



Geochemical anomaly recognition of rare earth elements using multi-fractal modeling correlated with geological features, Central Iran

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ABSTRACT

The aim of this paper is the geological studies and delineation of geochemical anomalies of lanthanum (La), cerium (Ce) and yttrium (Y) rare earth elements (REEs) in Saghand area, Central Iran. In order to recognize the mineralization zones considering their concentrations, the results of the sampled litho-geochemical data were processed by concentration–area (C–A) fractal model. The C–A log–log plots of the elements were generated and their thresholds were identified. Therefore, the high intensive geochemical anomalies of the studied elements were discriminated. A part of their high intensive geochemical anomalies are situated in the west of the study area occurred within the metasomatic, porphyry microdioritic and acidic volcanic rocks associated with epidotic alterations. The other high intensive geochemical anomalies of Ce and Y are located in the center of the study area. In addition, the moderate anomalies of La and Ce were located in the metasomatic units associated with epidote and chlorite alterations in the central part of the study area. The SE parts of the Ce moderate anomalies are probably related to basic dykes associating with epidotic alterations which are situated between metasomatic and microdioritic units. Based on the results obtained from multi-fractal modeling, the locations of the main anomalies of La, Ce and Y were recognized which all are in the western, central, southern, and SE parts of the study area. Several high and moderate concentration anomalies obtained from the C–A model were confirmed by ground surveying and compared with the achieved result from remote sensing investigation. According to the correlation between geological particulars and obtained REEs anomalies, it has been proved that the proper and promising areas are in metasomatite rock units, chlorite and epidote alterations in the western and central part of the study area. By Scanning Electron Microscope (SEM) studies of davidite and uraninite minerals, it was determined that the REEs mineralization in this area have taken place mostly in the form of replacement in radioactive elements uranium (U) and thorium (Th). The combination of the field observations and mineralogical studies based on the type of REEs mineralization in the study area revealed that one of the main factors controlling the mineralization is related to metasomatism.

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1. Introduction

Rare earth elements (REEs) were first discovered in 1787 when Swedish Army Lieutenant Karl Axel Arrhenius collected the black mineral ytterbite (later renamed gadolinite) from a feldspar and quartz mine near the village of Ytterby, Sweden (Weeks and Leicester, 1968). During those years, it has been proved that REEs comprise 17 elements, 15 of which are lanthanide elements, together with scandium and yttrium. These 17 REEs could be found in all REEs deposits, but their

distributions, concentrations, and other properties are varied. The elements have different ranges of crustal abundance; for example, cerium is the 25th most abundant element of the 78 common elements in the Earth's crust with 60 parts per million (ppm) whereas thulium and lutetium have the least abundance among REEs with about 0.5 ppm (Mason and Moore, 1982).

In rock-forming minerals, REEs generally occur in compounds as trivalent cations in carbonates, oxides, phosphates and silicates (Mason and Moore, 1982). REEs are classified as either “light rare earth elements” (LREEs) or “heavy rare earth elements” (HREEs). The definition of these elements is based on their electron configurations. The LREEs include lanthanum with atomic number of 57 through gadolinium with atomic number of 64, and the remaining elements comprise the

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Table 1

REEs abundance in Earth's crust, chondrite and composition of North America shales (ppm) (Haskin et al., 1968; Taylor and McLennan, 1985).

Lanthanides Group REE	Element	Symbol	Atomic number	Upper Crust Abundance (ppm)	Chondrite Abundance (ppm)	NASC (ppm)
LREE (Ce) + La	Lanthanum	La	57	30	0.34	32
	Cerium	Ce	58	64	0.91	73
	Praseodymium	Pr	59	7.1	0.121	7.9
	Neodymium	Nd	60	26	0.64	33
	Promethium	Pm	61	na	na	na
	Samarium	Sm	62	4.5	0.195	5.7
	Europium	Eu	63	0.88	0.073	1.24
	Gadolinium	Gd	64	3.8	0.26	5.2
	Terbium	Tb	65	0.64	0.047	0.85
	Dysprosium	Dy	66	3.5	0.30	4.54
HREE (Y) + Th + Sc	Holmium	Ho	67	0.80	0.078	1.04
	Erbium	Er	68	2.3	0.20	3.4
	Thulium	Tm	69	0.33	0.032	0.5
	Ytterbium	Yb	70	2.2	0.22	3.1
	Lutetium	Lu	71	0.32	0.034	0.48
	Yttrium	Y	39	22	na	na

HREEs (Table 1) (Haskin et al., 1968; Taylor and McLennan, 1985; Castor and Hedrick, 2006). Yttrium is classified in the HREEs group based on its similar ionic radius and similar chemical properties. In its trivalent case, which is similar to the other REEs, yttrium has an ionic radius of 90 pm,

while holmium has an ionic radius of 90.1 pm. Scandium is also trivalent; however, its other properties are not similar enough to classify it as either LREEs or HREEs (Mason and Moore, 1982). REEs mineral deposits are usually rich in either LREEs or HREEs; however, they rarely

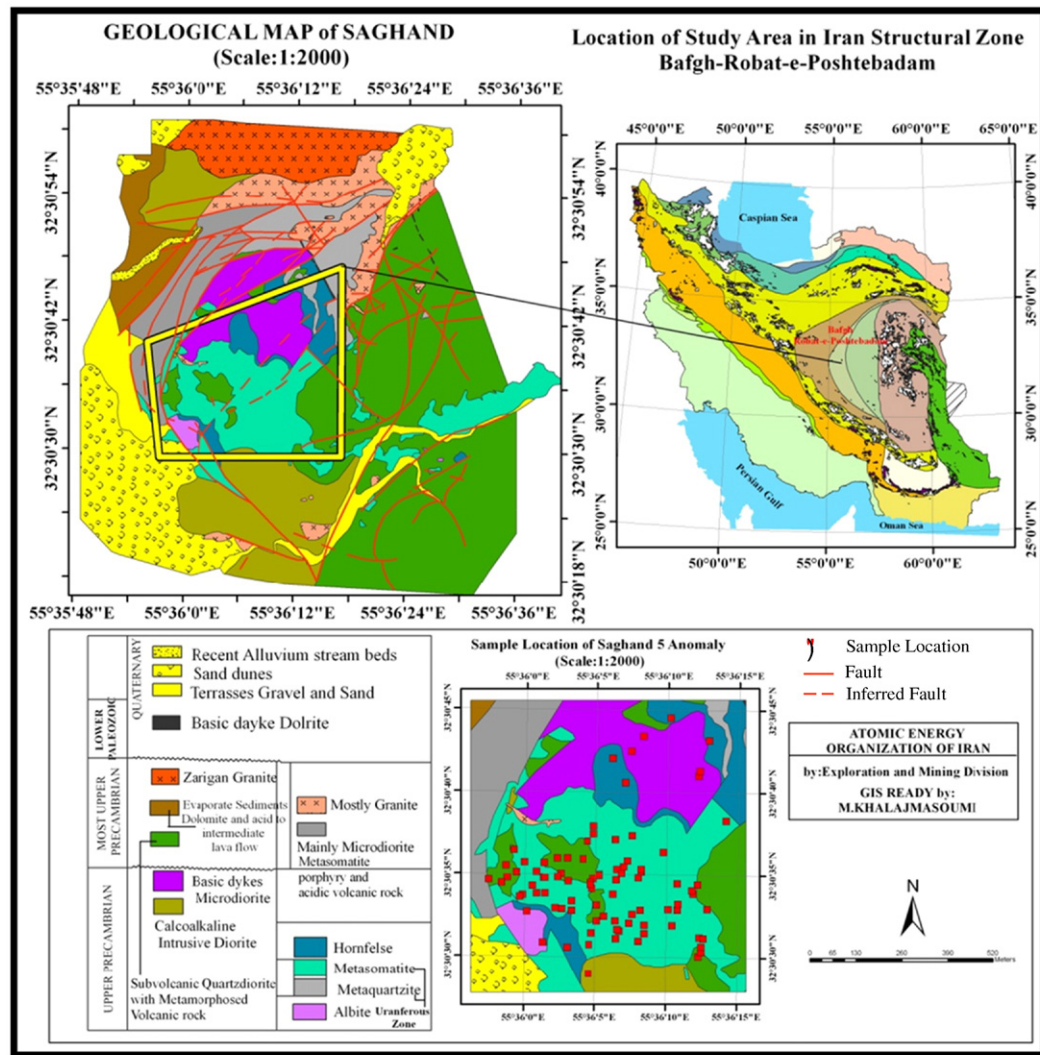


Fig. 1. Geological map and litho-geochemical sample location of the Saghand area (Scale: 1:2000) (Modified after Samani and Talezadeh Lari, 1988).

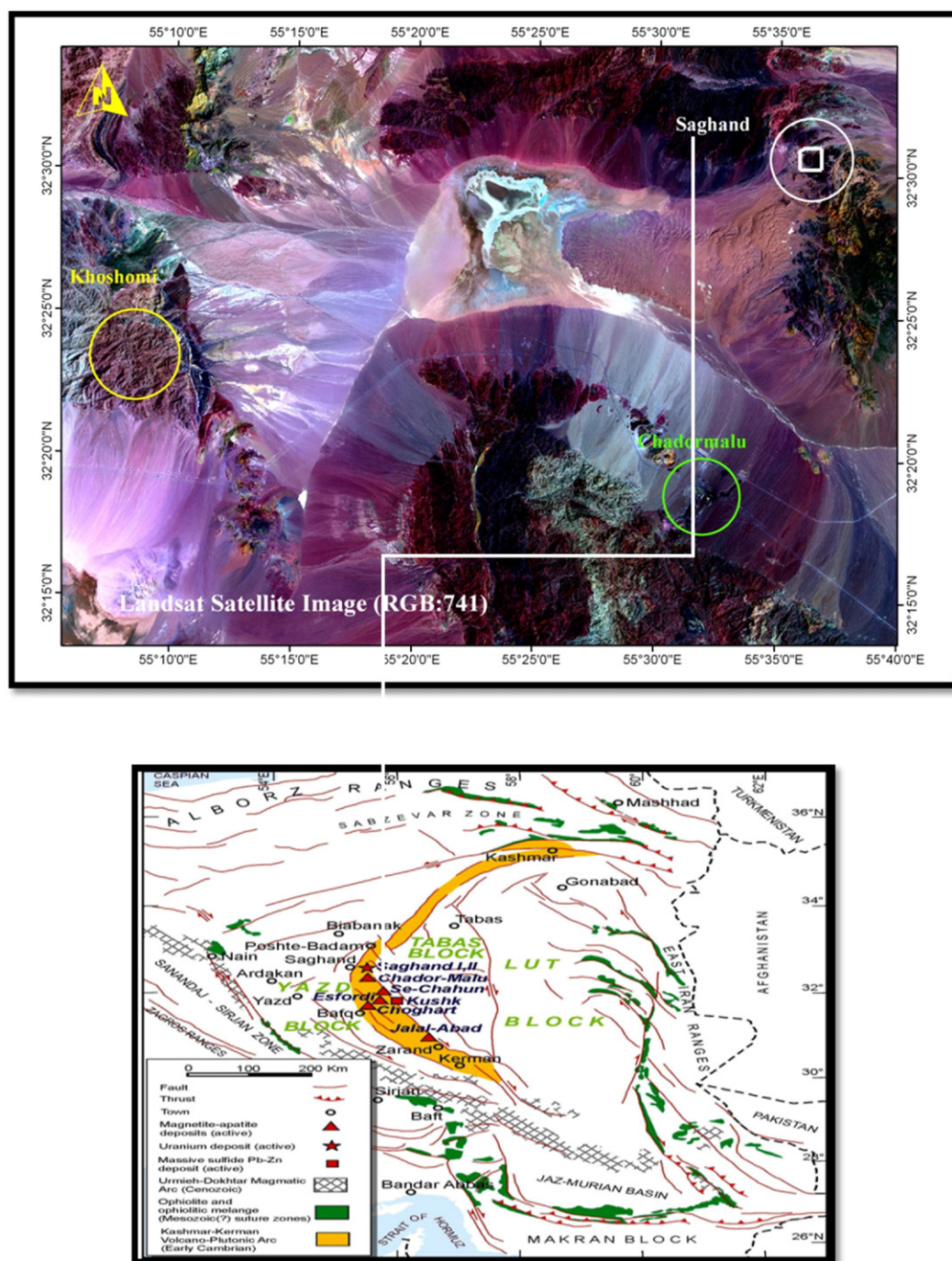


Fig 2. Location of Apatite-Fe deposits, radioactive elements, Pb-Zn massive sulfide in Bafq Robat-e-Posht-e-Badam block and Saghand area for REEs (Ramezani and Tucker, 2003).

contain both groups in significant quantities (Castor and Hedrick, 2006; Jonsson et al., 2014).

In Central Iran, there are Precambrian complexes consisting U, Th, V, Mn, Mo, Ti, Ba, apatite, REEs, stratiform Pb-Zn massive sulfides and different types of Fe ores (Samani, 1988; Förster and Jafarzadeh, 1994; Daliran and Stosch, 2005; Jami, 2005; Jami et al., 2007; Bonyadi et al., 2011). There are 70 occurrences of magnetite-apatite type mineralizations in Bafq-Robat-e-Posht-e-Badam area, located in Central Iran. There are also several REEs occurrences associated with magnetite-apatite (Chadormaloo and Lakeh Siah), phosphate (Esfordi and Gazestan) and placer monazite (Marvast) (Ramezani, 1997; Rahmani

and Mokhtari, 2003; Ghorbani, 2012b). Some of the average concentrations of magnetite-apatite and phosphate related to REEs in Central Iran are 1.27–1.65% in Esfordi, 1.15–1.57% in Gazestan, 0.56–1.85% in Lakeh Siah, 0.78–1.15% in Zarigan and 0.05–0.08% in Chah Gaz (Rahmani and Mokhtari (2003).

In recognition of geochemical anomalies, many research works have been published based on traditional mathematical and statistical methods (e.g., Ahrens, 1966; Tukey, 1977; Kürzl, 1988); however, it has been proved that these kinds of methods have some significant limitations in anomaly recognition (Cheng et al., 1994; Li et al., 2003; Carranza, 2009; Afzal et al., 2010; Hassanpour and Afzal, 2013; Heidari

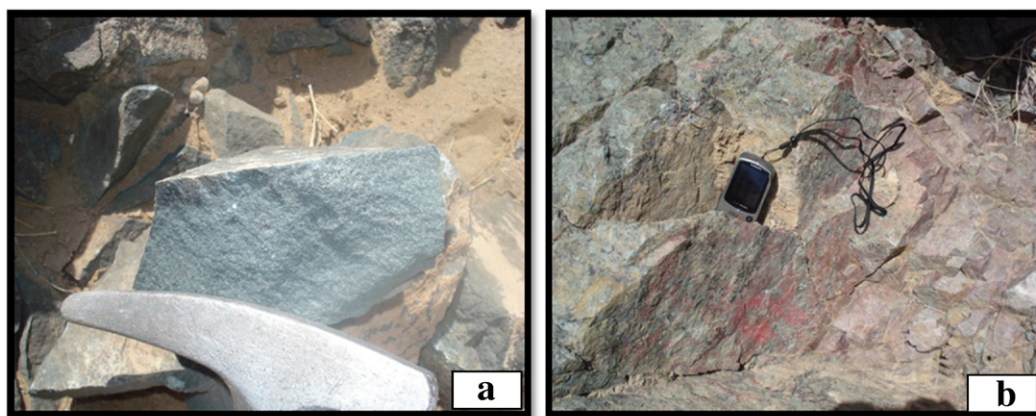


Fig. 3. Amphibole metasomatite rocks associated with alkaline magmatism phenomena and metasomatism in the Saghand area (a), albite-amphibole metasomatite (b).

et al., 2013; Nazarpour et al., 2014a, 2014b). In addition, these methods are based on the assumption of normal (Gaussian) or log-normal distribution of geochemical data (Armstrong and Boufassa, 1988; Limpert et al., 2001; Sadeghi et al., 2015). However, it has been shown that in many cases that geochemical data do not have normal or log-normal distributions (Razumovsky, 1940; Ahrens, 1954a, 1954b, 1966; Reimann and Filzmoser, 2000; Li et al., 2003; Bai et al., 2010; He et al., 2013; Luz et al., 2014; Sadeghi et al., 2015). As a result, other mathematical/statistical methods like fractal modeling have been proposed in recent years.

Mandelbrot (1983) proposed fractal geometry as a kind of non-linear mathematics, and it has been widely applied in the geosciences (Turcotte, 1986; Agterberg et al., 1993; Cheng et al., 1994; Zuo and Wang, 2016; Zuo et al., 2016). Regarding discrimination of geochemical anomalies from the background, several methods based on the concept of fractal have been proposed, such as concentration–area (C–A) fractal model (Cheng et al., 1994), spectrum–area (S–A) fractal model (Cheng, 2000), concentration–distance (C–D) fractal model (Li et al., 2003), singularity index (Cheng, 2007), concentration–volume (C–V) fractal model (Afzal et al., 2011), number–size (N–S) fractal model by Mandelbrot (1983) and its 3D form (Sadeghi et al., 2012b), and simulated size–number (SS–N) fractal model (Sadeghi et al., 2015). Geochemical dispersion patterns have fractal dimensions because they have similar qualities in different sizes, from microscopic to continental scales (Bolvik et al., 1992; Cheng et al., 1994; Davis, 2002; Li et al., 2003; Afzal et al., 2010; Bai et al., 2010; Sadeghi et al., 2012b; Arias et al., 2012; Heidari et al., 2013; Nazarpour et al., 2014a, 2014b). In addition, fractal/multi-fractal modeling has been used for delineation and description of relations among mineralogical, geochemical and

geological features based on surface and subsurface data (e.g., Evertz and Mandelbrot, 1992; Goncalves et al., 2001; Carranza, 2009; Carranza et al., 2009; Zuo et al., 2009, 2012; Afzal et al., 2011; Carranza and Sadeghi, 2012; Delavar et al., 2012; Sadeghi et al., 2012a, 2012b; Heidari et al., 2013; Sadeghi et al., 2015; Mohammadi Gonabadi et al., 2015). Fractal/multi-fractal models consist of the frequency distribution and the spatial self-similar or self-affine characteristics of geochemical variables and have been demonstrated to be effective tools for decomposing geological complexes and mixed geochemical populations and to recognize weak geochemical anomalies hidden within strong geochemical background (Cheng, 2007; Cheng and Agterberg, 2009). Multi-fractals are spatially intertwined mono-fractals with a continuous spectrum of fractal dimensions (Feder, 1988; Stanley and Meakin, 1988; Agterberg et al., 1996; Cheng and Agterberg, 1996; Cheng, 1999; Agterberg, 2001). Whereas mono-fractals are characterized by one fractal dimension, applied for binary patterns, multi-fractals have different fractal dimensions and they are applied in generating patterns with continuous spatial variability (Agterberg et al., 1994; Agterberg, 2001). Fractal geometry is based on the property of self-similarity, and the spatial variability of each feature is independent of the scale (Cheng et al., 1994). Multi-fractal theory may be interpreted as a theoretical framework that describes the power-law relations between areas enclosing concentrations. To show and prove if data distribution has a multi-fractal nature, a rather extensive computation is required (e.g., Evertz and Mandelbrot, 1992; Lima et al., 2003; Afzal et al., 2010, 2011; Heidari et al., 2013).

The main aim of this paper is to recognize and delineate different geochemical mineralization phases of three REEs, including La, Ce and Y in the Saghand area. The REEs mineralization is related the metasomatism. It is obvious that the mineralization of the radioactive elements and REEs in this area have taken place mostly in the form of replacement in the radioactive minerals

We analyzed all the REEs (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu and Y) by inductively coupled plasma optical emission spectrometry (ICP-OES) (the units of the measurement are ppm) in the study area, but in Central Iran (especially Bafq-Robat-e-Posht-e-Badam block) the LREEs concentrations are higher than the concentrations of HREEs; so, considering the above-mentioned points and to shorten the manuscript, three significant elements in the study area were selected for processing based on the expert's opinion. The REEs geochemical anomalies in this study, including La, Ce and Y, were distinguished using the C–A fractal model, based on the thresholds obtained from the C–A log-log plots. In order to correlate generated multi-fractal geochemical anomaly models and the geological features related to REEs in the study area, the geological map, ASTER satellite images (for

Table 2
Main statistical parameters of La, Ce and Y litho-geochemical values (ppm).

Parameters	Ce	La	Y
Samples	91 samples	91 samples	91 samples
Mean	636.0	667.4	618.9
Variance	353,606.4	435,540.8	338,711.9
SD	594.6	659.9	581.9
CV	0.9	0.9	0.9
Skewness	3.2	3.4	3.4
Kurtosis	14.0	16.4	14.2
Min	31.9	31.9	34.4
Max	4095	4734	3755
Median	498.2	524	465.3

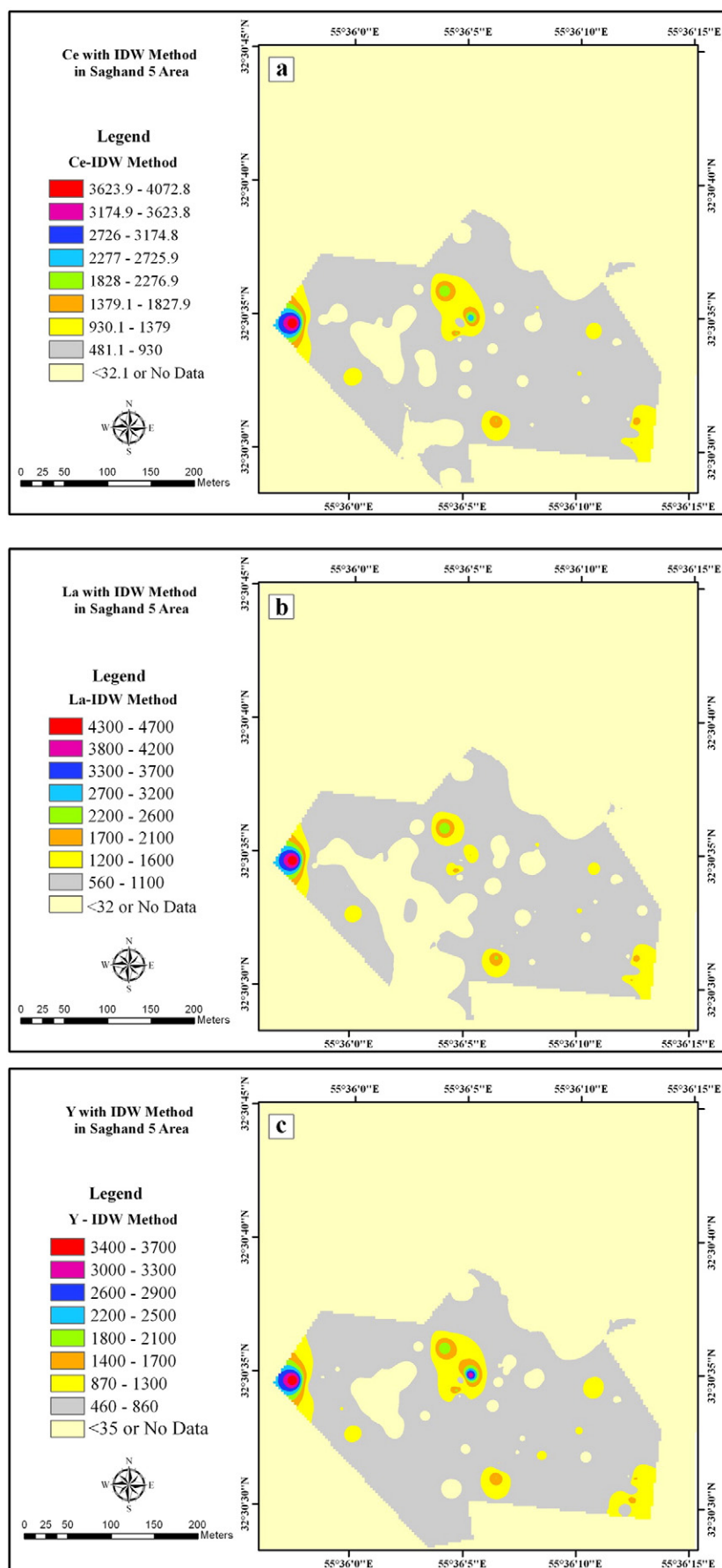


Fig. 4. The Geochemical maps of Ce (a), La (b) and Y (c) generated using the inverse distance weighted (IDW) in the Saghand area (Central Iran).

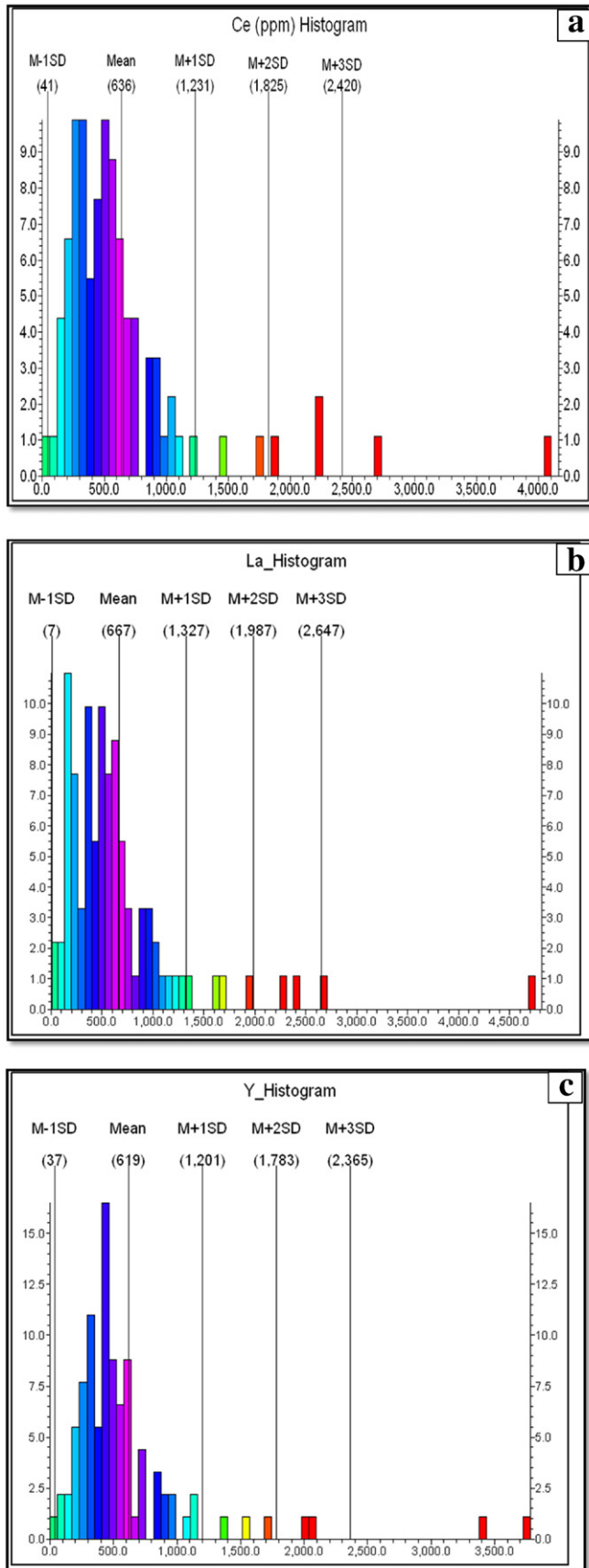


Fig. 5. Histogram of Ce (a), La (b) and Y (c) in litho-geochemical samples from the study area of Saghand, Central Iran.

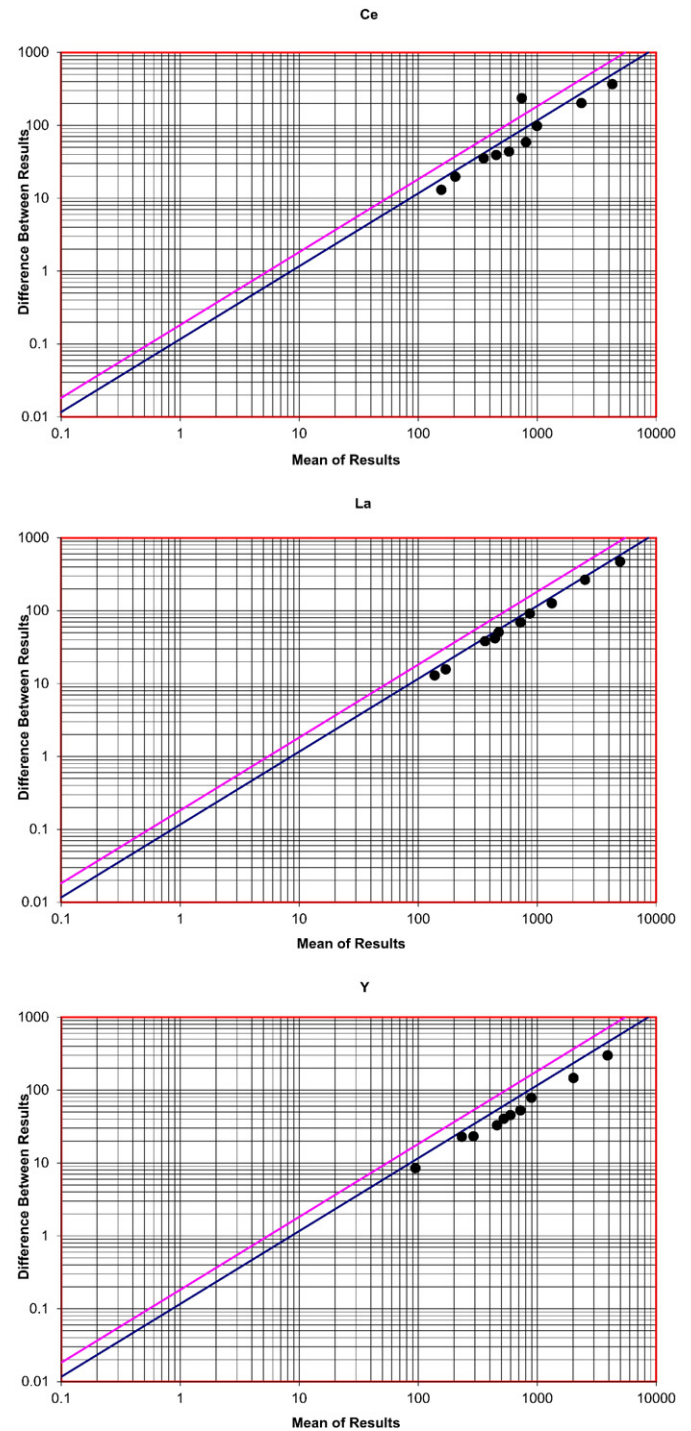


Fig. 6. The Thompson and Howarth diagram of Ce (a), La (b) and Y (c) in the Saghand area (Central Iran).

recognizing epidotization, chloritization, hematization and the other related alterations), petrographical and SEM data were applied.

2. Geological setting of the Saghand area

The study area is situated in the Bafq-Robat-e-Posht-e-Badam metallogenic belt in the Central Iran structural zone (Fig. 1) which is located 20 km of the south of Chadormaloo iron mine. In this district, there are some concentrations of REEs related to REEs-bearing iron-apatite ores such as Choghart, magnetite-apatite ores such as

Table 3

Average computational errors for Ce, La and Y in Saghand area, Central Iran.

Ce	La	Y	Ce-Duplicate	Error Value-Ce	La-Duplicate	Error Value-La	Y-Duplicate	Error Value-Y
4095	4734	3755	4463	8.600	5207	9.516	4055	7.682
2253	2657	2090	2456	8.601	2391	10.543	1943	7.283
1045	1264	854	947	9.868	1391	9.547	933	8.809
834	912	749	775	7.319	821	10.555	696	7.314
625	689	503	861	31.832	758	9.562	543	7.744
558	500	573	602	7.554	449	10.739	618	7.639
433	421	476	472	8.672	463	9.487	443	7.183
338	383	280	373	9.966	345	10.495	303	7.981
215	162	244	195	9.669	178	9.230	221	9.856
150	144	90	163	8.345	131	9.434	99	8.977
Error Mean of Elements				8.733		9.911		8.047

Chadormaloo and apatite-magnetite ores such as Esfordi. REEs minerals in REEs-bearing fluoroapatite or monazite are the reason for the REEs concentration within the magnetite mineralization in the Central Iran structural zone (Samani, 1988; Ramezani, 1997; Ramezani and Tucker, 2003; Fig. 2).

Based on the 1:2000 scale geological map of Saghand, the Saghand area consists of the Precambrian Beneshour complex, Tashk 1 and 2 formations, Riso infra-Cambrian formation and Zarigan granite related to late infra-Cambrian. The reported ages of the Beneshour complex and Tashk 1 and 2 formations are 544 ± 7 , 533 and 627 million years, respectively, based on U-Pb dating (Ramezani and Tucker, 2003). The Saghand area is underlain by a complex of pyroclastic rocks containing magnetite layers (Samani and Talezadeh Lari, 1988; Fig. 1). There are layers of pyroclastic tuff, shale and sandstone in the NW part of the area in addition to diabasic dykes in the complex. There are also some layers of cherty red iron rocks and hematite-magnetite with various thicknesses. Subvolcanic quartz-diorite with metamorphosed volcanic rocks underlies the NE part of the area. In the central part of the area, there are metasomatic rocks, calc-alkaline intrusives, diorite, albite and hornfels. Granitic and microdioritic rocks occur in the northern parts of the area (Samani and Talezadeh Lari, 1988).

The REEs-bearing mineralizations occur in the different rock types and ore-minerals in the area. The REEs deposits were generated by some forms of metasomatism, as they especially occur in metasomatic rock units. The substitution of radioactive ores has been metasomatized in the study area (Samani and Talezadeh Lari, 1988). Alkaline magmatism and metasomatism have progressively caused primary rocks in the area to be altered into metasomatic rocks, including amphibole-albite metasomatite, albitite and amphibole metasomatite (Figs. 1 and 3). Normally, REEs-bearing minerals form as inclusion or separate minerals within allanite, monazite or xenotime; but there are some REEs-bearing minerals containing Th and U such as davidite and uraninite minerals, such as this study area. In the study area, REEs have taken place in radioactive minerals (davidite and uraninite) in the Saghand metasomatized rocks. In this area, metasomatism is more than amphibolization and albitization (Samani and Talezadeh Lari, 1988; Fig. 3). The age of uranium mineralization in this area is about 500–550 million years (Samani, 1988).

3. Litho-geochemical data analysis and quality control

The Saghand study area is about 1 km². Geochemical sampling was done in this area using unsystematic sampling methods for identifying the REEs geochemical anomalies in the study area, with a view of the morphology of the area, the fault systems and the rock units in the region. At first, the network of sampling was designed systematically (six profiles on systematic sampling intervals of 100 m), but the sampling points were located in the debris in which a lot of drillings and borehole were; so, we did not get systematic sampling. Finally, 91 litho-geochemical samples (Fig. 1) were taken, and only 17 elements, including La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Y and radioactive elements of U, Th were analyzed using ICP-OES method. The unit

of the measurement of these analyses for REEs is ppm. The detection limit of these elements (La, Ce and Y) is 5 ppm. The REEs geochemical anomalies in this study, including La, Ce and Y, were distinguished using the C–A fractal model. Main statistical parameters associated with the three significant REEs in the study area, i.e., La, Ce and Y, have been demonstrated in Table 2. The histograms of these elements have been shown in Fig. 4 for litho-geochemical samples from the study area. The geochemical maps were generated using the geochemical data obtained for each element with Inverse Distance Weighting (IDW) method (Franke, 1982; Zimmerman et al., 1999; Juan et al., 2011 and Yasrebi et al., 2016). IDW method, as a type of determination of multivariate interpolation with a known scattered set of points, was applied for generating the interpolated maps (Fig. 5). The assigned values to unknown points are calculated by the weighted average of values available in the known points. The parameter values for generating the interpolated maps in this paper are cell-size of 3 m and power (controls the significance of surrounding points on the interpolated value) of 2. There are two ways to specify the searching neighborhood and we used a fixed method searching radius of 100 m.

The optimum sampling must be based on geochemical methods followed by the field experiment, a variety of sampling, sample preparation and analytical method approaches (Yasrebi et al., 2016). Any mistake in sampling and sample preparation may influence the results of the survey (Thompson and Howarth, 1978; Fletcher, 1981; Demetriades, 2014). For optimum using of the results of measurements, analysts must be aware of the degree of their confidence. For this purpose, the quality control testing was done to determine the stages of preparation and measurement error. In addition, the calculation method of duplicate data was applied using the graphical method of Thompson and Howarth (1978) (Govett, 1983; Fletcher, 1981) (Fig. 6). In this method, measurement accuracy is checked by analysis of duplicate samples. To calculate the relative error, the following formula is used:

$$e = \frac{2}{n} \sum_{i=1}^n \frac{|x_i - y_i|}{x_i + y_i} \quad (1)$$

where (n) is duplicate samples; x_i and y_i are measured values in the corresponding duplicate samples. Average computational errors for Ce, La and Y are 8.733, 9.911 and 8.047, respectively (Table 3). This method uses a logarithmic graph that the horizontal axis is the average sample pair and the vertical axis is the absolute value of the difference between the two measurements (Govett, 1983).

4. Concentration-area (C–A) fractal model

Cheng et al. (1994) proposed the C–A fractal model, which can be used to define the geochemical background and various anomalies, as the following form:

$$A(\rho \leq) \propto \rho^{-a_1}; A(\rho >) \propto \rho^{-a_2} \quad (2)$$

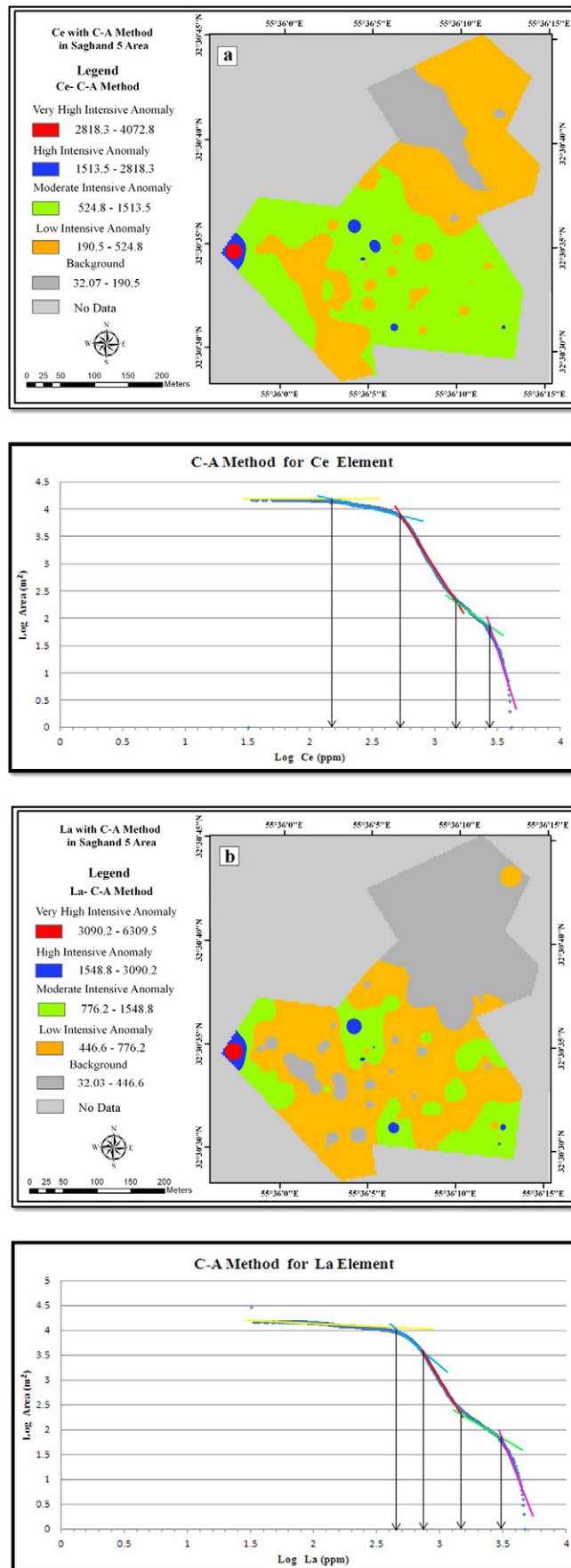


Fig. 7. C-A log-log Plots for Ce (a), La (b) and Y (c) and their geochemical anomaly maps.

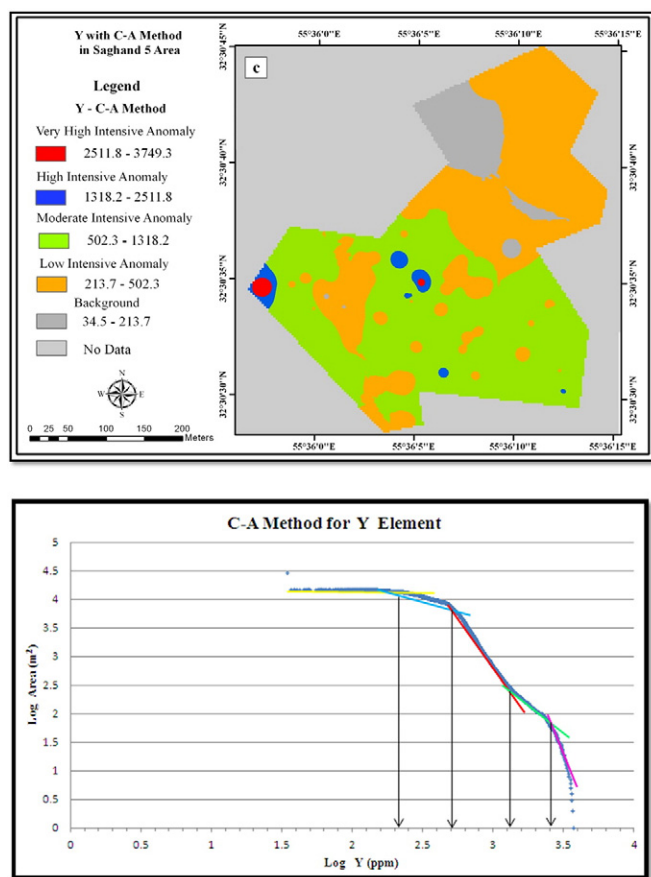


Fig. 7 (continued).

where $A(\rho)$ denotes area with background concentrations (ρ) less than or equal to a threshold concentration (v) or area with anomalous concentrations (ρ) greater than the threshold concentration (v), a_1 and a_2 are slopes of straight lines fitted to log-log plots of ρ versus $A(\rho)$. This model is based on the relationship between geochemical concentrations and their occupied area (Cheng et al., 1994; Zuo et al., 2012). In order to find threshold values of the geochemical data using C–A fractal modeling, straight line segments are fitted on the C–A log-log plot. The cross-points of the lines fitted are the desired threshold values to separate geochemical data into different populations, which may represent different factors such as rock types, mineralization, alteration and surficial geochemical processes (e.g., Gonçalves et al., 2001; Lima et al., 2003; Afzal et al., 2010; Heidari et al., 2013).

5. Application of multi-fractal modeling

In fractal modeling, there is no need to remove outliers; it means the whole data are applied without removing outliers and normalizing the data. So, in this study, the C–A fractal model was used to determine

thresholds for separation of regional background and anomalies per element. Log-log plots of element concentration values (C) versus the area of cells (A) with values greater than C were constructed per map of interpolated element concentration data.

In order to map La, Ce and Y geochemical anomalies, obtained from fractal modeling, the element contour maps were generated. Afterward, the C–A log-log plot were drawn for each element concentration, and the desired threshold were recognized (Fig. 7 and Table 4).

Based on the C–A log-log plots of the litho-geochemical data, the Ce thresholds were quantified and mapped (Fig. 7a): the left-hand line segment represents background values 32.07 to 190.5 ppm, the next two line segments represent low and moderate anomalies ranging from 190.5 to 524.8 ppm and from 524.8 to 1513.5 ppm, respectively. The right-hand line segment represents high anomalies from 1513.5 to 2818.3 ppm. The very high concentration anomalies are 2818.3 to 4072.8 ppm.

The left-hand line segment for La (Fig. 7b) represents background values (32.03 to 446.6 ppm), the middle one represents the low concentration anomalies ranging from 446.6 to 776.2 ppm. The moderate concentration anomalies are between 776.2 ppm and 1548.8 ppm, and high anomalies are from 1548.8 to 3090.2 ppm; the right-hand line segment represents very high anomalies from 3090.2 to 6309.5 ppm. The left-hand line segment for Y (Fig. 7c) represents the background (34.5 to 213.7 ppm), the middle line segment represents low concentration anomalies ranging from 213.7 to 502.3 ppm, and the moderate concentration anomalies are between 502.3 and 1318.2 ppm. The right-hand line segment represents high intensive anomalies from 1318.2 to 2511.8 ppm and a very high intensive anomaly is from 2511.8 to 3749.3 ppm.

Very high concentration anomalies, high and moderate anomalies of Ce, La and Y are related to metasomatism stage with subvolcanic quartzdiorite and metamorphosed volcanic rocks and metasomatite rocks in the study area. Basic magmatism had caused metasomatism and the creation of various rock units (Samani and Talezadeh Lari, 1988). Various metasomatite include three types of amphibole metasomatite, amphibole-albite metasomatite and carbonate metasomatite. Creating feldspar in this anomaly can be divided into two independent groups, feldspar of the first phase are generally albite and beige to white in color while posterior metasomatite albites are pink and generally have high radioactivity. Amphiboles are from thermolite, actinolite group and phlogopite expansion is limited to the edges of the carbonated intrusive. The background values and low concentration anomalies of Ce, La and Y are related to calcoalkaline intrusive, diorite and hornfels units.

6. Correlation between multi-fractal modeling and geological particulars

Based on Khalajmasoumi (2012), the amount of LREEs is more than HREEs in Saghand area, such as Magnetite-Apatite deposits in Yazd province, especially Bafq-Robat-e-Posht-e-Badam zone. In addition to the geochemical data layers, generated by the C–A fractal model, the other data layers of the study area such as geological, structural, petrographical, alterations (epidotic and chloritic) and SEM data had appropriate correlations with litho-geochemical data (Fig. 8); i.e., the geochemical anomalies of REEs are located in metasomatic albite and

Table 4
Background and anomaly values of Ce, La and Y in Saghand area, Central Iran.

Element	Background (ppm)	Low intensive anomaly (ppm)	Moderate intensive anomaly (ppm)	High intensive anomaly (ppm)	Very high intensive anomaly (ppm)
Ce	<32	190.5–524.8	524.8–1513.5	1513.5–2818.3	2818.3–4072.8
La	<32	446.6–776.2	776.2–1548.8	1548.8–3090.2	3090.2–6309.5
Y	<34.5	213.7–502.3	502.3–1318.2	1318.2–2511.8	2511.8–3749.3

amphibolite units, microdiorite, metasomatized acidic volcanic rocks, hornfels and quartz-diorite units (Fig. 8). By petrographic studies (Khalajmasoumi, 2012) in the area, three types of rocks, including volcanic, intrusive and metasomatic rocks were determined. Volcanic and sub-volcanic rocks include rhyodacite and spilite; intrusive rocks include diorite and quartz diorite (sub-volcanic), pyroxenite, peridotite, gabbro, and granite. Metasomatic rocks are base rocks for U and Th

mineralization in the area. These rocks are albite metasomatic, amphibole metasomatic, albite-amphibole metasomatic, amphibole-albite metasomatic. Original mineralizations of REEs have taken place in these metasomatic rocks (Fig. 9).

Another data layer applied for correlation between the multifractal modeling method for the assessment of the REEs geochemical anomalies was remote sensing, based on that of done by

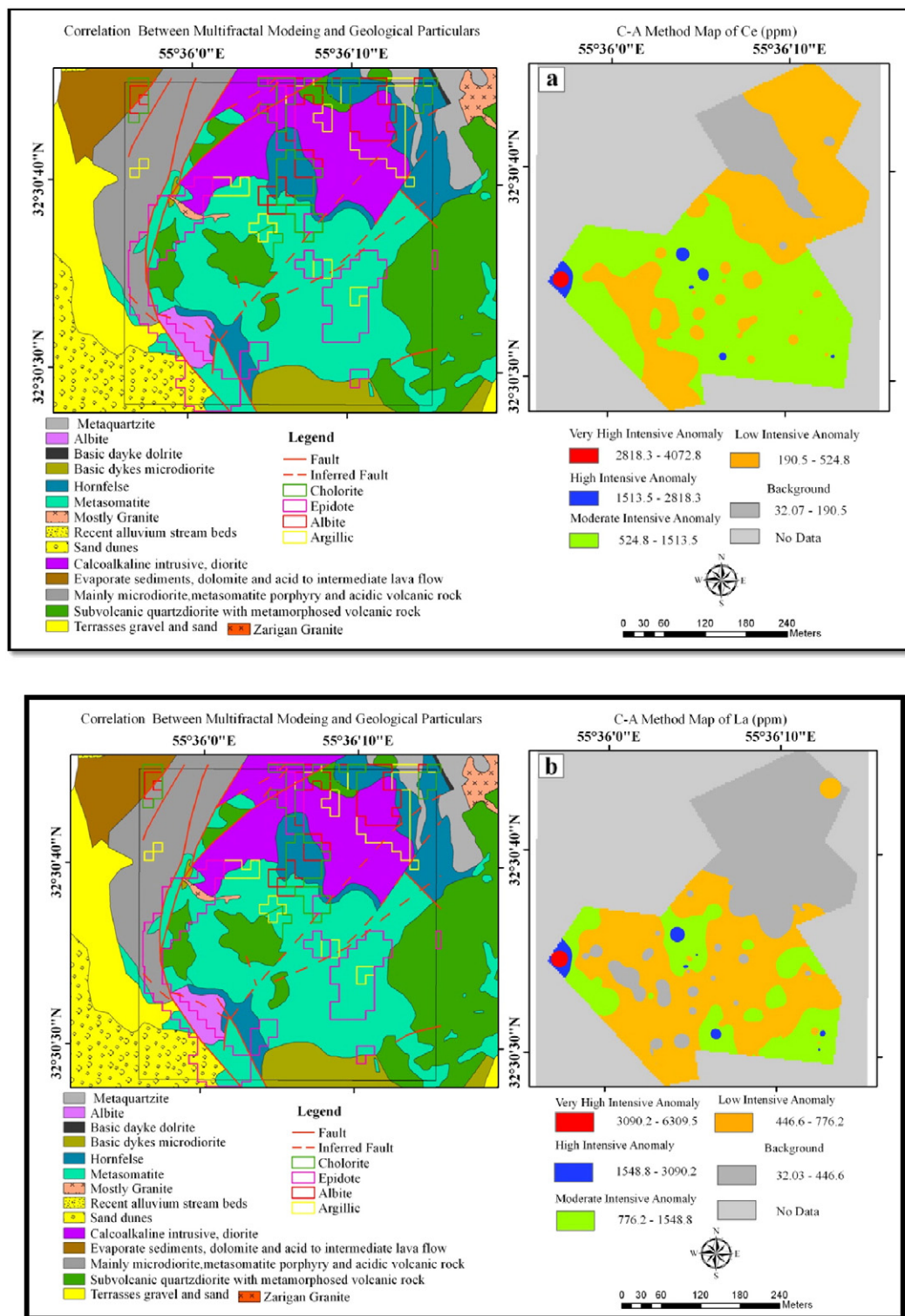


Fig. 8. Anomaly intensity maps of Ce (a), La (b) and Y (c) in the Saghand area based on the C-A fractal method with metasomatic albite, amphibolite unit, microdiorite, metasomatized acidic volcanic rocks, hornfels, quartz-diorite units and epidote, chlorite alteration and faults features in the Saghand area (correlation between multi-fractal modeling and geological particulars).

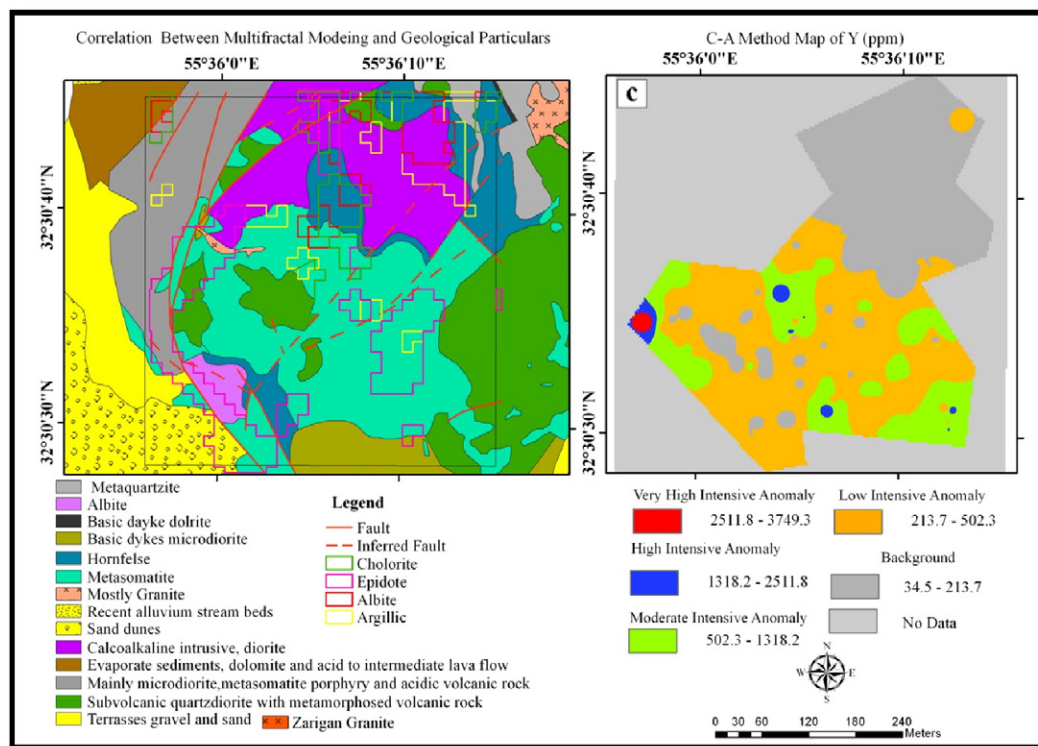


Fig. 8 (continued).

Khalajmasoumi (2012). The alterations related to radioactive elements (U and Th associated to metasomatite and igneous rocks) were extracted from the ASTER satellite images. The radioactive elements alterations were recognized by remote sensing. In the study area, the best alterations of U and Th were epidotic and chloritic alterations. By processing of the ASTER satellite images, it was observed that prevailing alterations associated with mineralization of the radioactive elements and REEs were epidotization, chloritization, argillization, hematitization (Khalajmasoumi, 2012; Fig. 10). The remote sensing methods applied were linear band prediction (LS-Fit) (Pohl and Van Genderen, 1998; Harris et al., 1998), matched filtering (MF) (RSI, 2003) and band ratio. Bonham-Carter et al. (1988) illustrated that the best algorithm for extraction of argillic alteration is MF. In addition, the best algorithms for identification of propylitic alterations, especially chloritic (Fig. 10a) and epidotic ones (Fig. 10b) are MF and $6 + 9/7 + 8$ band ratio. Sabins (1999) illustrated that the best algorithms for extraction of Fe-oxide alterations are LS-Fit and $2/1$ and $3/1$ band ratios.

Based on the results of the SEM studies on the metallic minerals of the polished sections of the study area, they were correlated with the high concentration anomalies parts of REEs resulted from the C–A fractal model of the metasomatic rock units in the study area. Therefore, based on the results of the distributions of davidite (Figs. 11a, b) and magnetite (Figs. 11e, f), it is obvious that mineralization of radioactive elements and REEs in this area have taken place mostly in the form of replacement in radioactive minerals (davidite- $X_2Y_5O_{12}$) and metasomatism area. In this formula, X represents Re, Ce, U and Y contains Fe^{2+} , Mg, Fe^{3+} , Cr^{3+} and V^{3+} . The concentrations of Ce and Fe are high (Fig. 11a and c) and that of Re is low (Fig. 11d). Considering these results, it is obvious that SEM studies of the metasomatic rock units are consistent with the geochemical anomalies.

7. Discussion

Mineralization of REEs in the study area is related to the metasomatism. There are two stages of metasomatism in the region; the first stage

includes granite production from magma segregation origin, or with high possibility under metasomatism and its movement as dykes and various intrusions in the host rock. This step caused contact metasomatism in the study area. Granite intrusives, created by metasomatism, are able to create amphibolization silicification in the study area. In the second stage, the basic magmatism had caused metasomatism and the creation of various rock units. Uranium as carbonate and sodium complex and in oxidant state (6th valence) is transported and the quadrivalent minerals of U such as uraninite and davidite have been deposited in various hosts while confronting with hydrothermal solutions. Radioactivity is caused by mineralization of Th, U and both of them with each other. Three types of various metasomatite in the study area include amphibole metasomatite, amphibole-albite metasomatite and carbonate metasomatite. Feldspar creation could be divided into two independent groups in the study area. The feldspars of the first phase are generally albite and beige to white in color while late metasomatite albites are pink and generally shows high radioactivity. Amphiboles are from thermolite, actinolite group and phlogopite expansions are limited. Amphibole-albite metasomatite, amphibole metasomatite and albitites are considered as good hosts of REEs (Samani, 1988). In addition, alkali metasomatite, albitization and alkali granite are proper hosts of REEs.

8. Conclusions

According to the results derived from the C–A fractal model and the log-log plots of the litho-geochemical data, it seems the very high concentration anomalies of Ce are between 2818.3 and 4072.8 ppm. The very high anomalies of La are from 3090.2 to 6309.5 ppm and very high intensive anomalies of Y are between 2511.8 and 3749.3 ppm. These results of litho-geochemical data with the C–A fractal model have been correlated with other layers such as geological, petrographical, SEM and remote sensing data.

The very high anomalies of Ce have occurred in the western part of the area associated to metasomatic albite, microdiorites and metasomatized acidic volcanic rock units. These rock units are suitable for substitution of REEs in the minerals and radioactive elements (U

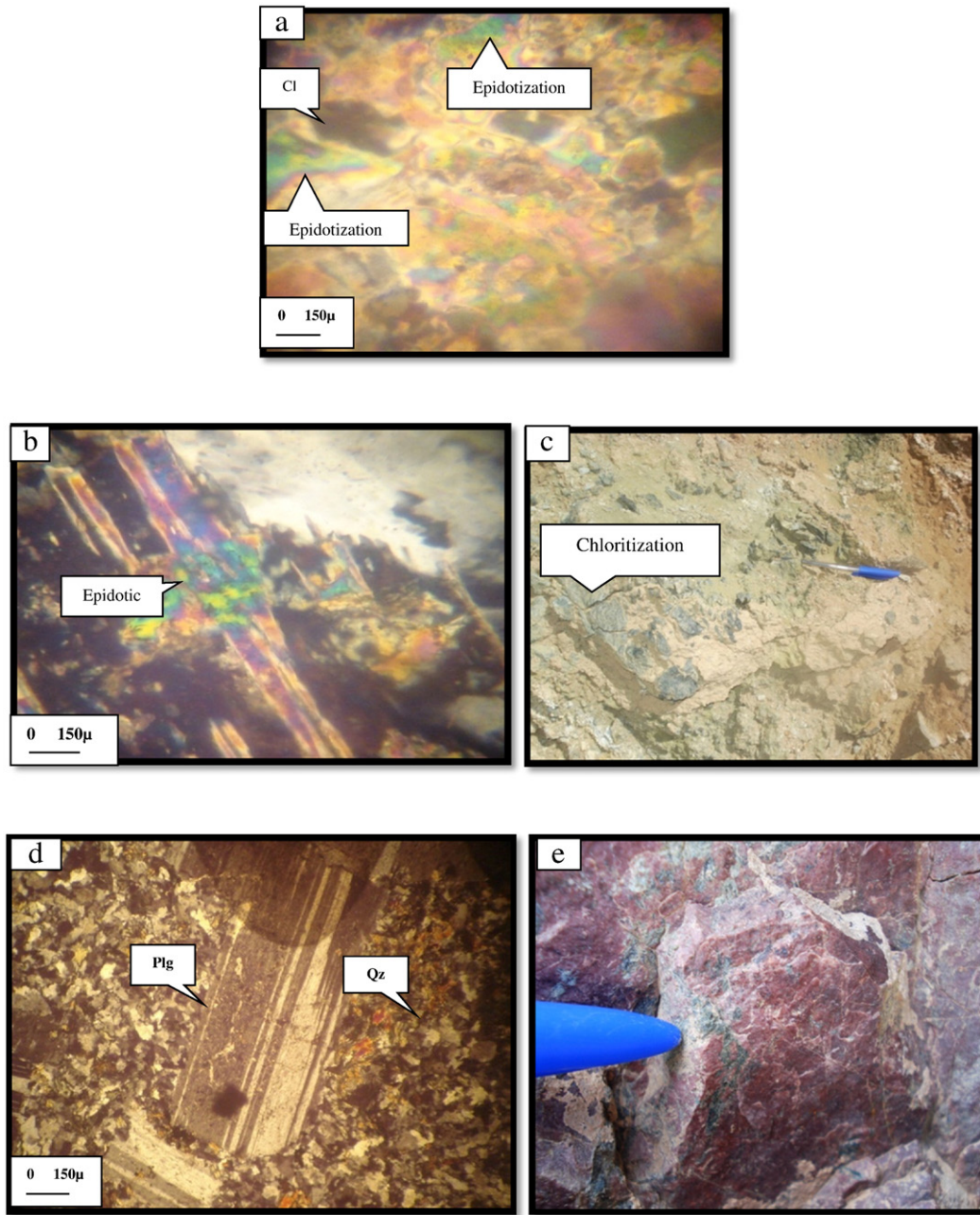


Fig. 9. Amphibole metasomatic rock and epidotization alteration (a, b, and Fig. 3a), chloritization alteration (c), albite metasomatic rock (d, e).

and Th) in the study area. Enrichment of the other elements such as U and Th is high and associated with the mineralization of REEs in the area. The results of Ce, La and Y geochemical anomaly mapping/recognition show that Y has a geochemical relation with U, while Ce has a geochemical relation with Th. There is a high value of U much more than the Th in metasomatite rocks, especially amphibole metasomatite and in these units, geochemical potentials of REEs are high.

Moreover, the remote sensing results reveal that the epidotic alteration is correlated with the Ce mineralization which conforms to the field observations and petrographical data. In addition, the Ce mineralization, occurred in quartz-diorite and metasomatite units, is related to the epidotic and chloritic alterations in the central part of the study area. The Ce anomalies in the eastern and SE parts of the area, occurred in quartz-diorite units, are associated with

epidotic alterations. The southern part of the area is composed of metasomatite units which have a border with microdiorite basic dykes, and the alteration type in this part is epidotic. The highest volumes of La (3090.2 to 6309.5 ppm) are in the western part of the study area associating with metasomatite albite units in addition to microdiorites and metasomatized acidic volcanic rock units. The alteration types in the western part of the study area are epidotic within the microdiorite units and metasomatized acidic volcanic rocks. The La anomalies in the central part of the area are in the metasomatite units associated with epidotic and chloritic alterations. In the western and central parts of the area, the highest volume of Y anomalies (2511.8 to 3749.3 ppm) has occurred in microdiorite units and metasomatized acidic volcanic rocks. Moreover, the epidotic alteration and the alteration types in the central

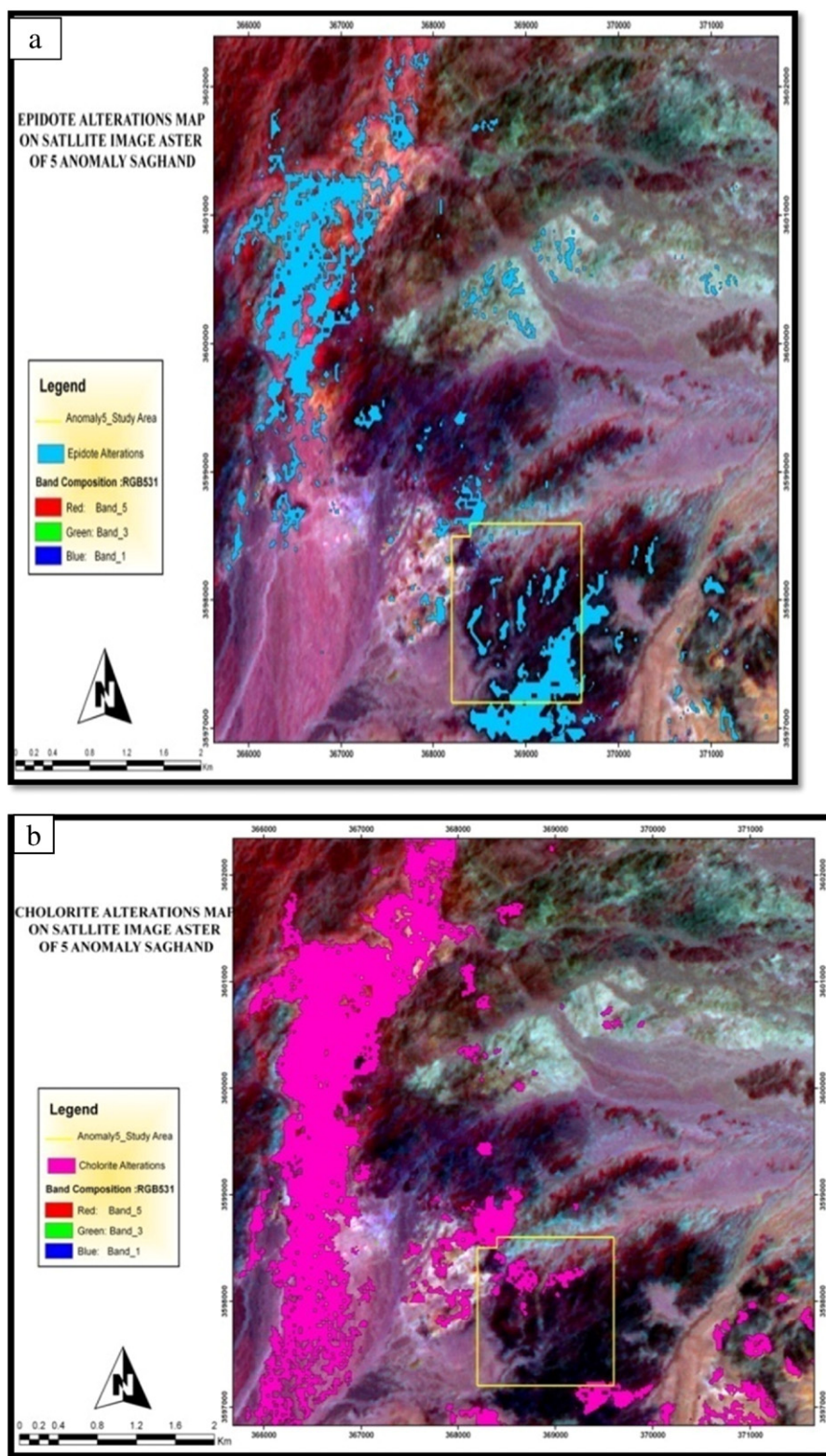


Fig. 10. Epidotic alterations (b) and chlorite alterations (a) extracted from the ASTER multispectral image in Saghand area, Central Iran.

part of the area are epidotic and chloritic. Hence, the high geochemical potentials of REEs are concentrated in the western, SW, central and SE parts of the study area within the metasomatite units. Meanwhile, the main alteration types of the area, which are epidotic and chloritic, were confirmed by field observations, petrographical, geological and remote sensing data.

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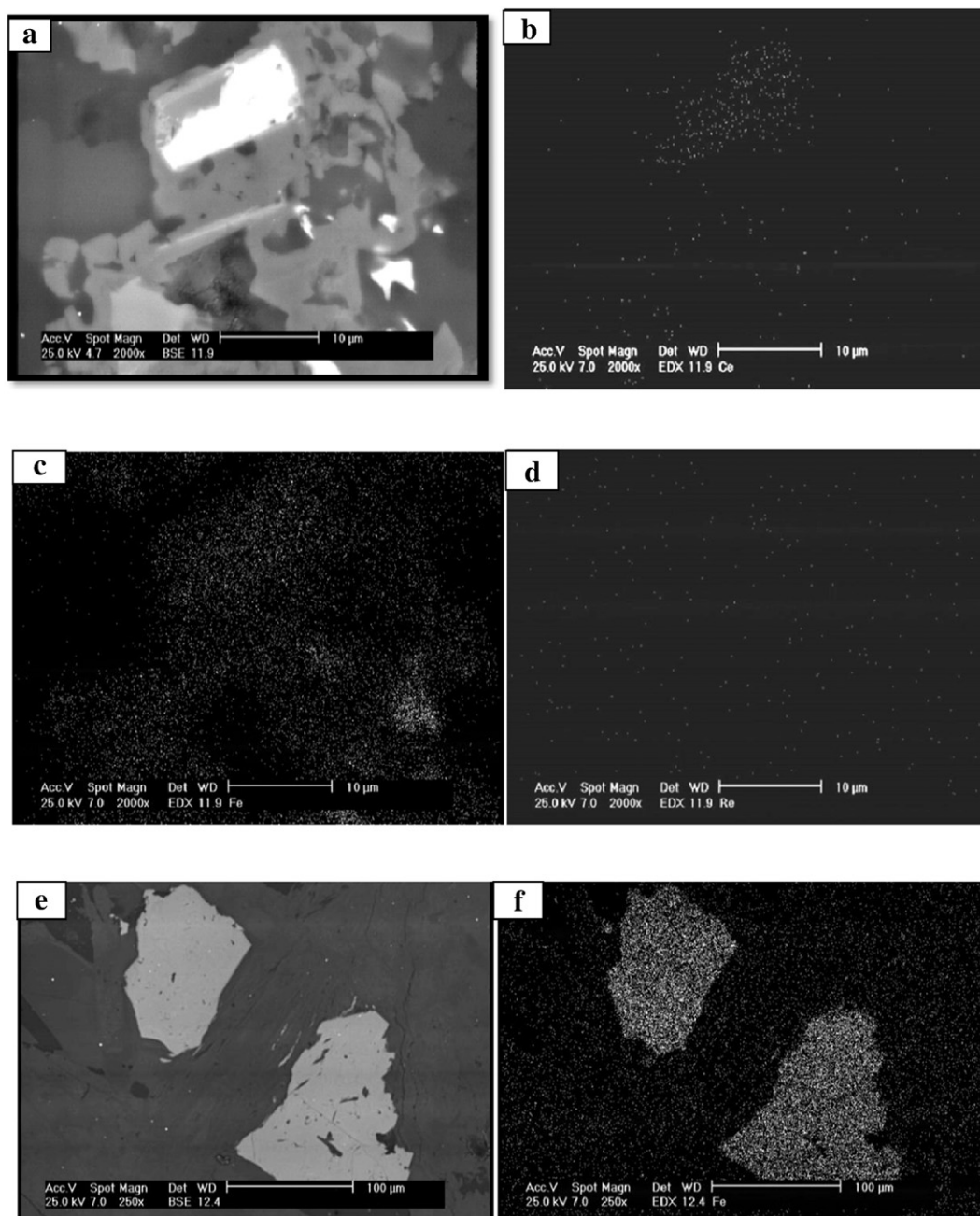


Fig. 11. SEM studies in davidite mineral (a), and magnetite (b), gathering of Fe (c), Ce (b) and Re (d) in davidite, gathering Fe (e and f) in magnetite sample in Saghand area.

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