology, structural, alteration, copper-gold geochemical anomalies, and magnetometric geophysical anomalies. Each exploration layer was divided into several classes based on priority. The mineral potential map was prepared by a combination of the information layers according to the effects and values of the layers. The impact of information layers is not the same in the final model, because it is necessary to prepare weighed maps of each information layer through a series of processes such as preparation of a buffer, reclassification, and rasterization of the maps. Then, the effective factors in weighing different exploration layers were described.

### *5.1 Lithological Layer*

Based on the geological studies and field observations, conducted in Janja exploration area, four lithological units were found to have outcrop in this area, including semi-deep intrusive units (DIO), Cretaceous flysch unit (Ku), volcanic and pyroclastic rocks (KPS), and Quaternary unit (Qt) (Figure 4). According to field observations, the Cretaceous flysch unit acted as the host rock in the area and was cut by a semi-deep intrusive diorite body. Different rock units were finally weighed based on their importance in mineralization. The highest weight was considered for intrusive and flysch units due to the presence of mineralization in the adjacent areas of these two lithological units in Janja exploration area. Other lithological units of the region did not contribute significantly to mineralization and were assigned the lowest weight. Figure 11 presents the scoring method for these lithological units.

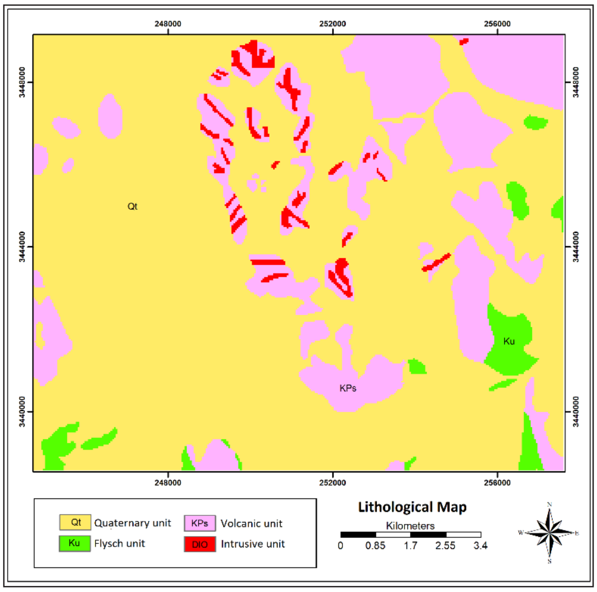

**Figure 4.** Lithological layer in the study area

### *5.2 Alteration Layer*

Remote sensing studies were used on ASTER sensor images to reveal argillic, propylitic, and phyllic alterations, while Landsat 7 images were utilized to reveal iron oxide alterations and prepare the alteration map of Janja exploration area. The band ratio method was to reveal regional alterations. ASTER sensing band ratio of 7/5 was used to reveal argillic changes (kaolinite), and the ration of 3/1 from the Landsat image 7 was utilized to detect iron oxide alterations (hematite, limonite, and goethite). Besides, ASTER sensing band ratios of (9+7)/8 and 7/6 were considered to reveal propylitic (chlorite and epidote) and phyllic alterations, respectively. Finally, all these alterations were merged, forming the map of alterations in the region (Figure 5), after which these alterations were weighed according to their relationship with mineralization. Figure 11 provides the method of scoring this exploration layer.

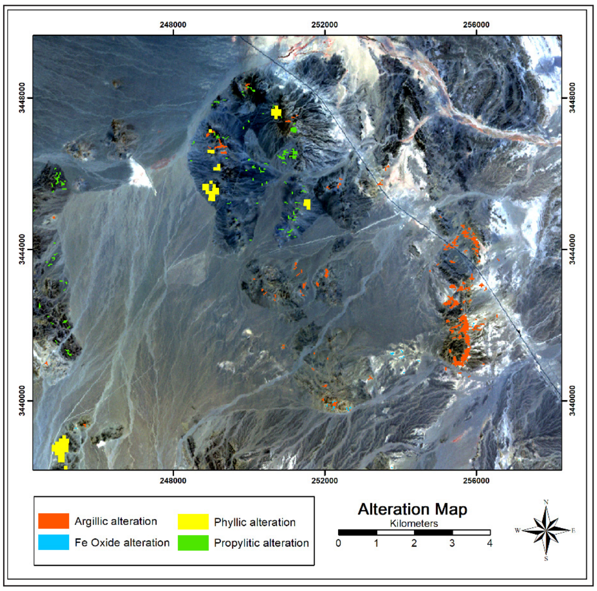

**Figure 5.** Alteration layer in the study area

### *5.3 Magnetometric Geophysical Anomaly Layer*

The magnetometric geophysical method was used to investigate changes in the intensity of the total magnetic field and examine the potential of this exploration area in terms of mineral deposits. Therefore, 110 profiles with east-west and 2 profiles with north-south direction underwent magnetometry, and a total of 18115 points were measured for the intensity of the total magnetic field. A map of the total magnetic field intensity of the study area was, then, prepared after the data collection and modification (Figure 6). Then the intensity of the magnetic field was divided into 5 classes and weighed. Figure 11 presents the scoring and classification of the total magnetic field geophysical map.

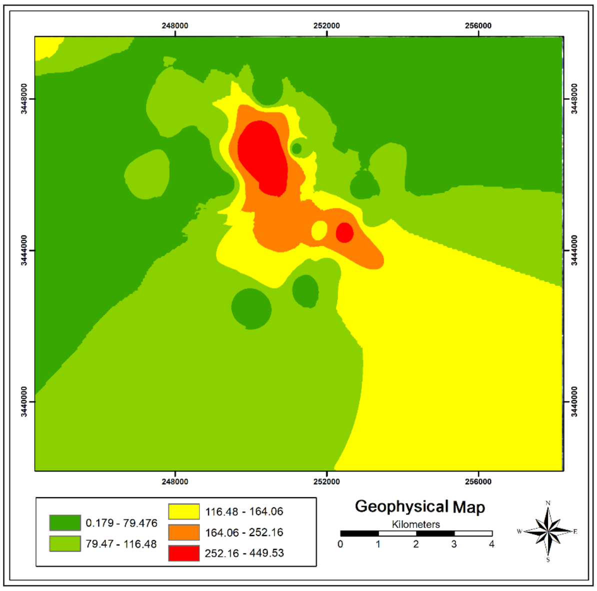

**Figure 6.** Geophysical layer in the study area

### *5.4 Geochemical Anomaly Layer*

The results of geochemical sampling of 153 stream sediment samples in the region were used to prepare the geochemical map of copper and gold anomaly. Figures 7 and 8 show the location of the collection of stream geochemical samples. The construction of this exploration layer aims to figure out the behavioral patterns of copper and gold elements in the sampling environment and to separate anomaly values related to mineralization. The isoplethic map of copper and gold elements was initially prepared (Figures 7 and 8). Then, the background, threshold limit, and anomaly values of the selected elements were calculated, using the threshold limit estimation method based on the mean values of X and the standard deviation of S. The formula (X+nS) was used to separate the anomaly from the background limit values. Accordingly, X+S was considered the threshold, and values higher than that represented different degrees of anomaly. Hence, the copper and gold geochemical anomaly maps were divided into 5 classes, assigning the highest and lowest weights to the highest-and lowest-grade elements, respectively. Figure 11 shows the scoring and classification of the copper and gold geochemical anomaly maps.

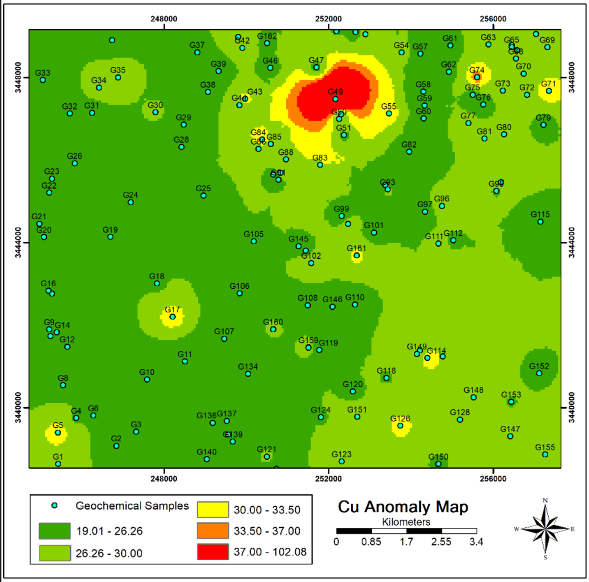

**Figure 7.** Geochemical layer of Cu in the study area

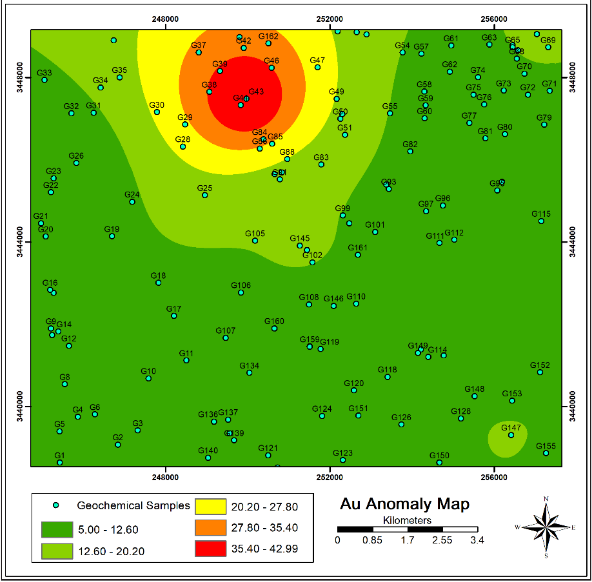

**Figure 8.** Geochemical layer of Au in the study area

### *5.5 Structural Layer*

The 1:100000 geological map of Khunik and the 1:10,000 mineralogical geological map of Janja exploration area were used to prepare the map of the faults in the studied area. The faults in the study area were initially digitized, after which the 500-meters area around the main faults were divided into 6 classes at 100-meter intervals (Figure 9). Given the investigation of geochemical, geophysical, and geological anomalies, it seems that the faults in the area have occurred after mineralization, which means that this exploration layer should be given the lowest score. Next, an information layer related to faults was created by scoring each class (Figure 11).

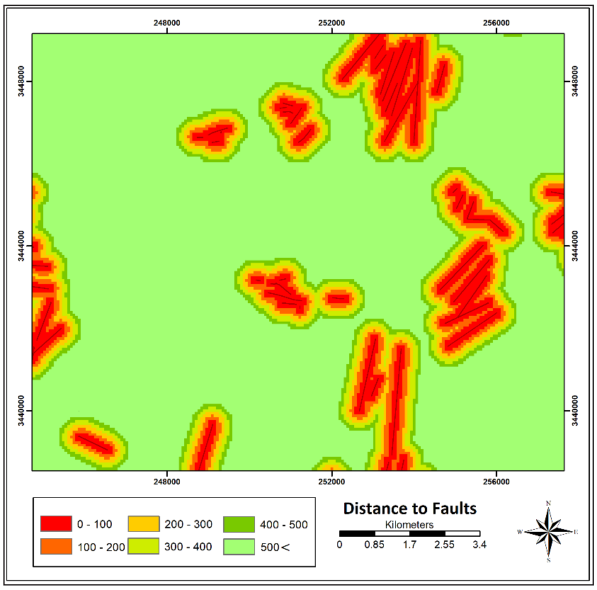

**Figure 9.** Structural layer in the study area

## 6. Results and Discussion

### *6.1 Analytic Hierarchy Process (AHP)*

The AHP is one of the multi-criteria decision-making methods based on the relative evaluation of weights (Jiajin, 1997; Saaty, 2001). Similar to the decision theory and inconsistency analysis, this method performs measurement on quantifiable and non-objective criteria (Vargas, 1990). From the viewpoint of the founder of fuzzy logic (Saaty, 1980), this method has several advantages, including unity, complexity, cross correlation, hierarchical structure, measurement, consistency, integration, balance, collective judgment, and repetition. This method is based on pairwise comparisons of factors and allows decision makers to examine different factors while making it possible to consider different quantitative and qualitative criteria in the problem (Ngai, 2003). AHP has been proposed based on human brain analysis for complex and fuzzy problems (Chen, 2001) and includes three main steps of generating hierarchy, determining priorities, and logical compatibility (Macharis et al., 2004; Ghodsipour, 2009). This method has had recently extensive applications for the analysis of complex problems in mining, civil engineering, and geological sciences (Rahimi Shahid and Rahimi, 2016 & 2017; Rahimi Shahid et al., 2019). The AHP steps (Carranza, 2009) are presented in the following to prepare an exploration potential map and determine the areas prone to mineralization in Janja exploration area.

#### *6.1.1. Development of AHP*

The hierarchical structure is a graphical representation of a complex problem with at least three levels, at the top of which is the overall goal, and at the next levels, there are criteria, sub-criteria, and options (Dagdeviren, 2008; Vahidnia et al., 2009). Figure 10 shows the hierarchical structure of the exploration layers of the Janja exploration area, presenting a four-level hierarchy of goal, criterion, sub-criteria, and options. Converting the topic under investigation into a hierarchical structure is the most important part of hierarchical analysis because the process of hierarchical analysis involves breaking down difficult and complex problems into partial elements that are hierarchically related and connecting the main goal of the problem to the lowest level of the hierarchy. Hence, the problem is changed into a simpler form consistent with the human nature and mind (Cimren et al., 2007).

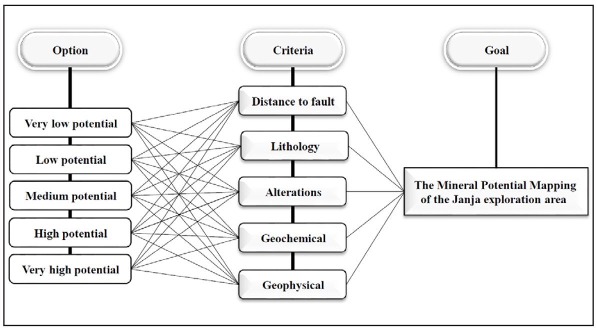

**Figure 10.** Hierarchical structure for mineral potential mapping in Janja exploration area.

### *6.1.2. Weights of Evidential Layers*

After breaking down the problem into hierarchies, the elements of different levels are compared pairwise and valued based on the importance of the two criteria (Carranza, 2008). In other words, the weighing criterion for information units is based on the highest contribution of factors within the layer (Lopez and Zink, 1991). Table 1 provides the values of preferences for pairwise comparison of factors according to the importance of two criteria in the study area (Saaty, 1980).

**Table 1.** Preference values for pairwise comparisons (Saaty, 1980)

| Verbal | Numerical |
|---|---|
| Same Importance | 1 |
| ModerateImportance | 3 |
| Strong Importance | 5 |
| Very Strong Importance | 7 |
| Absolut Importance | 9 |
| Intermediate Values | 2; 4; 6 and 8 |

### *6.1.3. Preparation of Pairwise Comparison Matrix*

The pairwise comparison method was used in this step to create a 5×5 matrix, after which different criteria were compared one by one, and the corresponding values were assigned based on the Saaty screening (Table 2).

**Table 2.** Pairwise comparison matrix for AHP

| Criteria | Geochemical | Alterations | Geophysical | Lithology | Distance to fault | Weight |
|---|---|---|---|---|---|---|
| Geochemical | 1 | 3 | 6 | 7 | 8 | 0.510 |
| Alterations | 0.33 | 1 | 4 | 5 | 7 | 0.272 |
| Geophysical | 0.16 | 0.25 | 1 | 4 | 5 | 0.126 |
| Lithology | 0.14 | 0.2 | 0.25 | 1 | 3 | 0.059 |
| Distance to fault | 0.12 | 0.14 | 0.2 | 0.33 | 1 | 0.033 |
| Sum | 1.75 | 4.59 | 11.45 | 17.33 | 24 | 1 |

The geometric mean of each row of the matrix was divided by the sum of the geometric mean of the columns to calculate the weight of each criterion. The resulting value for consistency ratio (CR) in the matrix was 0.09, indicating an acceptable level of weighing results. CR is a consistency index from a pairwise comparison matrix, which is randomly generated and has a value depending on the number of elements and their values. A CR value of <0.1 indicates an acceptable level of consistency in the pairwise comparisons; otherwise, the values of the ratio represent inconsistent judgments (Dey and Ramcharen, 2000).

According to investigations, the two factors of (copper-gold) geochemical anomaly and alteration were the most important influencing criteria in increasing the mineral potential of the region with weights of 0.510 and 0.272, respectively. Figure 11 shows the classification of the layers and weighing different categories due to the large number of calculations and paired matrices. Figure 11 shows the inconsistency ratio for the matrix rank of five effective factors, confirming their consistency. Finally, after the processing was performed, the exploration potential map was prepared using the AHP method (Figure 12).

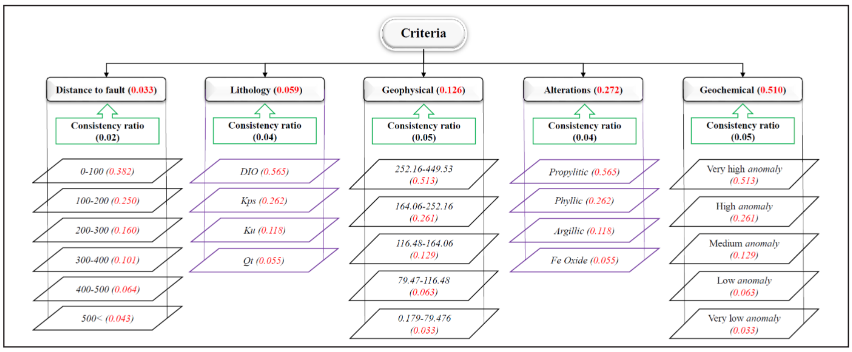

**Figure 11.** Calculated weights for the criteria and their classes in the AHP model

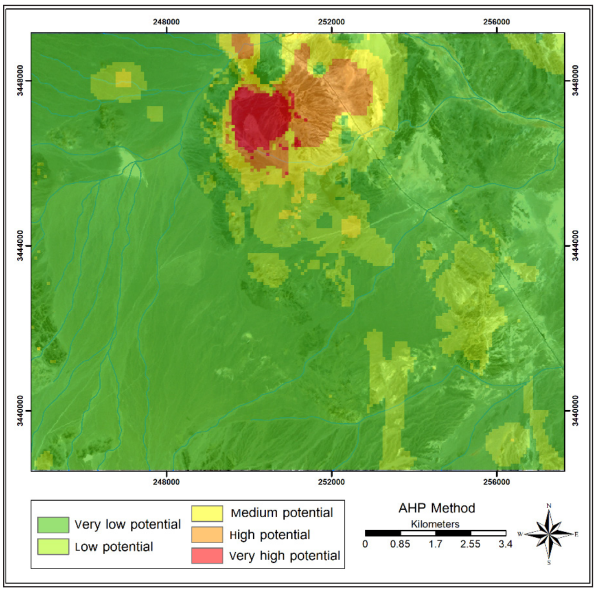

**Figure 12.** Mineral potential map of the study area generated from AHP method

### *6.2 Fuzzy Logic Method*

Fuzzy logic, which is knowledge-based, is another method for the mineral potential map preparation (Whateley and Evans, 2006). Acceptable results can be achieved with the help of this method, particularly when mineralization and mineral indices are limited, expert opinions, and assignments of logical coefficients and weights to information layers (Harris et al., 2001). The fuzzy logic method was first introduced by Zadeh (1965) and is defined based on fuzzy sets with no certain limits. The fuzzy set theory uses a range of values between zero and one to express the degree or value of the members of a set (Novriadi et al., 2006; Tangestani, 2009; De Gruijter et al., 2011) with zero representing a lack of full membership and one indicating full membership (An et al., 1991). The classes of each map can have a membership value between zero and one. Fuzzy logic has been recently used in the exploration of areas with high mineralization potential, and particularly in determining areas suitable for exploratory drilling. Some research conducted in this field includes the studies by An et al. (1991), Eddy et al. (1995), Carranza et al. (1999), KourePazan Dezfouli (2008), Yousefi et al. (2012 & 2014), Shahi and Kamkar Rouhani (2013), Alaei Moghadam et al. (2014), Ghadiri-sufi and Yousefi (2016), Tabaei et al. (2017), Khajehmiri et al. (2018), and Barak et al. (2018). Table 3 shows five useful operators of And, Or, Product, Sum, and Gamma fuzzy operators used in this method to combine the exploratory data (An et al., 1991; Carter, 1994). In the provided relations, μi indicates the ith membership function, and n represents the number of membership functions supposed to be combined.

**Table 3.** Types of operators used in the fuzzy logic method (Bonham-Carter, 1984; An et al., 1991; Carter, 1994)

| Operators | Operator relationship |
|---|---|
| Fuzzy AND | $\mu_{\text{Combination}} = \text{MIN}(\mu_A, \mu_B, \mu_C, \dots)$ |
| Fuzzy OR | $\mu_{\text{Combination}} = \text{MAX}(\mu_A, \mu_B, \mu_C, \dots)$ |
| Fuzzy Product | $\mu_{\text{Combination}} = \prod_{i=1}^{n} \mu_i$ |
| Fuzzy Sum | $\mu_{\text{Combination}} = 1 - \prod_{i=1}^{n} (1 - \mu_i)$ |
| Fuzzy Gamma | $\mu_{\text{Combination}} = (\text{Fuzzy Algebraic Sum})^{\gamma} * (\text{Fuzzy Algebraic Product})^{1-\gamma}$ |

This study used the three operators of Sum, Or, and Gamma to combine the exploration layers (Figure 13). The fuzzy membership function MSLarge was initially used to fuzzify all information layers. According to this function, the fuzzy membership values are calculated based on the mean and standard deviation of the initial data, where higher initial values have higher fuzzy scores. The values of all the information layers were placed in the range of 0 to 1 using the MSLarge method in the layer fuzzification step, after which all the exploration layers were fuzzified and the values of all the layers were homogenized. Then, the fuzzified layer of gold and copper geochemical anomalies was combined using the Or operator to prepare the fuzzified geochemical anomaly map of the region. In the next step, the fuzzified alteration, structural, and lithological layers were combined using the Sum fuzzy operator to obtain the map of alteration, lithology, and structure of the region. Finally, using the Gamma fuzzy operator (G=0.9), the mentioned exploration layers and the fuzzy geophysical anomaly layer were combined to provide the exploration potential model of the study area (Figure 14). According to the exploration potential map obtained by the fuzzy logic method, the highest potential was in the central and northern parts of the region, resulting from the significant overlap of geochemical and geophysical anomalies corresponding to the diorite unit outcrop in the region. Hence, this area seems to be the most optimal to conduct exploratory excavations.

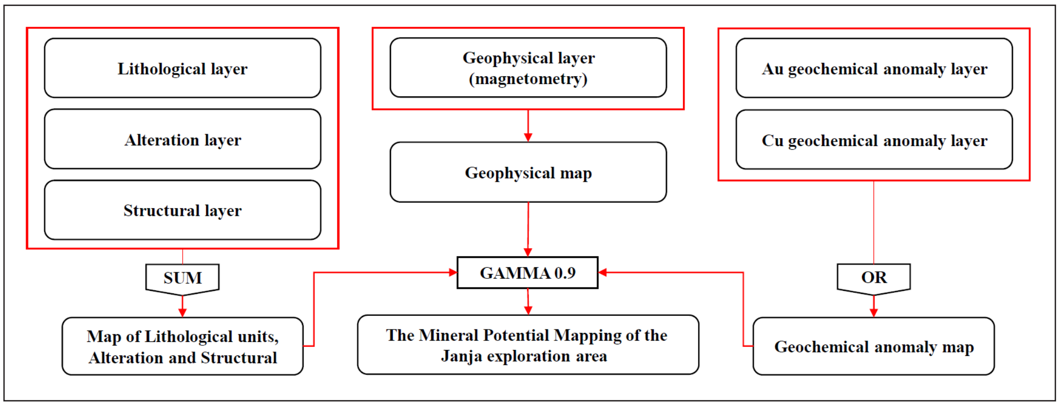

**Figure 13.** Flow chart of the fuzzy logic method

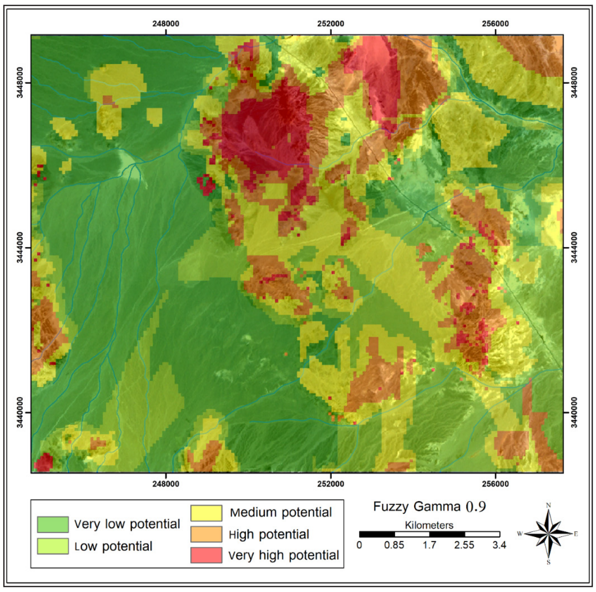

**Figure 14.** Mineral potential map of the study area generated from Fuzzy logic method

### *6.3 Evaluation of Mineral Potential Models*

There are various methods for evaluating mineral potential zoning maps, one of which with extensive applications is comparing the results of these maps with the data of exploratory boreholes. Shirmard et al. (2014) used exploratory boreholes to evaluate and validate the mineral potential map of the Neysian porphyry copper deposit. In a similar study, Alaei Moghadam et al. (2014) used the results of drilling boreholes to confirm the validity of zoning. According to their results, the manual classification method with 5-class, compared to 3-class separation, had the highest compatibility with exploratory wells. The present study has also used the manual classification method with 5-class separation as the best method for zoning. The data from 12 exploratory drilling boreholes were used to evaluate the mineral potential models provided. Figure 15 shows the location of these boreholes in the mineral potential maps prepared. The profiles of copper and gold grade changes were drawn for each borehole with respect to the depth to evaluate the drilling results (Figures 16 and 17). Each borehole was placed in a certain class in terms of the amount of gold and copper considering the copper and gold grade changes, their maximum and minimum values, and the grade of copper and gold in each borehole.

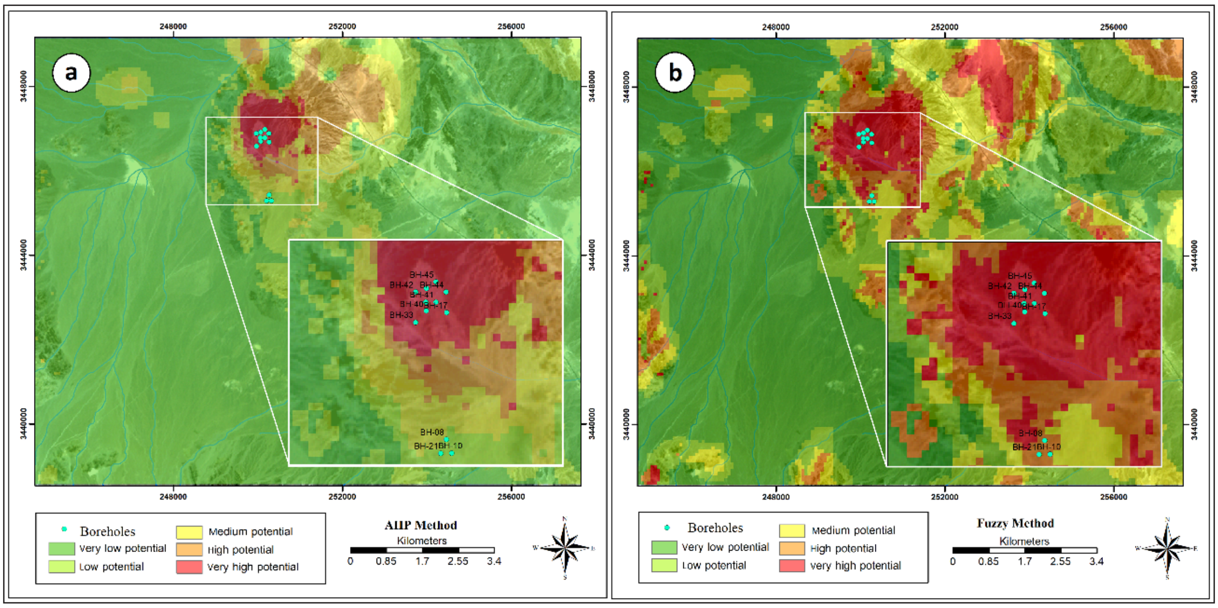

**Figure 15.** The location of the boreholes in mineral potential maps prepared by a) fuzzy logic and b) AHP method

The pixel values of the exploratory boreholes were matched with the drilling results to evaluate the prepared maps (Table 4). First, the prepared mineral potential maps were separated into 5 classes using manual classification methods. The values of the pixels related to the boreholes in the mineral potential maps were then extracted, determining the class of each borehole based on the values of each pixel in one of the defined classes. Then, the class, determined for each borehole, was compared with the status of that borehole according to Table 4, which defines the very high, high, average, low, and very low mineral potentials with values of 5 to 1, respectively. If the class of boreholes overlaps with their existing status, zero is recorded in the final evaluation table. On the other hand, if the status of the actual class of the borehole differs from its status on the map, one of the values -1, -2, -3, and -4 is recorded in the final evaluation table. The overlap of each prepared map with exploratory boreholes was calculated using Eq. (1)

$$a = 1 - \frac{e}{E} \qquad (1)$$

In which, a, e, and E represent the overlap of boreholes with prepared maps, the number of negative points, and the total number of non-overlap. Eq. (2) was used to calculate the total number of the boreholes non-overlap. Table 4 shows the evaluation of maps prepared by the AHP and fuzzy logic methods. According to the results, AHP and fuzzy logic methods had 62.5% and 54.17% overlap, respectively, indicating that AHP had better performance than fuzzy logic. A study by Yousefifar et al. (2013) also showed that AHP was the most suitable among the index overlay methods, AHP, and fuzzy logic methods for combining exploration layers in Dalli (copper and gold) porphyry deposits. In the study, conducted by Hossein Ali et al. (2008), 88% of overlap was found by the comparison of the mineral potential map prepared by AHP and the results of exploratory boreholes:

$$\text{(number of boreholes with real average condition} \times 1\text{)} + \text{(number of boreholes with non-average real condition} \times 2\text{)} = \text{total number of conditions} \quad (2)$$

**Figure 16.** Cu concentration (ppm) versus depth (m) in exploratory boreholes in the study area

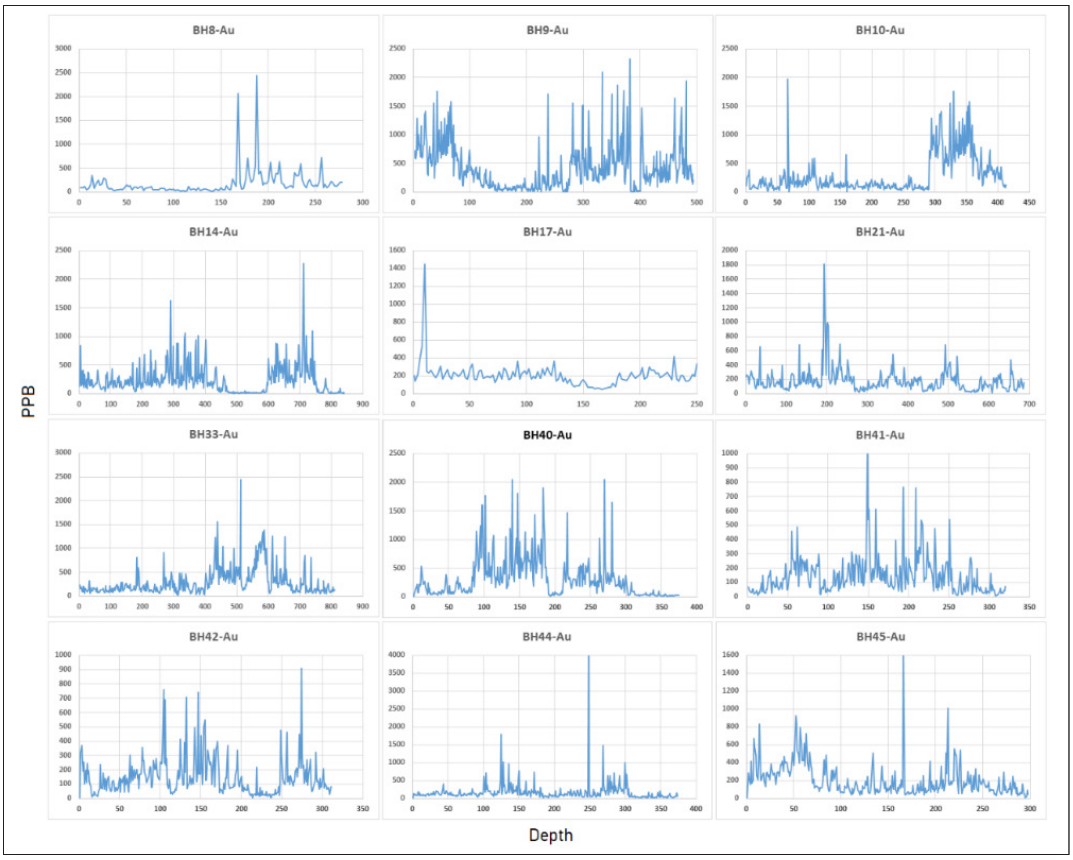

**Figure 17.** Au concentration (ppb) versus depth (m) in exploratory boreholes in the study area

**Table 4.** Overlap of exploratory boreholes with mineral potential maps

| The original status of the borehole | | AHP | | Fuzzy Logic | |
|---|---|---|---|---|---|
| Borehole | Status | Status | Assessment | Status | Assessment |
| BH-08 | 2 | 2 | 0 | 4 | -2 |
| BH-09 | 2 | 5 | -3 | 5 | -3 |
| BH-10 | 2 | 2 | 0 | 4 | -2 |
| BH-14 | 5 | 5 | 0 | 5 | 0 |
| BH-17 | 5 | 5 | 0 | 5 | 0 |
| BH-21 | 4 | 2 | -2 | 4 | 0 |
| BH-33 | 5 | 5 | 0 | 5 | 0 |
| BH-40 | 5 | 5 | 0 | 5 | 0 |
| BH-41 | 4 | 5 | -1 | 5 | -1 |
| BH-42 | 4 | 5 | -1 | 5 | -1 |
| BH-44 | 4 | 5 | -1 | 5 | -1 |
| BH-45 | 4 | 5 | -1 | 5 | -1 |
| Match rate (%) | | 62.5 | | 54.17 | |

### *6.4 Providing Optimal Drilling Locations*

Figure 18 shows the best location to continue exploration drilling according to the investigations conducted and the exploration potential maps prepared. Hence, it is recommended to carry out new drilling operations only in the optimal areas located on this map. As shown in this Figure, the northern portion of the study area is the best location for future excavations. This area covers around 6 km$^2$ and corresponds to the geological unit of diorite and granodiorite porphyry.

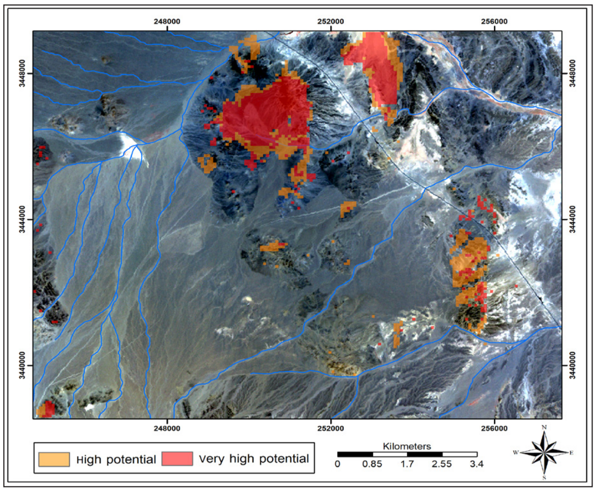

**Figure 18.** The location of high potential areas for future exploratory investigations

## 6. Conclusion

The current study used two methods of fuzzy logic and analytic hierarchy process to prepare a mineral potential map and determine optimal drilling locations in Janja exploration area situated in the structural zone of eastern Iran. The final exploration map resulting from the combination of lithology, structural, alteration, Cu and Au geochemical anomalies, and magnetometric geophysical anomaly, obtained by these two methods, confirmed the high exploration potential in the central and northern parts of the region. Accordingly, a significant overlap of the anomalies of the mentioned maps was indicated in this area, and the presence of minerals was confirmed. The mineral potential maps, prepared by the results of exploratory boreholes, were then compared and validated in terms of the accuracy of the results. According to the comparison between the results of drilling boreholes and the exploration potential map, prepared by these two methods, the AHP method led to a higher level of accuracy than the fuzzy logic method. This difference is because AHP measures the importance of each exploration layer based on expert opinion and their priority according to exploration principles compared to other layers, reducing the possibility of error and confirming the validity of the method through the inconsistency rate calculation. Following all the studies and processing conducted, a region with an area of 6 km$^{2,}$ corresponding to the geological unit of diorite and granodiorite, can be considered for future exploratory investigations, particularly in Janja exploration area. Accordingly, it will be possible to avoid the waste of money and time in areas without any mineralization potential if future exploration activities focus on such areas.

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