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Relationship between Fe-Cu-REEs mineralization and magnetic basement faults using multifractal modeling in Tarom region, NW Iran

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In this paper, a Concentration-Distance to Magnetic Faults (C-DMF) fractal model was applied to distinguish Fe, Cu and REEs mineralized zones based on their distance to basement faults derived via airborne geophysical data and field survey maps in the Tarom region at the western Alborz-Azerbaijan belt, NW Iran. The application of the C-DMF model was utilized for mineralization classification in the Tarom 1:100,000 sheet which reveals that the main Fe, Cu and REEs mineralization have an inverse correlation with their distances to magnetic faults (fault lineaments). The Cu ores within acidic rocks and the Fe/REEs mineralization within intermediated rocks are located in the Northern and Southern parts of the Tarom region, respectively. Furthermore, the basement fault and intrusive rocks have overlapped and they have important roles for these metallic deposits/occurrences. Based on the C-DMF log-log plots, Fe, REEs and Cu high-grade mineralization values are larger than 48.31%, and 3.8%, with respective distances of 451 and 732 m to the nearest magnetic faults. The results obtained from the fractal modeling indicate a positive relationship between Fe, REEs mineralization and the basement faults. Consequently, Cu mineralization has a weak relationship to faults in comparison with Fe and REEs.

Introduction

Alborz-Azerbaijan zone is characterized by extensive Cenozoic magmatic activity with calc-alkaline-potassic character, in northwestern Iran (Berberian and King, 1981; Moinvaziri, 1985). The volcanic rocks of this zone have been formed in magmatic arc and back-arc tectonic setting in a post-collisional setting (Berberian, 1983; Allen et al., 2003; Hassanzadeh and Wernicke, 2016). The U-Th/He apatite isotopic data in the region is the Miocene continental collision of Iran

(Stockli et al., 2004). Iron-apatite ores host rare earth elements in the study region.

The recognition of the structural condition is significant for mineral exploration especially in reconnaissance and prospecting stages. Relationship between structures and mineralization is a fundamental study for regionalized exploration for magmatic and hydrothermal ore deposits (Pirajno, 2009; Mustansar et al., 2016). The ideas about the relationship between mineralization and geological structures were introduced in 1950s (Adib et al., 2017; Nabilou et al., 2018). Airborne geophysical data are useful instruments to determine structures especially basement faults (Safari et al., 2016; Ahmadfaraj et al., 2019). To explore the relationship between structures, several mathematical methods specifically fractal modeling are widely adopted (e.g., Agard et al., 2005; Safari et al., 2016; Adib et al., 2017; Nabilou et al., 2018; Ahmadfaraj et al., 2019). Distribution and dispersion of elements rely on geological features such as magmatic rocks, sedimentation, structures (e.g., faults), metamorphism and mineralization. These have self-similarity characteristics, so they can be explained by fractal/multifractal methodology (Mandelbrot, 1983; Turcotte, 1986; Meng and Zhao, 1991; Li et al., 2003; Agterberg, 2012; Daneshvar Saein et al., 2012; Afzal et al., 2014, 2015, 2017; Khalajmasoumi et al., 2016; Yasrebi and Hezarkhani, 2019; Kouhestani et al., 2019; Pourgholam et al., 2021). These studies have found a meaningful correlation between geological (e.g., geochemical, geophysical) and geometrical properties (Cheng et al., 1994; Hassanpour and Afzal, 2013; Karami and Afzal, 2015; Nazarpour, 2018). Nouri et al. (2013) developed fractal modelling according to the relationship between main/basement faults for mineral exploration in reconnaissance stage.

The current research aims to scrutinize the relationship between faults especially basement faults with Fe, Cu and REEs mineralization in the 1: 100,000 Tarom sheet (NW Iran). These occurrences/deposits were classified based on their distance to NW basement faults (first generation of faults) by Concentration-Distance to Magnetic Faults (C-DMF) fractal model. In this research, faults are extracted from the airborne geophysical data and field observations.

Geological Setting

The Alpine-Himalayan folded belt is divided into two branches including Alborz-Azerbaijan structural zone in the north and Zagros mountains at the south and southwest as a result of the closure of Tethys Ocean with the E-W trending in Iran Plateau (Davoudzadeh and Schmidt, 1984; Sengör, 1984). The western part of Alborz-Azerbaijan structural zone with WNW-ESE trending was distinguished by Cenozoic magmatic activities in Alpine-Himalayan folded belt (Berberian and King, 1981). This region was formed in tectonic conditions of magmatic and back arcs (Allen et al., 2003; Nabatian et al., 2014a; Tahmasbi et al., 2016; Wan et al., 2018).

There is magnetite-apatite mineralization which was originated from quartzmonzonite magma in relationship with the closure of Neo-Tethys Ocean (Fig. 1) and also Tarom batholith (Nabatian et al., 2014a,

2015; Mokhtari et al., 2018). Based on the geological map (Fig. 2), the deposits of Sorkheh-Dizaj, Ali Abad, Morvarid, Zaker, Golestan Abad deposits and their connection with some geological units and intrusive masses have been identified. The main intrusive masses at this area are composed of quartz monzonite to quartz monzodiorite and the coarse crystals with porphyritic texture including plagioclase, pyroxene and quartz. The minor minerals of these intrusive rocks are comprised of magnetite, zircon, apatite and sphene. Circulation of hydrothermal solutions or fluids into these intrusive masses have led to mineralogical changes including the conversion of plagioclase to clay minerals, sericite, epidote, and calcite.

The Tarom region (NW Iran) comprises of the metallic mines and deposits specially Cu, Fe, Pb, Zn, REEs with hydrothermal genesis (Mokhtari et al., 2018). These deposits (e.g., Morvarid and Sorkheh-Dizaj) are in metallogenic region with Late Eocene magmatic and volcano sedimentary host rocks (Nabatian et al., 2014). In Tarom region,

Figure 1. Sanandaj-Sirjan zone (yellow shading) within the broader Alpine-Himalayan collision zone (inset) and location of Paleotethyan and Neotethyan sutures (thick dashed lines), major boundaries of continental fragments (thin dashed lines), and ophiolite bodies (colored areas). Abbreviations: QR, Qezel Ozan Sefidrud River; ZR, Zayandehrud River; HR, Halilrud River; GD, Gavkhooni depression; and JD, Jazmurian depression (Hassanzadeh and Wernicke, 2016).

Fe, Cu and REEs mineralization has hydrothermal source such as the Fe-Cu-REEs deposits of the world (Nabatian et al., 2017).

Tarom area (Fig. 2) is located in the eastern Zanjan district, NW Iran. There are polymetallic deposits specifically Fe, Cu and REEs (Nouri et al., 2013) which are part of the Tarom polymetallic zone as part of the Alpine-Himalayan Mountain Range. There are two great intrusive masses, volcanic rocks and other small outcrops with basic, acidic and intermediate compositions. Moreover, large granitic and granodioritic bodies intruded into the Eocene rocks. They represent intrusive bodies of the Pyrenean orogeny phase which intruded along the deep direction of NW-SE major fault zones in the Tarom mountain range (Fig. 2). There is sub-volcanic intrusions with silicification, argillic, propylitic and sericitic alteration zones. The altered intrusions contain Cu, BP, Zn, Au, Ag and Fe ore minerals such as chalcopyrite, chalcocite, malachite, magnetite, galena and sphalerite. Mineralized

Cu veins including malachite, chalcocite, bornite and azurite occur in Eocene ignimbrites and tuffs which have similar trends to the major faults in the area, especially NNW-SSE (Azizi et al., 2010).

Mineralization of the iron oxide-apatite of the region mostly occurs in the form of veins within the intrusive mass of quartz monzonite to quartz monzodiorite, and to a lesser extent within the volcanic rocks of Eocene. Mineralization is detected in the NE-SW and E-W directions, and follows the faults extensions. In these deposits, mineralization embraces magnetite, apatite, monazite, and to a lesser extent pyrite, chalcopyrite and bornite, and still to a lesser extent mineral, e.g., ilmenite and spinel magnetite. There are many metallic mines/deposits such as Sorkh-Dizaj, Ali Abad, Morvarid, Zaker and their relationship are displayed in Fig. 2. The major intrusive rock is microquartz diorite/monzonite as the main host rock of metallic ores especially in Morvarid deposit (Fig. 3; Nabatian and Ghaderi, 2014).

Figure 3. Mineralization of apatite iron ore within monzogranite to syenogranite and creation of economic reserve of iron and rare earth elements in Morvarid mine in Tarom belt of Zanzan.

In the study area, magnetite-apatite ores were formed as veins in intrusive rocks. The mineralogy of these deposits contains magnetite, apatite, monazite, actinolite, pyroxene, quartz, calcite and a little sulfidic mineralization such as pyrite, chalcocopyrite and bornite. The trends of faults in the study area are NE-SW and NW-SE (Figs. 2 and 3). The mechanism of all of the faults related to the deposits (based on this research) are reverse/thrust (Nouri et al., 2013). Allen et al. (2003) and Guest et al. (2006) specified that the faults of western Alborz are sinistral strike slip such as Ipack, North Ghazvin and Roudbar faults (Fig. 4). On the other hand, most faults in the Zanzan region are dextral strike slip. Based on their intersections, there are several blocks in the form of wedges. Furthermore, there are short variations of crust's form due to the measurement of velocities (Vernant et al., 2004) and low values of seismic activities in Zanzan region (Tatar and Hatzfeld, 2009). The main faults in relationship with seismic, unconformities and mineralization activities are Soltanieh, Dizaj Abad and Morvarid faults (Solaymani et al., 2011).

The Soltanieh fault, as a strike slip fault, is more than 222 km between Abhar and Zanzan. The main feature form of this fault is the movement of Quaternary alluviums potentially responsible for the massive earthquake in 1803 (Berberian, 1983). The Morvarid fault is a strike slip fault of 20 km length and NNE-SW trending, and cross-cut drainages to the left direction and other Quaternary features (Figs. 4 and 5).

Materials and Method

Petrography and Ore Microscopy

Field studies, petrography, ore microscopy, electron microprobe analysis (EMPA), ICP-MS, XRD and XRF are used to analyze the samples of the Tarom granitoides and mines. The analysis of minerals was performed by means of Philips-Xpert Pro XRD machine, and we

Figure 4. Active and Quaternary faults in the Zanzan Region (Solaymani et al., 2011).

have used Leo 1450 Vp Scanning Electron Microscope (SEM), and electron-probe microanalysis CAMECA EPMA (SX 100 model) to help identify minerals by their composition. Considering the mineralogy and ore microscopy studies, the most abundant minerals are magnetite (30–40%), plagioclase (30–35%), quartz and apatite (10–15%), phlogopite (3–7%), chlorite (2–4%), zeolite (2–4%), and calcite (about 2%). hematite, goethite, and lepidocrocite are an iron-bearing oxide and hydroxide minerals. They are also formed with a frequency of 2–4% due to magnetite and pyrite modification: pyrite (about 2%), covellite and sphalerite (less than 1%). Monazite is also found in small amounts in the form of fluid inclusions in quartz and apatite (Fig. 6).

Aeromagnetic Data and Reductions

The key component of this study is the image enhancement of the existing aeromagnetic datasets acquired by the Geological Survey of Iran (GSI) in 2011. Aeromagnetic surveys were flown with a flight height of 150 m and a nominal flight line spacing of 500 m in direction NE-SW, perpendicular to the dominant trend of geology in the

area. After applying the preliminary corrections of the measurements, the observed geomagnetic data was corrected using diurnal variations. To obtain magnetic anomalies associated with local magnetic variations of rocks, it is necessary to remove the normal geomagnetic field of the study area from the data. The normal geomagnetic field used for the reduction was the International Geomagnetic Reference Field (IGRF) computed by GEOMAG program.

Magnetic Fault Extraction

The airborne magneto metric data were practiced to delineate the subsurface structures of the Tarom area. This geophysical approach is the Analytic signal filter to demonstrate linear structures. This filter is incorporated with the “shaded relief image”.

There are a number of approaches that involve working with quantities and calculations from the observed magnetic and gravity data. Additionally, they do not heavily rely on the magnetization direction. The best-known approach of this type is the analytic signal concept (Nabighian, 1972). Evidently, the vertical derivative of the magnetic

Figure 5. Sinistral cross-cut drainages and Quaternary features by Morvarid fault (Google Earth, 2015).

Figure 6. Petrography of samples at different scales (SEM-BSE images): (A) Magnetite and hematite are involved by gang, pyrite is replaced by goethite (+150–300) microns; (B) photo micrograph of plagioclase, quartz, apatite, calcite, zeolite, phlogopite and chlorite (+150–300) microns; (C) gang minerals specially quartz, plagioclase, phlogopite, lepidocrocite, as well as monazite involvement in apatite (+75–150) microns; (D) Existence of free magnetite and hematite in Sample (–75) microns. Mag = magnetite; Hem = hematite; Cal = calcite; Qtz = quartz; Phl = phlogopite; Pl = plagioclase; Ap = apatite; Zeo = zeolite; Mon = monazite; Cal = calcite; Lep = lepidocrocite; Gan = gang.

and gravity field can be calculated from the horizontal derivative by the Hilbert transform, denoted as H . It is subjected to a fast and accurate method of computing the vertical derivative from a given magnetic or gravity profile.

$$\partial M / \partial z = H[\partial M / \partial x] \quad (1)$$

where M is the magnetic or gravity anomaly data. Furthermore, these two quantities can be combined into a two-dimensional quantity known

as the Analytic Signal (AS):

$$AS(x, z) = \partial M / \partial x + i \partial M / \partial z \quad (2)$$

where i denotes imaginary number. The amplitude of the analytic signal is defined as:

$$|AS(z)| = \sqrt{(\partial M / \partial x)^2 + (\partial M / \partial z)^2} \quad (3)$$

The amplitude of the analytic signal is a symmetric bell-shaped function (Hsu et al., 1998; Ansari and Alamdar, 2010). By examining its profile across a magnetic source, the analytic signal can be used to show the edges of the causative body. Similarly, for the 3-D case, the analytic signal is given by Blakely (1996):

$$AS(x, y) = (\partial M / \partial x) + (\partial M / \partial y) + i(\partial M / \partial z) \quad (4)$$

where its amplitude is defined as

$$|AS(x, y)| = \sqrt{(\partial M / \partial x)^2 + (\partial M / \partial y)^2 + (\partial M / \partial z)^2} \quad (5)$$

As aforementioned, the maximum value of the analytic signal determines the edges of a magnetic or gravity body. However, the use of analytic signal in the 3-D case seems insufficient to detect geologic boundaries for the sake of the interference effects from adjacent causative bodies. Under these conditions, the detected edges from the bodies are not detachable. Since the existing interference condition in many cases is not negligible, the enhancement of its resolution or using other replacement techniques becomes important.

Subsequently, the results of that are used to build a structural model to help understand the subsurface structure of the study area. Hence, the structure of basement faults is extracted from airborne magneto-metric map (Fig. 7). The rose diagram is generated based on the extracted basement faults and the trend of faults is NW-SE, as presented in Fig. 8b. The main trend of the basement faults is correlated with major trends of other types of faults especially active and Quaternary faults as shown in Fig. 4.

Figure 7. The magnetic maps based on airborne magnetic data with the "Analytic signal" filter in 1:100,000 Tarom area.

Figure 8. a) The basement faults map which are detected from Analytic signal magnetic data (Fig. 6); b) magnetic basement faults map and its rose diagram.

C-DMF Fractal Model

The methods based on fractal geometry in geological sciences are applied to analyze the intricate forms of geological features, especially in the branch of structural geology. Fractal analysis is also useful to characterize and separate the geochemical and mineralized populations, particularly in economic geology, mineral exploration and geophysics (Cheng, 1999; Carranza, 2008; Afzal et al., 2014). The principles of these methods are the reverse relationship between occupied geometrical spaces (perimeter, area, volume or distance to a geological

event) and the regionalized variables (e.g., elemental concentration; Khalajmasoumi et al., 2016; Afzal et al., 2017). This model has the following equation (based on Nouri et al., 2013):

$$\text{DBF} (\geq \rho) \propto F\rho^{-D} \quad (6)$$

As observed in the equation, the basement faults extracted from magnetic map. ρ and D show elemental concentration and fractal dimension in equation 1. In this research, it is used as a Concentration-Distance to Magnetic Faults (C-DMF) fractal method.

Figure 9. The C-DMF fractal modeling for relationship between Fe mines/deposits and the magnetic basement faults.

Results and Discussion

As a result of the C-DMF model, Fe, Cu and REEs mineralization were classified according to their distance to faults. This modeling includes the log-log plots as display in Figs. 9, 10 and 11. Tables 1–3 demonstrates the components of this model. The faults that play an important role in the Fe, Cu and REEs mineralization includes the

Tarom-MF1, Tarom-MF2, Tarom-MF3, Tarom-MF4, Tarom-MF5, and Tarom-MF6. Based on Fig. 9, it can be seen that Fe concentrations in mine/deposits increase close to the faults. The Fe, Cu and REEs concentrations were classified by the C-DMF models as depicted in Figs. 9, 10 and 11, and Tables 1–3. There are four populations for Fe and Cu and three populations for REEs. Main ore mineralization thresholds for Fe, Cu and REEs are 48.41%, 3.8% and 946.71 ppm, respectively.

Figure 10. The C-DMF fractal modeling for the relationship between Cu mines/deposits and the magnetic basement faults.

Figure 11. The C-DMF fractal modeling for relationship between REEs mines/deposits and the magnetic basement fault. This model contains of logarithmic fractal diagram and the symbol map with the color-scheme based on that.

Chooorenab mine has Fe average equal to 50% (Table 1) which has the highest distance (1181 m) and Morvarid3 mine with Fe mean=42.4% which has the lowest distance (44 m) to the TAROM-MF1 fault. The distance of Shah Bolugh mine with Fe an average of 34% to the TAROM-MF3 fault is 1060 m. The distance of Gozal Dareh (Fe mean=42.1%) to the TAROM-MF4 fault is 624 m. Chorzagh mine with an average of Fe equal to 40.8% has the longest distance (1591 m) and Ghinarjeh mine with Fe 44% ore average grade which has the shortest distance (730 m) to the TAROM-MF5 fault. The highest value of Fe (59.4%) is related to Golestan Abad mine (Table 1), whose distance to TAROM-MF1 fault is 253 m. Also, the lowest value of Fe (59.4%) in Table 1 is related to Shah Bolugh mine whose distance to Tarom-MF3 fault is 1060 m. Mechanisms of nearest Fault to all mines/deposits are reverse/thrust (Nouri et al., 2013).

With respective averages of 5% and 2%, Amir Abad and Ganjineh

Zarrin mines have the longest distance (732 m) and shortest distance (521 m) to the TAROM-MF1 fault, respectively (Table 2). In addition, Geligeh mine with Cu mean equal to 2.2% has the longest distance (1278 m; Table 2) to this fault. Furthermore, the Tarom Anomaly mine with Cu 5.6% has the shortest distance (621 m) to the TAROM-MF2 fault. Yahya Abad and Valider mines have Cu mean equal to 0.9% and 9%, respectively, and have the corresponding longest distance (4131 m) and shortest distance (621 m) to the TAROM-MF3 fault. The distance of Qeshlaq mine with Cu 2.1% to the TAROM-MF4 fault is 1690 m. Shilandar mine with Cu 1.8% has the longest distance (2746 m) and Kale Kash mine with Cu 3.4% has shortest distance (1523 m) to the TAROM-MF5 fault. The distance of Sorkh mine with Cu 1.2% to the TAROM-MF6 fault is 224 m.

The highest value of Cu (9%) in Table 2 is related to Valider mine, whose distance to TAROM-MF3 fault is 278 m. Furthermore, the

Table 1. Concentration-Distance to Magnetic Faults (C-DMF) model components for Fe

Deposite/Mine Name	Fe (%)	Distance to fault (m)	The nearest fault	Population in log-log plot
Sorkheh Dizaj	50	628	Tarom-MF1	Black
Morvarid3	42.4	44	Tarom-MF1	Green
Zaker	43	55	Tarom-MF1	Red
Choorenab	50	1181	Tarom-MF1	Black
Golestan Abad	59.4	253	Tarom-MF1	Black
Ali Abad	58.3	145	Tarom-MF1	Black
Morvarid	48.5	918	Tarom-MF1	Black
Sorkheh Dizaj2	48.4	451	Tarom-MF1	Red
Shah Bolugh	34	1060	Tarom-MF3	Blue
Gozal Dareh	42.1	624	Tarom-MF4	Green
Chorzagh	40.8	1591	Tarom-MF5	Blue
Ghinarjeh	44	730	Tarom-MF5	Red

Table 2. Concentration-Distance to Magnetic Faults (C-DMF) model components for Cu

Deposite/Mine Name	CU %	Distance to fault (m)	The nearest fault	Fractal population	References for each mines/deposits
Amir Abad	5	732	Tarom-MF1	Black	(Ganji, 2005)
Ganjineh Zarrin	2	521	Tarom-MF1	Green	Ganji, 2005)
Tarom Anomaly	5.6	621	Tarom-MF2	Black	(Nazarinia et al., 2011)
Geligh	2.2	1278	Tarom-MF2	Green	(Nazarinia et al., 2011)
Kuhian	1	555	Tarom-MF3	Blue	(Nouri et al., 2013)
Nughl Abad	2	779	Tarom-MF3	Green	(Nouri et al., 2013)
Valider	9	278	Tarom-MF3	Black	(Ganji, 2005)
Lahneh	1.8	933	Tarom-MF3	Blue	(Ganji, 2005)
Yahya Abad	0.9	4131	Tarom-MF3	Blue	(Nazarinia et al., 2011)
Qeshlaq	2.1	1690	Tarom-MF4	Green	(Nazarinia et al., 2011)
Kale Kash	3.4	1523	Tarom-MF5	Red	(Nazarinia et al., 2011)
Shilandar	1.8	2746	Tarom-MF5	Blue	(Nouri et al., 2013)
Sorkh	1.2	224	Tarom-MF6	Blue	(Nouri et al., 2013)

Table 3. Concentration-Distance to Magnetic Faults (C-DMF) model components for REEs

Deposite/Mine Name	REEs ppm	Distance to fault (m)	fractal population	Mine/Deposit References
Ali Abad	1257	108	Black	(Korei et al., 2016)
Zarnan	511.3	1174	Blue	(Korei et al., 2016)
Choorenab	775.1	1186	Blue	(Korei et al., 2016)
Golestan Abad	928.7	315	Red	(Korei et al., 2016)
Zaker	946.7	30	Red	
Morvarid	1201	49	Black	
Esmail Abad	1950	160	Black	
Sorkheh Dizaj	1143	86	Black	

lowest value of Cu (0.9%) in this table is related to Yahya Abad mine, with its distance to Tarom-MF3 fault as 4131 m. The Choorenab mine with an average value of REES as 775.1 ppm has the longest distance (1186 m) and Zaker with the value of REES 946.7 ppm has the shortest distance (30 m) to the TAROM-MF1 fault (Table 3).

The highest value of REEs (1950 ppm) in Table 3 is related to Esmail Abad mine, with its distance to TAROM-MF1 fault being 160 m. Additionally, the lowest value of REEs (511.3 ppm) in this table is related to Zarnan mine, whose distance to Tarom-MF1 fault is 1174 m.

Based on Figs. 9, 10 and 11 and Tables 1, 2 and 3, the following results can be observed:

1) Tarom-MF1 is the nearest fault to Sorkheh-Dizaj, Sorkheh dizaj2, Morvarid, Morvarid 3, Zaker, Choorenab, Golestan Abad and Ali Abad Fe deposits.

2) Tarom-MF3 is the nearest fault to Shah Bolugh Fe deposit.

3) Tarom-MF4 is the nearest fault to Gozal Dareh Fe deposit.

4) Tarom-MF5 is the nearest fault Chorzagh, Ghinarjeh Fe deposits.

According to Fig. 10 and Table 2, it can be found that Tarom-MF1

is the nearest fault to Sorkheh Dizaj, Zaker, Choorenab, Golestan Abad, Morvarid, Esmail Abad, Zarnan and Ali Abad Cu deposits. Fig. 11 and Table 3 show Tarom-MF1 as the nearest fault to Sorkheh-Dizaj, Zaker, Choorenab, Golestan Abad, Morvarid, Esmail Abad, Zarnan and Ali Abad REEs deposits.

At this point all the distances between the deposits and the nearest fault are in Tables 1, 2 and 3. Similarly, based on C-DMF model (Fig. 9) all the distances of the high grade mineralization values to the nearest magnetic faults are less than 918 m and in the Table 1, the last population has high-grades mineralization values with grades of $48.41\% \leq \text{Fe} \leq 59.37\%$. Furthermore, as seen in Fig. 10 and Table 2, the last population with the grades between 5 and 9% for Cu, and related distances are less than 1523 m. Nevertheless, observing Fig. 11 and Table 3, we can find that the distances (to the related faults) less than 86 meter are related to REEs concentration between 946.71 and 1950 ppm as the last population. Consequently, the main REEs mineralization are located near a magnetic basement fault at SE part of the study map, as depicted in Fig. 11. In addition, the main iron ores are situated in the central and southern parts of the map Fig. 9. Major Cu deposits are located in the western, SE and NW parts of this map, as shown in Fig. 10.

Conclusion

Based on the results of this study, there is a direct relationship between increasing Fe concentration of study area deposits with extending the distance to the nearest fault, using C-DMF fractal modeling. This methodology can be used for an appropriate exploration in the other similar regions. According to the amount of Fe, Cu and REEs grades of mines, high Fe and REEs concentrations are in the south of Tarom area but the concentration of Cu is reduced from N-NW to S-SW of the study area. In this way, the high grades of Cu are located in the NW, W and centre of Tarom geology map, with the high Cu concentration and the grades 3.8–9% (except Amir Abad high-grade Cu deposit which is in the south). Likewise, the iron, copper and REEs ore deposits of study area were classified well by means of the mentioned fractal relations. Regarding the last population in C-DMF diagrams with the grades between 48.41 and 59.37% thresholds in Fe, 5 and 9% thresholds in Cu and also 946.71 and 1950 ppm thresholds in REEs, the distances are progressively smaller than 918, 1523 and 86 meters to the first generation of mantic fault (NW-SE).

Hence, the basement faults are visible on the magnetic maps according to the results of logarithmic diagrams. They have the minimum distance to high concentrations of Fe, and REEs deposits. In other words, the basement or main faults are the factor of structural controller of these deposits/mines and Cu mineralization. It was revealed by the proximity of reverse basement faults with the mine/deposits and their impact on mineralization in Late Eocene units. Occurring in the extensional fractures, mineralization was formed because of the intrusion in Late Eocene. Consequently, the continental crust became fragile due to the normal fault. Then, the lava and fluids ascended and deposited in the middle of sediments and surface by the fragile crust and extensional fractures where intrusions have occurred. These normal faults changed into the reverse faults next to the Fe, Cu and REEs mineralization after the closure of these basement faults in the next periods. Accordingly, the Fe, Cu and REEs mineralization appeared in the greatest depth and

under the wrinkled sediments with faulting. It can be inferred that mineralization has been influenced by the Eocene and Late Eocene.

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