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A fuzzy-based prognosis of ore mineralization potentials in Ramand region (Qazvin province)

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Abstract

The Ramand region is a part of the magmatic belt in Urmieh-Dokhtar structural zone in Iran, located in the SW of Buin-Zahra. This area mainly consists of felsic extrusions such as rhyolites and rhyodacites. Argillic alterations with occurrences of mineralized silica veins are abundant in most of the volcanic units. In this research work, we used the GIS facilities for modeling the Ramand geo-spatial databases according to the Fuzzy logic algorithms. The main phase of mineralization occurred in the altered regions and is located near the cross cut fault systems. Therefore, the main criteria for integration were the geological, structural, geophysical, and remotely sensed (Landsat7, ETM^+) layers. Also we used a contoured aeromagnetic map for revealing and weighting lineaments. By the Fuzzy techniques applied, all the evidential themes were integrated to prognosis of ore mineralization potentials based on γ = 0.75. As a result, the hydrothermal alterations and their relevant post-magmatic mineralization were introduced in the south and eastern parts of the Ramand region by the fuzzification procedures. Our highlighted recommendation for more exploration activities is focused on the geophysical land surveys (electric and magnetic fields), and the geochemical sampling from mineralized regions in the depth and outcrops of alterations.

Keywords: *Alteration, Mineralization, Hydrothermal, Fuzzy Logic, Ramand.*

1. Introduction

In most of the geographical environments, mineralization processes have a genesis and spatial association with the geological-structural processes. Both the remote sensing and geo-physical techniques are comfortable for regional explorations. Also geo-statistical techniques produce spatial variables with more precision than the traditional statistics for modeling the altered mineralized regions. As a rule, a fuzzy-based mathematical integration not only facilitates spatial analyses but also increases the chance of promising areas.

The geographic information systems provide an appropriate virtual environment for designing valid exploration models [1]. In fact, the use of spatial association provides an organized processing and compilation of the geological, structural, and geo-physical evidences for mineral exploration purposes in the feature of prognostic maps [2]. In the current research work, we use a fuzzy modulation of the Ramand exploratory records to emphasize on the remotely sensed and geo-magnetic evidences of hydrothermal alterations that may have potentials for ore minerals. Therefore, the main purpose of this research work is to introduce the priorities of the solution-related mineralization within or next to the altered occurrences. Fuzzy modeling proposed by An et al. (1991) [3], Karimi et al. (2008) [4], Wright & Carter (1996) [5], and Mukhopadhyay et al. (2002) [6] have been used in order to identify the mineral potentials associated with the magmatic-hydrothermal systems. For example, Carranza et al. (2001) [7] have used fuzzy logic for identification of the epithermal gold deposits in Philippine. Eddy et al. (1995) [8] have also

used the fuzzification techniques for the mineral exploration purposes in the Mississippi (Canada).
A fuzzy-based model usually points out to the potential areas accurately, which is very effective for implementation of the exploration operations due to reduction in time and costs as well as rapid decision-making purposes. All the spatial data modelers have three stepwise phases including data gathering (database formation), database analysis, and database integration (fusion step). For fuzzy models, the integration algorithms are subjected to a unique membership function that is legitimated by non-Boolean strings (real random variables 0 till1).

2. Study method

Producing a mineral potential map is the first step in this research work with focuses on one or more path-finder elements, which eventually leads to a prospecting model of the ore deposits. This model is usually started by a unique data acquisition from regional exploratory databases and goes on by preliminary processing of the geological and structural evidences that should be extracted from the satellite and geophysical signatures. The integration step is a mathematical software, possibility for spatial dataset merging to unified gridded prognostic maps.
Mathematical calculations discriminate between the similar and non-similar characteristics of the elements [2]. The pre-requisite for achievement of the mineral potential maps of a region is the proportional weighting with the value of geo-spatial data that is affected by the type and method of classifications [9]. The integration selections and their logical mechanisms actually depend on the volume of databases. As a rule, for limited databases (lesser acquisition), the suggested method is the knowledge-based or expert systems; otherwise, for populated databases as well as multivariate accumulations, the data-driven integrations have better results than the experts.
In the knowledge-driven methods, the appropriated weights to the indicator layers are based upon the experiences of the experts (geologists, geophysicists, etc.) [10]. In other words, in order to find the target areas with not a lot of evidential themes, the modeling priorities should be assigned by specialists, while due to gathering the valuable and adequate databases, data-driven models are recommended [11]. For example, Weight of Evidences (WofE) is the most important and applicable integrative method that is implicated for both the data and expert modeling purposes (intermediated course). Also Logistic Regression (LR) and Neural Networks (NNs), known as two important data-driven algorithms, are used for the geoscience and natural disasters.
On the other hand, Boolean logic, index overlay, fuzzy set theory, inference networks and decision trees, demister-Shafer, and analytical hierarchy process (AHP) are among the most common algorithms of knowledge-driven methods. According to the varieties and volume of the spatial databases, fuzzy logic algorithm was selected for introducing the mineral potential map of the Ramand region. The fuzzy theories indicate that a range of values between zero and one can be used to express the degree (value) of membership [12]. Zero means the lack of membranes, and tendency of one means to be full of membranes. The other values between zero and one indicate a proportional membership among the differential numbers.
For a minimal case of exploration, the membership functions are used to show the relative importance of each layer as well as the relative importance of each layer classes in order to produce the prognostic map [2]. In practice, the weighted layers have been used to represent the role and number of the criteria fitted with promising areas based on GIS soft-facilities. The role of logical operators is important among spatial integrations. Table 1 shows the important operators and their results listed in a fuzzy method. It is to be noted that the gamma operator, which is due to the combination of the embodied concepts in logical operators of Product and Sum, has the top potential for selection of the exploratory measures and with changes of gamma coefficient (values between of 0 and 1); significant changes are obtained in the exploratory models so that with increase in the gamma value, the confidence interval of estimates is reduced, and more promising areas are introduced, while with reduction of this quantity, the confidence intervals of estimations are increased, and this reduces the promising areas [2].

Table 1. Definition of fuzzy operators (μ_i is fuzzy membership function for i map; i = 1,2,3,…,n; and μ_A, μ_B, and μ_C are membership values for A,B, and C map) [2].

fuzzy operator	Operator equation	Performance
AND	$\mu_{Combine} = \mathrm{Min}(\mu_A, \mu_B, \mu_C, \ldots)$	The production output map with minimum membership values.
OR	$\mu_{Combine} = \mathrm{Max}(\mu_A, \mu_B, \mu_C, \ldots)$	The production output map with maximum membership values.
Product	$\mu_{Combine} = \prod_{i=1}^{n} \mu_i$	Output map values ≤ The shared membership values.
Sum	$\mu_{Combine} = 1 - \prod_{i=1}^{n} (1 - \mu_i)$	Output map values ≥ The shared membership values.
Gamma	$\mu_{Combine} = \left(\prod_{i=1}^{n} \mu_i\right)^{1-\gamma} \times \left(1 - \prod_{i=1}^{n}(1-\mu_i)\right)^{\gamma}$ γ is Parameter between zero and one	By correct choice, gamma can be the increasing role of the fuzzy sum and the lowering role of fuzzy multiplied to limit the state of equilibrium.

3. Geology of Ramand region

The Ramand region is a part of Qazvin province that is located in the SW of Buin-Zahra and southern side of Danesfehan. This area belongs to the NW corner of Saveh geological map (1:250000-scale). Also in the 1:100000 map of Danesfehan, the Ramand region can be seen in the center of geological units. The main road ways are from Tehran, Shahryar, Eshtehard, Buin-Zahra, and Danesfehan [13]. Based upon the structural-sedimentary zoning of Iran, the Ramand region is located in the NW of central Iran. The Ramand Mountain with an approximate area of 70 square kilometers has been coordinated in 35° 42' to 35° 45' of north and 49° 37' to 49° 45' of east. In fact, mountains are several parallel outcrops extended from NW to SE with partly a rough topography [13]. The Hasanabad fault is the most important and the oldest structure in this region, which has been extended from east to west with a rough topography in the north trends (Ramand Mountain). This fault is affected by the recent structural movements (Paleogene and Quaternary). A new trend of Hasanabad lineament with NW-SE direction has been found and mostly contributed in the formation of magmatic differentiations (post-magmatic phases) in the studied area [14]. The Ramand intrusions are mostly hidden with rare and confined features of alterations next to Eocene-Oligocene diabase dykes. The Ramand volcanisms consist of rhyolites, rhyodacite tuffs, crystal tuffs, and rhyodacite lava flow (Figure 1).

Apart from the magmatic facies, several sedimentary formations have been extended due to the recent (Quaternary) hydromorphic activities, and affected by young volcanic traces such as brecciated fragments and hydrothermal alterations. Alteration halos have been well developed and included a variety of clay minerals (argillic) and iron oxides (goethite, limonite, and hematite). Also some well-distributed silicifications have occurred in the main phases of the host unit mineralization that is mainly located in the rhyodacites and rhyolitic formations. The simultaneous presence of alterations and their spatial relationships with the crushed zones of fault systems is from symptoms the formation of post-magmatic phases and the genesis of ore-bearing fluids (hydrothermal resources) that manifested alteration halos with vein type mineralization [15]. Abundance of clayey minerals (such as Kaolinite) is an important indication of the presence of hydrothermal activities and their impressive role at the leaching of the rocks [13].

4. Discussion

A well-done prognosis of mineralization requires a logical integration according to the SDM concepts. The spatial data usually merge together on the basis of mathematical algorithms in order to find the optimum regression values for weighting purposes. In this regard and after obtaining databases, the ordinary statistical techniques such as buffering of structures and re-classification of the contours are necessary for weighting alterations and scoring mineralization evidences [2]. From a geomatical viewpoint, the logical operators for spatial analysis require indicator layers with grid or raster isometric templates for quantitative description of the phenomenon [2]. As a result, logical operations were carried out on all the data, which is outlined as below:

4.1. Geo unit layer

Geological units have the main roles in mapping alterations and identifying host unit potentials. The Ramand geological units have been revealed and extracted from 1/100000 sketch map of Danesfehan [13]. Some unique features including magmatic felsic rock units and neo-structural lineaments have been selected and separated due to their spatial associations with the events of alterations (Figure 1). Using buffering algorithms (GIS-based), the above-mentioned features are required to convert to grids (Table 2) for input to models. The weighting process is also based upon the geological-structural evidences. The results obtained can be shown as an indicator map of geological units (Figure 2). Here, scoring the host units depends not only upon the rates of alterations but also on the strength and types of mineralization (metallic and non-metallic in crushed zones).

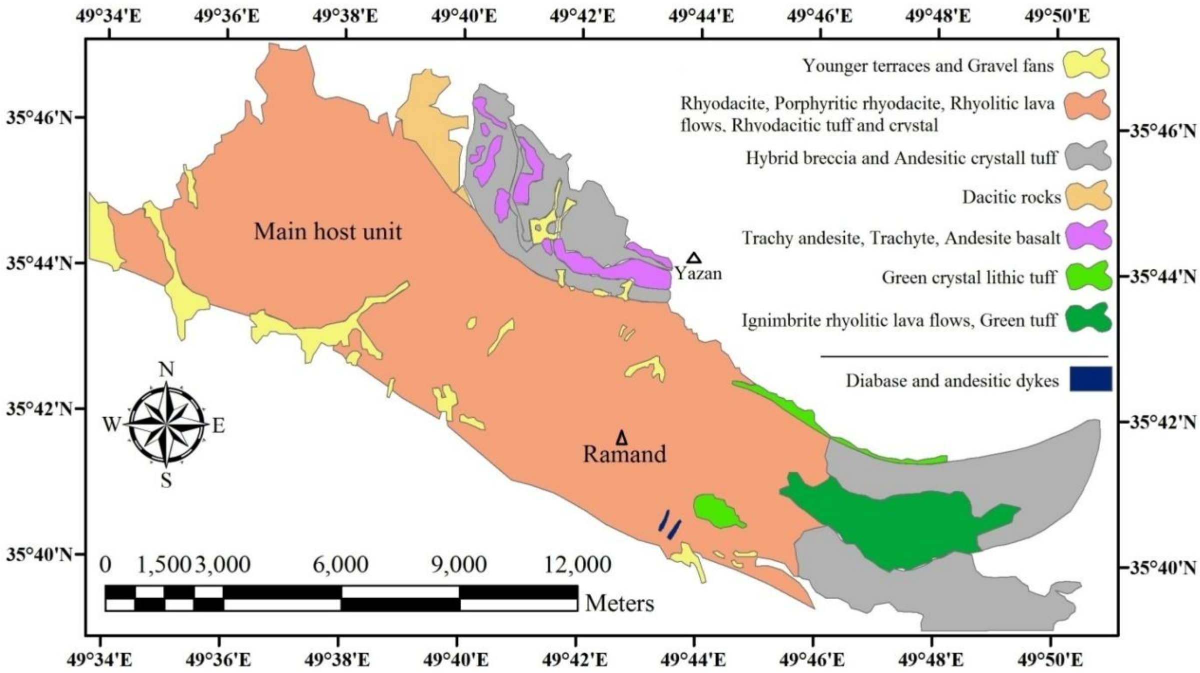

Figure 1. Geological unit map in Ramand region (Main host unit consist of rhyodacite and rhyolite igneous rocks, rhyodacitic tuff, crystal tuff, and rhyodacitic lava flows) [13].

Table 2. Fuzzy weighting to geological units in Ramand region.

Geological Units	Observed units in the area	Main unit	Eocene-Oligocene	Rhyodacite, Porphyritic rhyodacite, Rhyolitic lava flows rhyodacitic tuff and crystal tuff	Weight
		Minor units		Green crystal lithic tuff	0.8
			Quaternary	Younger terraces and Gravel fans	0.1
	Observed units around the area	Minor units	Eocene-Oligocene	Ignimbrite rhyolitic lava flows, Green tuff	0.6
				Hybrid breccia and Andesitic crystal tuff	0.55
				Trachy andesite, Trachyte, Andesite basalt	0.45
				Dacitic rocks	0.3

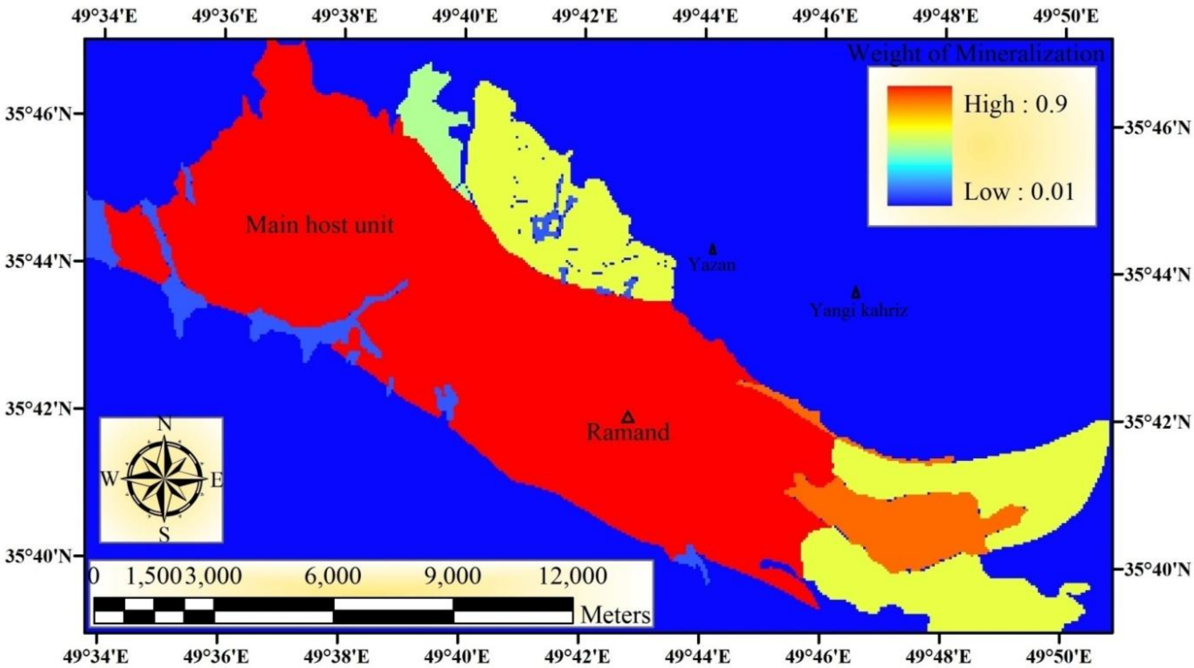

Figure 2. Indicator map of Ramand geological units layer. (Exploration priority of geological layers determined by fuzzy logic so that red color (highest: 0.9) is indicative of highest and yellow color (least: 0.1) is indicative of least talent in mineralization).

4.2. Layer of hydrothermal alterations

Remote identification of hydrothermal alterations is one of the efficient tools available for mineral explorations according to satellite information. In this research work, the ETM^+ images (Landsat7) have been used for identification of the hydrothermal alterations by applying selective principle component analysis (SPCA) (Crosta-tech) [16] and a new qualified band rationing technique (M-ratio) [17].

Crosta-tech offers a selective PCA to find and confirm the relevant EM reflections (detected from surfaces) to hydrothermal alterations. Crosta-tech has been well-done according to Ramand ETM^+ photomap shown in Figure 3. This figure indicates a simultaneous presence of clayey and iron oxide alterations. Decreasing the input bands is a mathematical key to obtain the main but unique spectrums related to the mineralization processes. A minimal spectral interfere is required to reduce spectral noises by correlating the numerical kernels (matrixes) of the bands. For ETM^+ images, PCA has 3 steps, as below:

-1, 4, 5, 7 band selection for mapping clayey minerals (argillic alteration).

-1, 3, 4, 5 band selection for mapping iron oxides as a rural alteration around magmatic intrusions.

After the above-mentioned steps, two series of components exist and highlighted based upon their spectral contrasts by PC4. In Table 3, the F and H letters refer to iron oxides and clay mineral alterations, respectively. In other words, a band group has 4 spectral components known as PC1, PC2, PC3, and PC4 according to Crosta-tech Eigenvalues variations, of which, PC4 contains the best frequencies of rock unit alterations [16].

-At the final step, Crosta-tech uses a simple arithmetic operation (algebraic SUM) to combine Eigen vectors into unified component by H+F statement, which is represented by a specific spectral signature indicated by the hydrothermal alterations.

Considering the necessity of color composite production, available PC4s corresponded to red, blue, and green visible spectrums (RGB) in Table 3 (Crosta-tech formula) and then illustrated in Figure 3 as FCC map.

In this figure, brownish reds indicate clayey minerals. Dark blues indicate iron oxides (and hydroxides). Yellow to light green colors represent both mineralization of the clays and iron oxides (hydrothermal aggregation).

Table 3. Results of Crosta method for color band composition in Ramand region ($F(PC_4)$ = Fourth level of eigenvectors that related to spectral changes of iron oxides (in blue filter), $H(PC_4)$ = Fourth level of eigenvectors that related to spectral changes of clay minerals (in red filter), $H(PC_4)+F(PC_4)$ = Fourth level of eigenvectors that related to spectral changes of clay minerals and iron oxides (in green filter)).

Red	Green	Blue
$H(PC_4)$	$H(PC_4)+F(PC_4)$	$F(PC_4)$

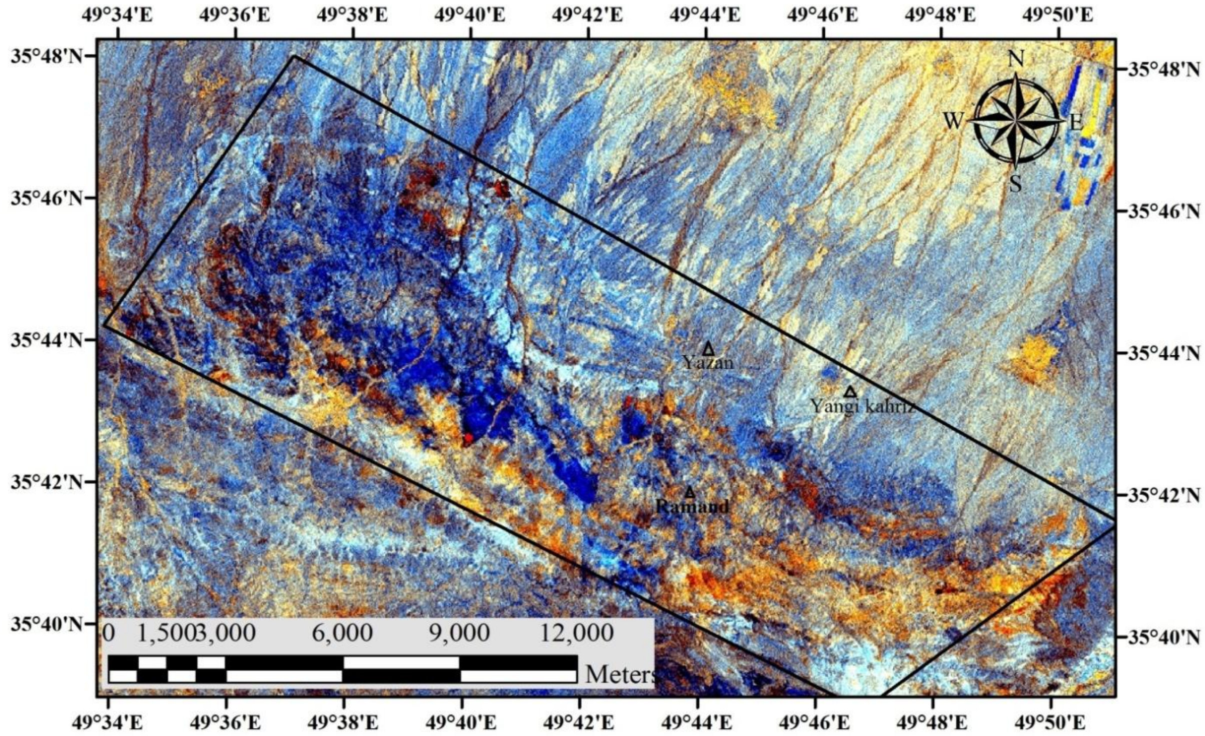

Figure 3. ETM$^+$ mage of selective principal component analysis to Crosta method in Ramand region (yellow and orange to yellowish colors indicates hydrothermal alterations in studied rectangle area).

In practice, some areas with yellow to orange color reflections are considered as altered mineralized targets affected by hydrothermal solutions that is originate from magmatic differentiations. When the above-mentioned alterations correlated with the dacite and rhyodacitic host units, there are more chances to find ore mineral traces than other types of rock units in this region [16].

M-ratio technique: It is a revised and updated rationing method introduced by Mehrnia (2015) for enhancing the contrast of images and detection of spectral changes in association with the hydrothermal alterations. This method uses two different spectral ranges to increase the difference of wave lengths by dividing the max values (as numerators) of min values (as denominators) of specific reflections [18]. For the current research work (ETM$^+$ images), 4 image processing steps were considered, as below:

- Obtain the band ratios of 3/1 and 5/7 to determine the iron oxide and clay mineral reflections, respectively.
- Obtain a contrast band ratio (4/3) for increasing the spectral discriminations between the altered and non-altered regions.
- Composite band ratios using visible RGB with respect to the Table 4 considerations.
- Apply Intensity, Hue, and Saturation (IHS) high-pass filter in RGB composition for qualitative spectral enhancement that is shown in Figure 4.

Table 4. Combined of band ratios by M-ratio method with aim of identifying hydrothermal alteration areas in color photo-maps of Ramand region.

Red	Green	Blue
3/1	5/7	4/3

From technical procedures, M-ratio is the same as other types of rationing techniques but it has two spectral advantages to verify solution-related alterations in magmatic environments. The first one is using the ratio of 4/3 for confident discard purposes. The second one is using the IHS qualitative filter that is proposed [18] and well-done here to increase the spectral contrast more than quantitative filter applies.

Considering M-ratio, areas with Red and Green colors indicate iron oxides and clay minerals, respectively. Therefore, areas with yellow to orange colors represent the presence of alterations with both iron and clayey facies aggregations due to weathering or hypogenic processes. In this composition, Blue and Purple colors just show the barren regions for increase the band contrast between the altered and non-altered regions.

In Figure 4, the areas that are affected by hydrothermal alterations represent yellow to orange colors found near the cross-cutting structures (crushed zone with brecciated facies) [17]. Comparing Crosta alterations with M-ratio results show embedded but real hypogenic alterations according to the rationing algorithms.

To achieve an accurate result, remotely sensed alterations (according to Crosta and M-ratio techniques) have been queried and used to appropriate weighting of the layers in the GIS environment. As a rule of M-ratio, numbers and territories of hydrothermal alterations are more limited than Crosta-tech photomaps. It means that a real relevant spectrum to the Ramand hydrothermal alterations may be introduced by Crosta PCA but requires topological verification based on M-ratio signatures.

Most of the solution-related mineralizations are found and spatially limited in or around the faulted regions. Also hydrothermal halos are usually patched and embedded by the crossing lineaments. Mentioned evidences realize this fact that hypogenic alterations appear in small facies with local mineralization traces on the Earth’s crust.

Contrary hydrothermal systems, hydromorphic halos, mostly extend around terraces and follow meanders or fans morphologically [19]. In the Ramand region (current research work), there are many kinds of alterations, some of which are originated from hypogenic resources and hosted by volcanic formations experimentally. As a result, two manners of image processing techniques (Crosta and M-ratio) have been used and correlated together for revealing hydrothermal alterations, as shown in Figure 5. In this figure, we have zoom in remote sensing to prepare a unified alteration layer that is comfortable for the fuzzification purposes.

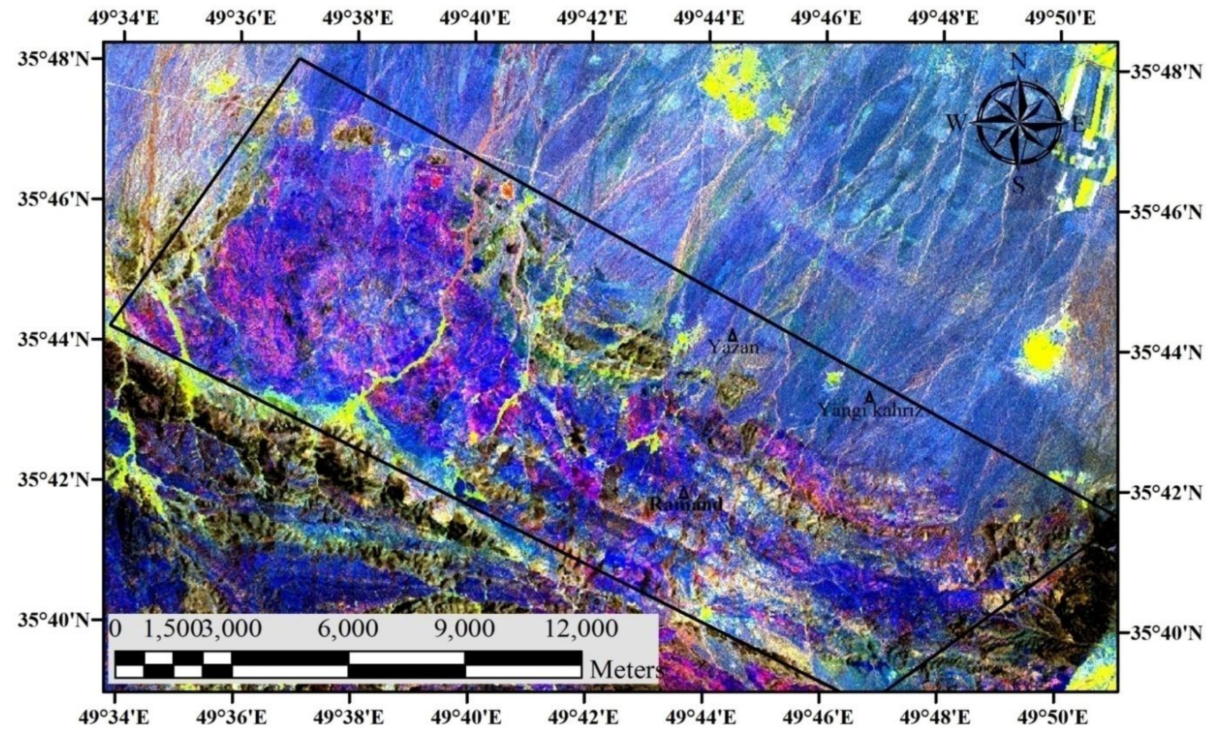

Figure 4. Applying M-ratio technique in ETM$^+$ Images of Ramand region (yellow and orange colors indicate hydrothermal alterations in studied rectangle area).

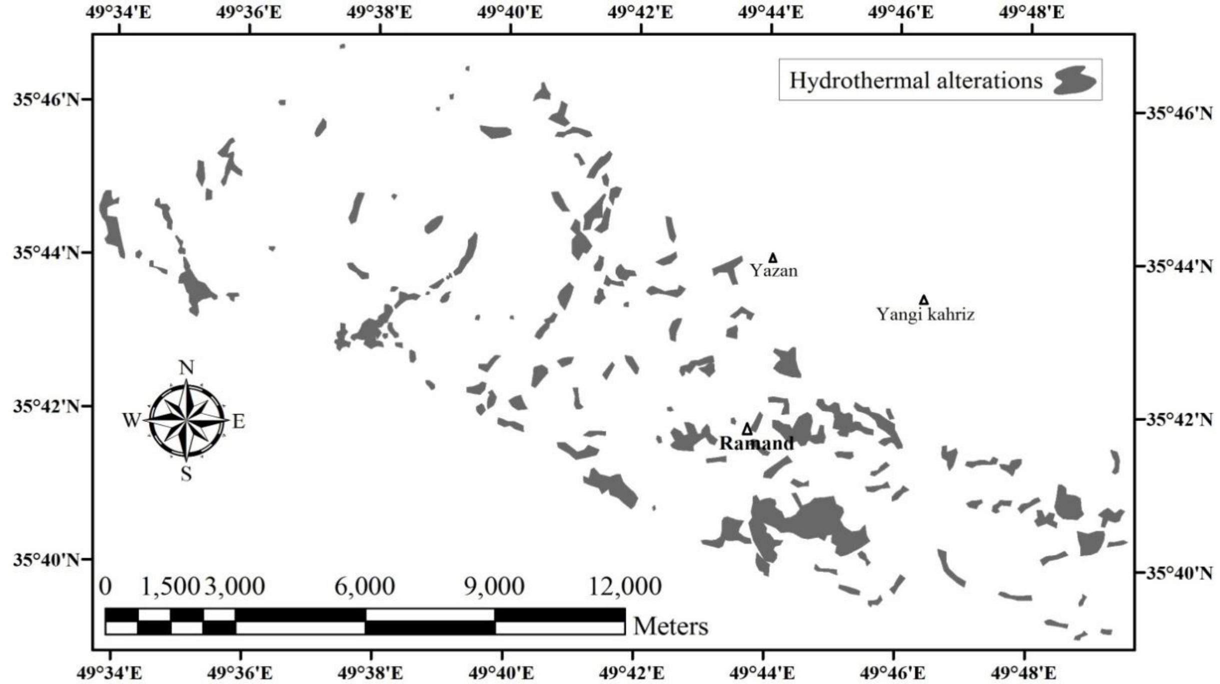

Figure 5. Hydrothermal alteration area map in Ramand region (This map was obtained from overlapping of Crosta and M-ratio methods).

Another essential layer may be derived from the intersection points between two or more cross-faulted systems. It is due to the fact that the structural events usually have a main role in the cycling process of thermal solutions and cause genesis of ore bodies in hypogenic environments. Figure 6 represents some main and minor hydrothermal alterations with close spatial association with the structural events. As shown, the Ramand hydrothermal alterations are not only found in near places of geological structures but are locally mineralized in adjacent of intersected lineaments. Therefore, our fuzzy scoring process depends on the buffering radius of the structures as well as the distances from intersections. Moreover, in a real fuzzification, all weightings of the events should be correlated and confirmed by the mineralization processes. For instance, the Ramand altered regions have different content of ore minerals based upon their distances from the intersected structures on volcanic formations. Then membership functions may acquire different values (scores) according to the structural controllers and their eventual associations with the altered mineralized regions.

4.3. Layer of fault systems (observed)

In the post-magmatic environments, Fault systems act as structural controllers among the mineralization processes. Solution-related deposits are usually found within brecciated crushed zones [20]. The layer of structures extract from geo-maps due to enhancement and vectorize of the lineaments [13]. Geological structures (observed faults) have more fuzzy scores than the other structures (geophysical, remotely sensed, etc). In this research work, the structural patterns are weighted according to their spatial relationships with the hydrothermal alterations. As a result, the linear patterns have been divided into two categories: the main and minor (hidden) fault systems. The main types have a chance to obtain greater weighting values than the minor types. It is due to the fact that the main structures have meaningful association with hydrothermal alterations as well as hydrothermal mineralization in the Ramand region. Buffer zones (effective radius) have been selected equal to 300 m around the main structures that consist of three interior layers with an interval distance of 100 m. Figure 7 shows a buffered pattern of structures according to the Ramand geological evidences (observed faults).

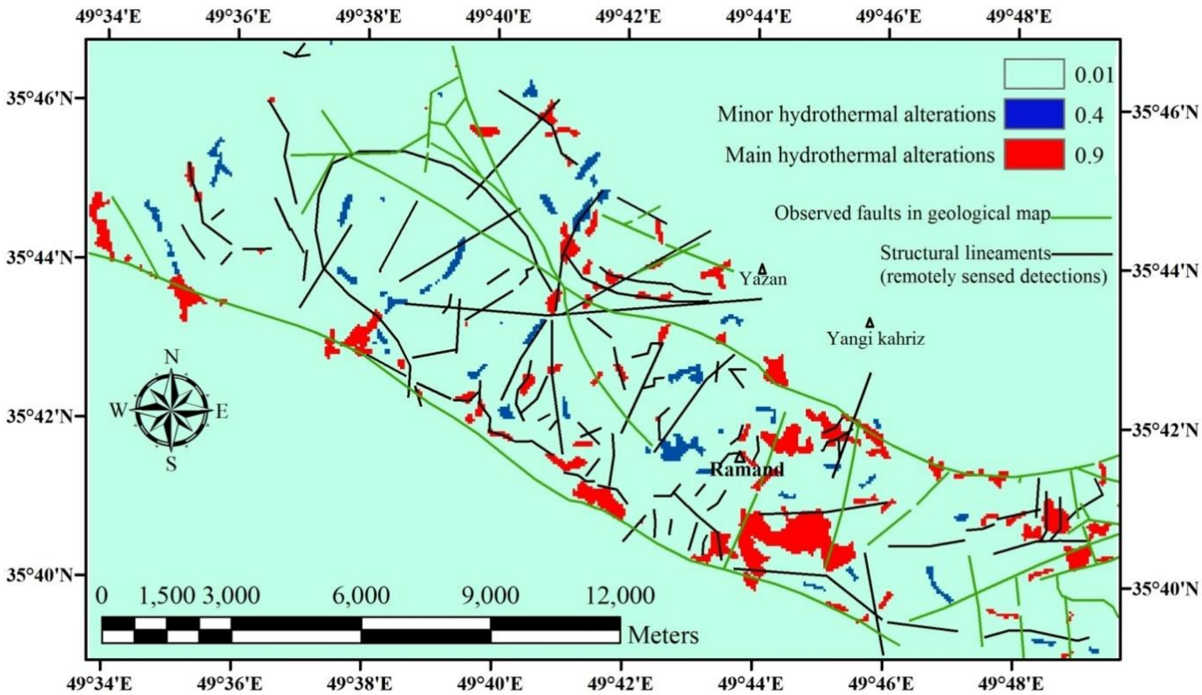

Figure 6. Indicator map of detected hydrothermal alterations in Ramand region (red = main hydrothermal alterations, blue = minor hydrothermal alterations, green = observed faults in geological map, black = structural lineaments (remotely sensed detections)).

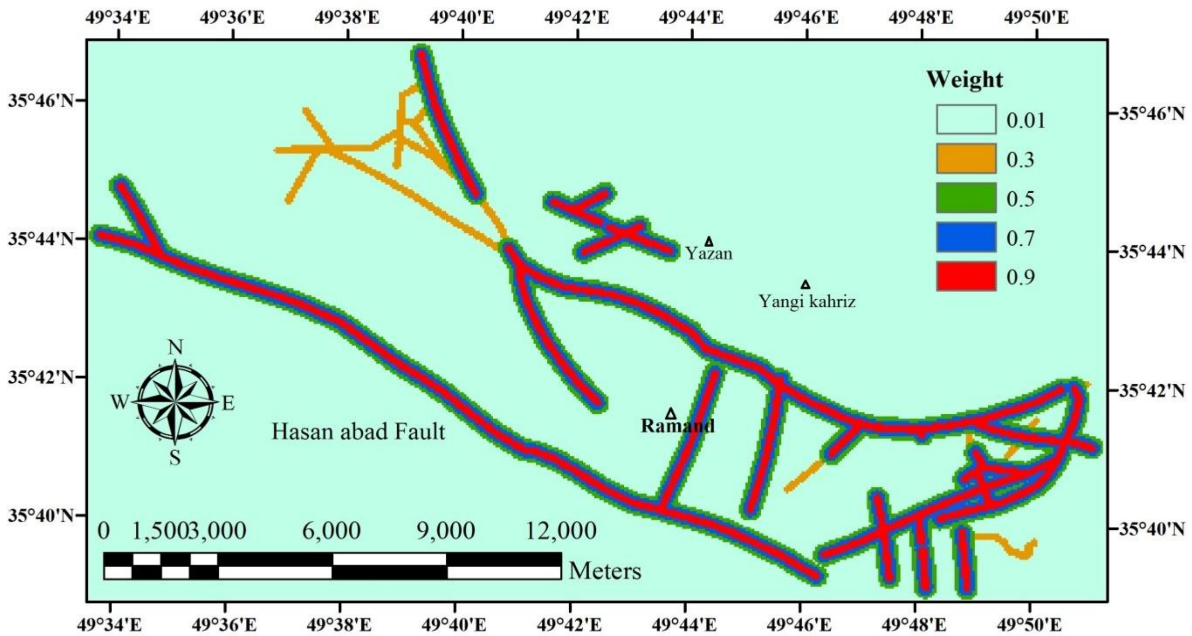

Figure 7. Indicator map of Observed faults layer in Ramand geological map according to geological considerations (Buffer range for main faults: red = 0-100 (m), blue = 100-200 (meter), green = 200-300 (m) and buffer range for minor faults: brown = 0-100 (m)).

4.4. Layer of lineaments (remotely-sensed)

Although detection of the remotely-sensed lineaments is easier than direct observations, the verification step is so difficult and requires adequate geological evidences to verify the processed features practically. Anyway, in cases of the presence a meaningful spectral interfere between the structural and nonstructural events, many constraints such as in atmosphere or plant cover prevent from accurate identification of structural lineaments by the remote-sensing techniques [21]. According to the Ramand geological investigations, there are several cases of structural vents association with ore mineralization process within hydrothermal alterations that realize the necessity of qualitative filter apply (321 IHS) to increase the ability of drawing lineaments, as shown in Figure 8.

For remotely-sensed lineaments such as what was said about geological faults, the patterns of structures have been divided to the main and minor groups: main and secondary. Then weighting to criteria depend on the relationships between location of lineaments and alteration occurrences in the Ramand region; it means that a greater weight is given to the main types because of having a closer relationship with the hydrothermal processes. In other words, the ability of mineralization in faulted areas is stronger than the areas with lesser or absence of fault systems. The buffering result for remotely-sensed lineaments is shown in Figure 9. In this figure, the remotely-sensed features (seized from 321-IHS image) have a commensurate weighting to mineralized alterations, and are ready to merge with other exploratory evidences.

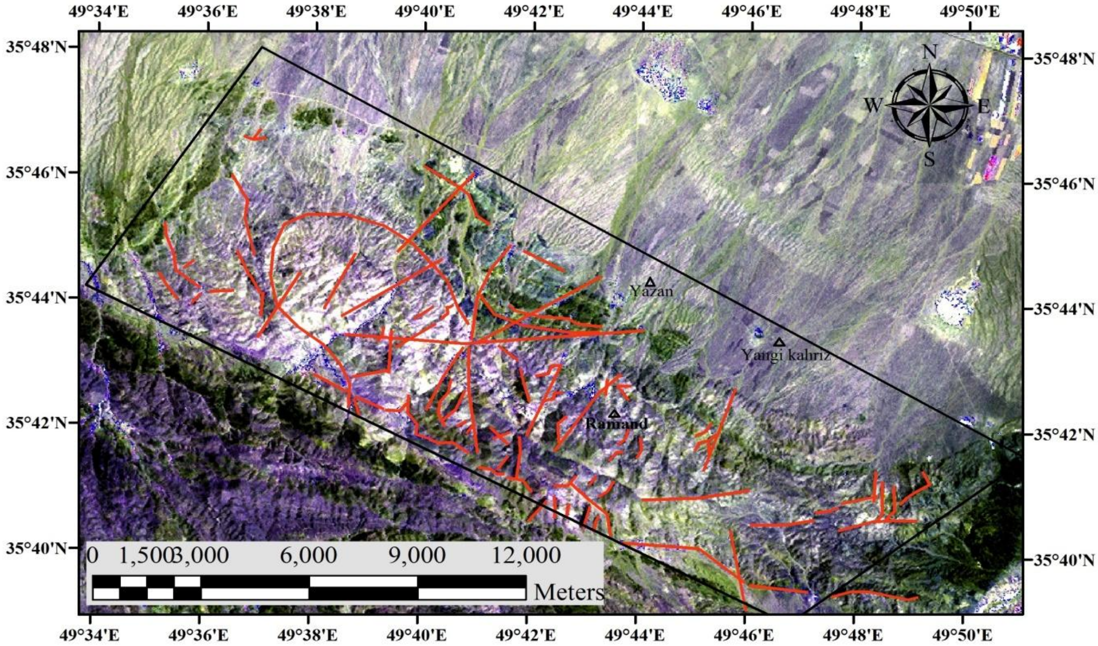

Figure 8. Detection of structural lineaments (red color) by applying an IHS filter on RGB = 321 image of Ramand region.

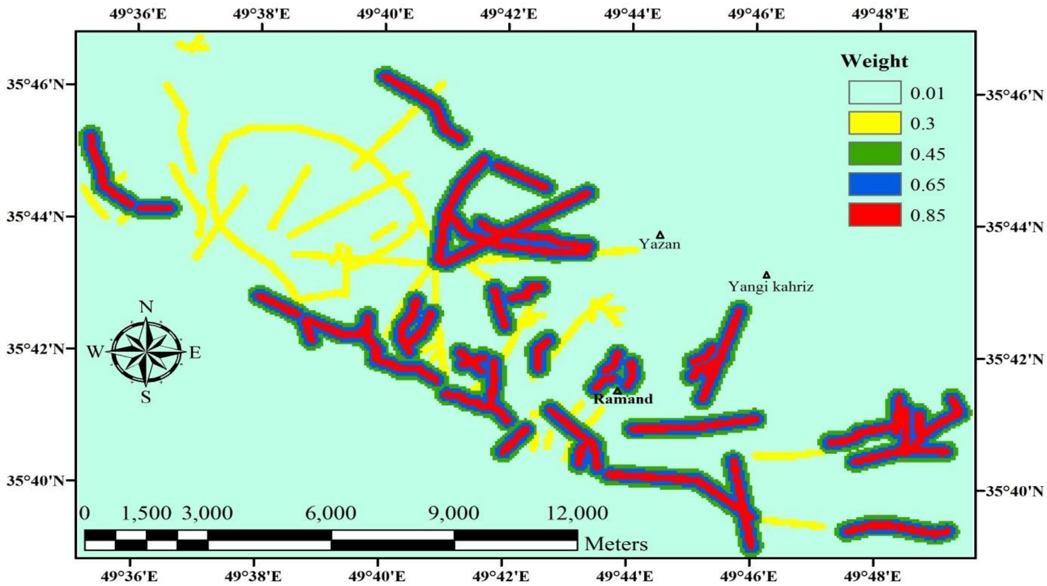

Figure 9.Indicator layer of structural lineaments (remotely sensed) in Ramand region (Buffer range for main remotely-sensed lineaments: red = 0-100 (m), blue = 100-200 (m), green = 200-300 (meter), and buffer range for minor remotely-sensed lineaments: yellow = 0-100 (m)).

4.5. Layer of lineaments (aeromagnetic)

Airborne magnetic survey is a well-known and reliable technique, in which unique fabrics maybe indicated as observed or hidden fault systems [22]. By comparing the aeromagnetic fabrications with other geophysical productions, we realize the possibility and advantage of magnetic gradients to appear lineaments and coincide them with the real geological structures. In this research work, we have gridded aeromagnetic data to produce contoured map as a basic theme for detecting lineaments. Also the aeromagnetic data have been surveyed by GSI in 2001 based upon a regional prospecting scale (1:50000) and (7.5 km * 0.5 km) of measuring intervals.

The geo-statistical interpolation has been well-done based on the GIS spatial analyst facilities.

Figure 10 shows the magnetic contours and their confirmed lineaments locations in the Ramand region. The main criteria to find and to confirm these lineaments are: detecting the surface of gradients based upon the magnetic changes in contoured maps; drawing linear fabrics along the surfaces of gradients and revealing polarization effects in both sides of some magnetic anomalies [23].

From a geo-physical viewpoint, aeromagnetic lineaments appear as indiscrete shapes (segmented features) and are usually found as parallel couples. Those linear forms that have meaningful correlation with the faulted regions are introduced as structural lineaments (themes with high scores). In contrast, those lineaments that do not match with the geological structures may be represented by the hidden fault systems with lesser credit than observed (themes with low to moderate scores).

Considering the aeromagnetic lineaments that have close relations with the Ramand mineralized regions, two types of features classified, as below:

The first is main lineaments that are usually observed in the vicinity of altered regions and obtain high scores because of their association with mineralization processes.

The second is the minor lineaments that represent the hidden structures and obtain low to moderated scores because of their unknown association with mineralization processes.

It should be noted that the buffer radius assumption around the main lineaments has been determined equal with 100 m, while this radius for minor lineaments has been determined to be equal to 50 m. After weighting to fabrics, the indicator map has been plotted and reclassified into the structural (red) and hidden (blue) lineaments, as shown in Figure 11.

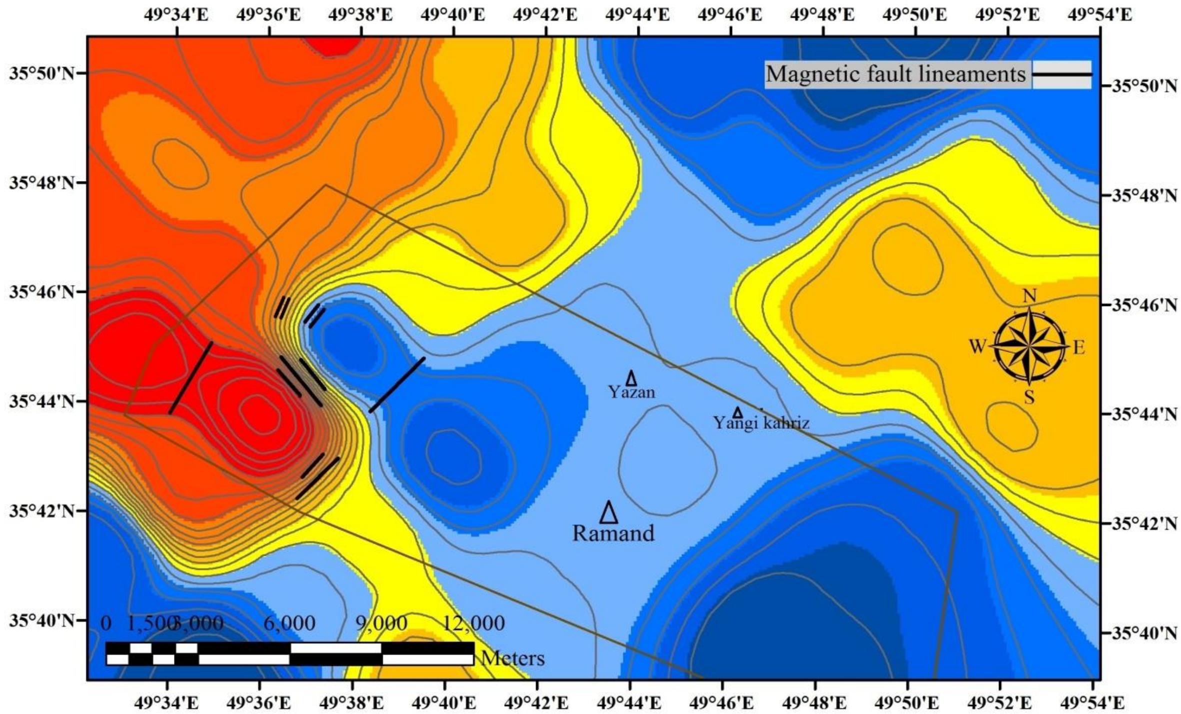

Figure 10. Magnetic structural lineaments (black solid lines), detected within Ramand exploration region with considered measures on aeromagnetic data (guide of Figure10 is expressed in Table 5).

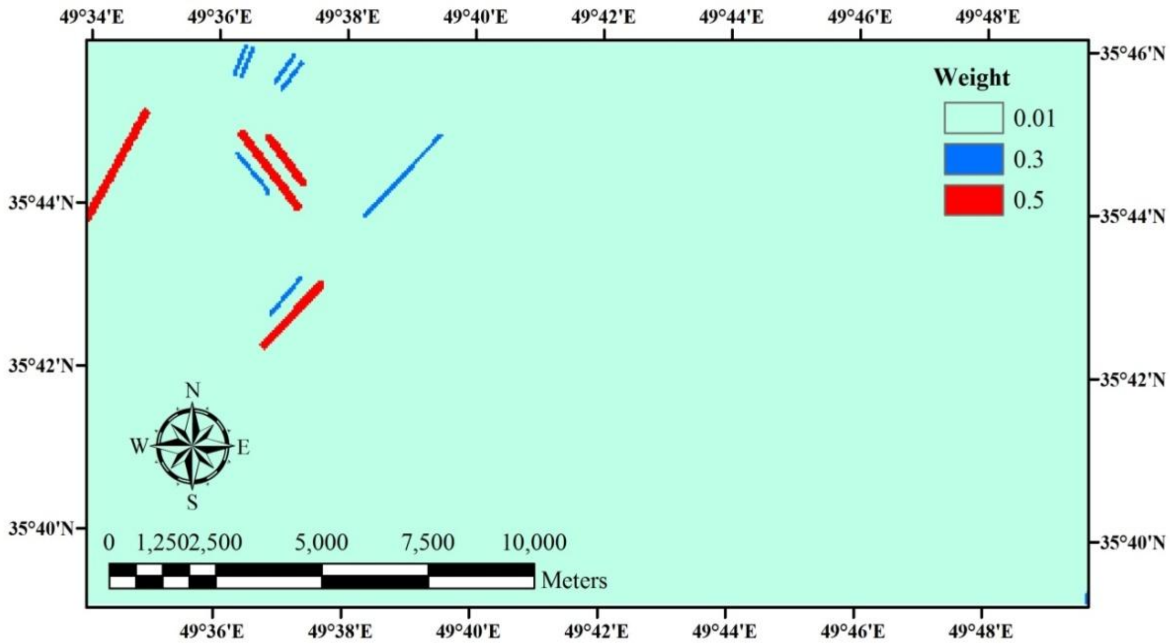

Figure 11. Indicator layer of structural lineaments, detected from Ramand aeromagnetic databases (Buffer range for main structural lineaments: red = 0-100 (m) and buffer range for minor structural lineaments: blue = 0-50 (m)).

4.6. Layer of aeromagnetic field intensity

In terms of geophysics, most of the hydrothermal alterations cause meaningful losses in the magnetic field of host units. The mechanism of such changes depends on heat effects (Curry Temperature) within hydrothermal systems and crushing effects at the surfaces of altered regions (brecciated facies zones). In other words, ascending thermal solutions as well as abundance of crushed zones in geological environments are two main factors that control the decreasing rate of magnetic susceptibility. As a rule, the fewer susceptibility in host units has a low magnetic field intensity that is usually observed in hydrothermal alterations [24].

In this research work, the total magnetic responsibilities have been separated into three gridded population including background, threshold, and anomalous regions. From a spatial viewpoint, the places of thermal alterations may correspond to the threshold of magnetization [22]. Also a big part of clayey halos (argillic alteration) has a low magnetic responsibility placed in the background of magnetization. In Table 5, the scoring values are proportioned to changes of magnetic intensity. The maximum fuzzy weighting have been allocated to the threshold values and depend on the significant variation of magnetic susceptibilities next to the altered regions. Figure 12 represents the plotting result of weighted aeromagnetic contours with assumption of 9 classes (as Arc-GIS default) for re-classification of the final indicator layer to merge with the other criteria.

5. Fuzzy-based mineral potential map

By introducing the indicator layers and weight them based on the geological, structural, and geophysical considerations, all spatial data was prepared to fuzzy integration using gamma = 0.75. Gamma is a famous algebraic operator consisting of “Sum” and “Multiple” functions to realize a modified prognostic model according to Fuzzy logic algorithms. [2]. Also this operator subject to some variables of which values depend upon the fusion purposes. For instance, selecting gamma values close to 1 causes appearing broad areas that in most cases have an exaggerated suitability concept. In such cases, the logical operator (gamma0) act as the algebraic sum with low accuracy results in prognostic models (confidence interval is less than 50%).

On the other hand, selection of gamma values close to zero give rise some results similar to multiple functions. In this case, small targets are usually identified based upon a maximum accuracy assumption in the weighted layers (confidence intervals is greater than 95%).

Although using the multiple logical operator gives rise to a maximum accuracy and confidence, it is not recommend to introduce suitability maps by γ = 0.00. It is due to the fact that in geological cases, there are other suitable areas that due to

applying a high sensitive model never come to estimations (ignored targets).
In a practical logical operation, by increasing the gamma values greater than 0.5, the confidence interval of estimations comes down and gives rise to introducing several promising areas (increasing in BIAS), whereas with decreasing in the gamma values (lesser than 0.5), the confidence interval of estimations will be increased and the promising areas appear in fewer targets consequently (reducing in BIAS). Meanwhile, we can select the gamma values between 0.5 and 0.8 for introducing comfortable prognostic models with the aim of reconnaissance studies in the mineralized regions [2]. Figure 13 is a fuzzy-based prognostic map for studying the potential of hydrothermal mineralization in the Ramand altered regions. This map is produced by integration of the indicator layers using gamma = 0.75. As a result, several target areas have been introduced in the Ramand region (under 68% of confidence) and realized this modeling adaptation with identification of hydrothermal alterations in the geological environments.
In practice, the above-mentioned promising areas (see Figure 13) are mainly hosted by young volcanic formations and sampled for petrography, geochemical analyses, and ore mineralogy.

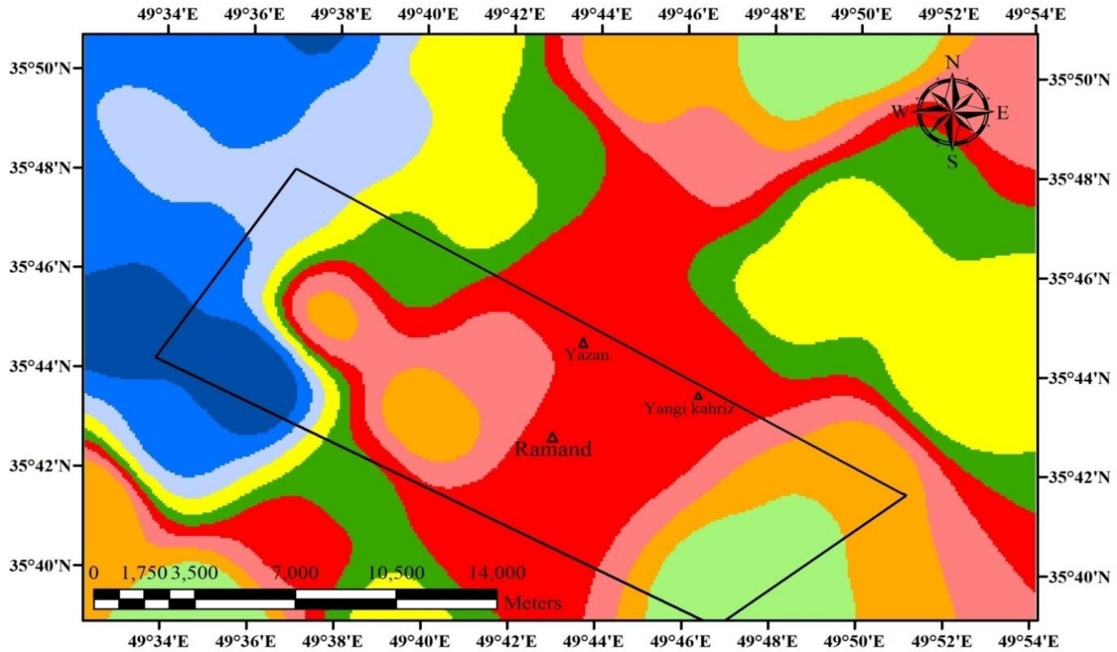

Figure 12. Indicator layer of magnetic field depletion in Ramand alteration zones (this figure guide, in Table 5).

Table 5. Fuzzy weighting to magnetic intensity values in 9 different classes based upon evidence of hydrothermal alteration in Ramand region.

Figure 10	Magnetic intensity (n.t)	Weight	After Fuzzification (Figure 12)
	39638.11328-39662.125	0.6	
	39662.12551-39677.88281	0.7	
	39677.88282-39693.35156	0.85	
	39693.35157-39708.875	0.9	
	39708.87501-39726.88281	0.5	
	39726.88282-39755.26172	0.4	
	39775.26173-39787.03125	0.3	
	39787.03126-39819.69141	0.2	
	39819.69142-39862.39063	0.1	

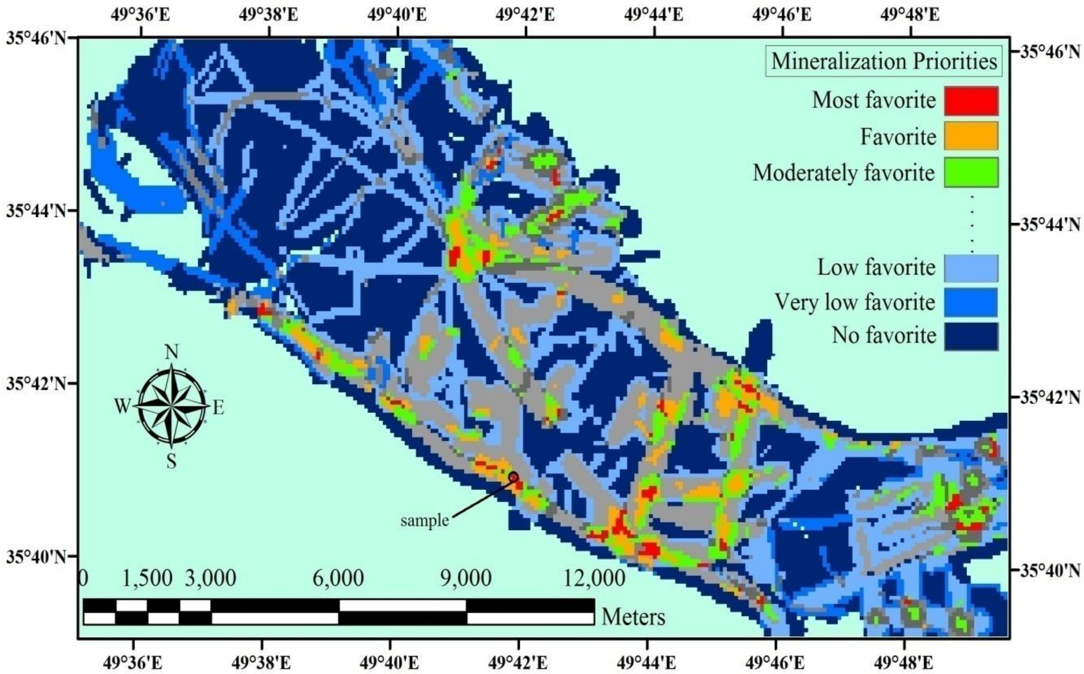

Figure 13. Fuzzy-based prognostic map of hydrothermal mineralization in Ramand region (Mineralization priorities: red: most favorite, orange: favorite, green: moderately favorite, light blue: low favorite, blue: very low favorite, dark blue: no favorite).

Figure 14 illustrates ore microscopic sections sampled from the southern mineralized formation according to the fuzzy model (longitude: 49 41 48; latitude: 35 4054; Figure 13). Iron and copper mineralization (such as Goethite, Chalcocite, and Chalcopyrite) are usual in favorite horizons and mostly distributed around the brecciated outcrops.

In altered regions, mineralogical phases containing various type of clay minerals formation (illite to kaolinite) beside silicification appearances at the veins and veinlets that represent the role of ascending thermal solutions in the endogenic enrichments.

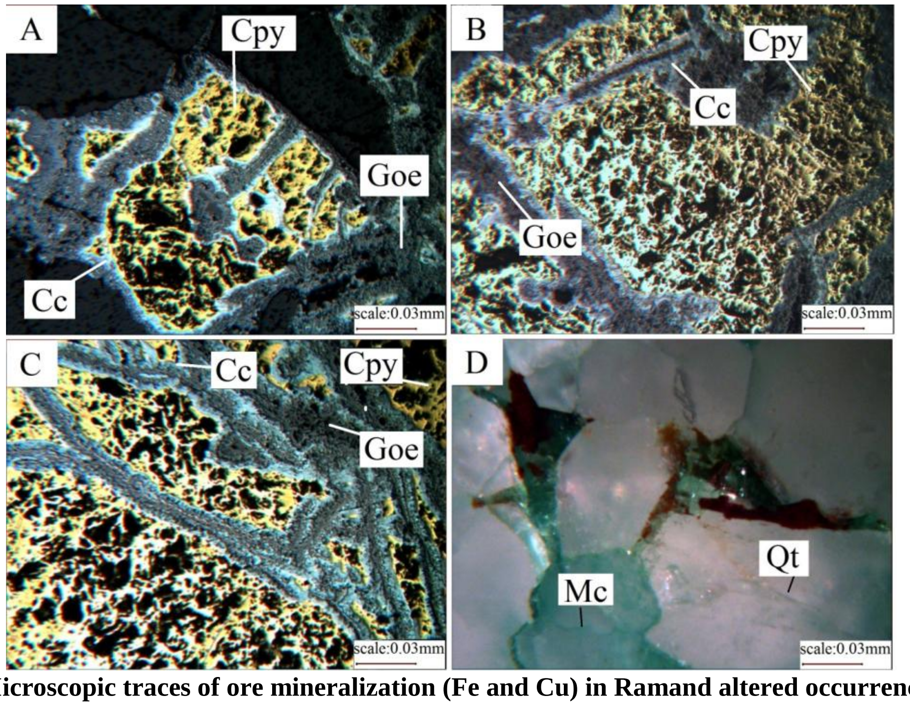

Figure 14. Microscopic traces of ore mineralization (Fe and Cu) in Ramand altered occurrences, A, B, C: parallel nicols, field of view = 0.0.3 mm, 200X, D: vertical nicols, field of view = 0.0.3 mm, 200X. (Cpy = Chalcopyrite, Cc = Chalcocite, Goe = Goethite, Qt = Quartz, Mc = Malachite [25]).

Ore samples (A, B, C, andD in Figure 14) are collected from silica veins (quartz mass) surrounded by argillic alteration and controlled along crossed fault systems. As shown in this figure, ore minerals appear as phenocrysts, and mostly consist of iron oxides as well as copper sulfides. On the other hand, quartz and clays may appear in massed forms and occasionally fill the whole of background. Quartz masses may contain relicted particles of malachite as a usual but weathered form of copper minerals.

As well as the southern part of the Ramand region, there are probable mineralization potentials in the eastern targets (see Figure 13) whose microscopic specifications should be observed and realized the same as the southern targets.

6. Conclusions

One of the most important expertise for mineral exploration is the ability for gathering data, querying information, and analysis of spatial dataset for introducing a comfortable prognostic map with geological evidences for making decision on how to go on and improve exploration phases for the time being.

It is noted that for increasing the domain of indicator layers, the number of variables should be increased and qualified with logical operators. For instance, an accurate prognostic model that can be used for regional mineral explorations (such as Ramand region), at least require three abilities to obtain the best qualitative results. The first is the ability of regionalization. The second is the ability of computerization. The third is the ability of fuzzification.

For Ramand databases, all mentioned abilities such as regional covering of the features, synchronizing spatial databases with each other, and fuzzy modeling are available. With this possibilities, we could focus on the geological and structural evidences as well as the geophysical and remotely-sensed indicators for a fuzzy-based prognosis of ore mineralization potentials next to the altered formation of the Ramand region.

According to the fuzzy prognostic map (Figure 13), the southern parts of the Ramand region may be faced with several mineralization phases due to the presence of thermal solution activities (in Neogene).

Meanwhile, a lesser alteration content was recognized in the eastern parts of the Ramand region with the same mineralization potentials for detail exploration purposes. It is noted that the southern targets are strongly mineralized and extended within faulted alterations.

Therefore, it is strongly recommended to plann a new phase of mineral exploration program based on semi-detailed sampling and land-surveyed geophysics (geomagnetic, geo-electric, etc.) with emphasis on hydrothermal mineralization such as Fe, Cu, Au, and Pb in altered brecciated regions.

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کاربرد مدل‌سازی فازی با هدف شناسایی آثار دگرسانی گرمابی در منطقه رامند (استان قزوین)

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چکیده:

منطقه رامند بخشی از نوار ماگمایی ارومیه- دختر واقع در زون ساختاری ایران مرکزی است که از نظر جغرافیایی در جنوب غربی شهرستان بویین‌زهرا و ضلع جنوبی دانسفهان قرار دارد. منطقه مذکور به طور عمده شامل سنگ‌های آذرین اسیدی با ترکیب ریولیتی و ریوداسیتی است. آثار دگرسانی‌های رسی و پیدایش رگه‌های سیلیسی در سنگ‌های آتش‌فشانی به وفور مشاهده می‌شود. در این مطالعه با استفاده از الگوریتم منطق فازی و سازوکار تلفیق داده‌های مکانی (در محیط GIS)، نقشه پیش داوری از وضعیت پتانسیل‌های معدنی مرتبط با فعالیت‌های کانه‌زایی ماگمایی- گرمابی تهیه شده است. لایه‌های مورد استفاده شامل اطلاعات زمین‌شناسی، زمین ساختی، تصاویر ماهواره‌ای (سنجنده ETM^+) و شواهد کمی به دست آمده از سنجش‌های مغناطیس هوابرد می‌باشند که پس از پردازش مقدماتی داده‌ها و دستیابی به نقشه‌های پربندی وزن‌دهی شده (لایه‌های نشانگر)، فایل‌های رستری (سلولی) موجود در قالب شبکه استنتاج فازی و با انتخاب مقدار عملگر گامای $\gamma =$ ۰/۷۵ تلفیق شده‌اند. بدین ترتیب آثار توأم دگرسانی و کانه‌زایی منطقه رامند با تأکید بر توان معدنی ذخایر ماگمایی- گرمابی به صورت نقشه پیش داوری فازی معرفی شده‌اند. در این نقشه نواحی مستعدی وجود دارند که از اولویت پی‌جویی ذخایر فلزی در عمق رخساره‌های دگرسانی برخوردارند؛ لذا در پایان تحقیق، برخی از نتایج و پیشنهادهای لازم با هدف ادامه فعالیت‌های اکتشافی (در فاز تفصیلی) مطرح شده‌اند.

کلمات کلیدی: دگرسانی، کانه‌زایی، گرمابی، منطق فازی، رامند.