

ORIGIN OF CHOGHART IRON OXIDE DEPOSIT, BAFQ MINING DISTRICT, CENTRAL IRAN: NEW ISOTOPIC AND GEOCHEMICAL EVIDENCE

F. Moore* and S. Modabberi

Department of Geology, Faculty of Sciences, Shiraz University, Shiraz, Islamic Republic of Iran

Abstract

The origin of the Proterozoic Choghart iron oxide deposit in the Bafq mining district of Central Iran has been the subject of a long-standing dispute. Some authors believe that it was formed from magma, while others suggest metasomatic replacement of preexisting rocks. The present study on the basis of new oxygen isotope, REE and geochemical data concludes that neither of these two hypotheses can alone explain the formation of Choghart deposit. Instead, it is suggested that the separation of an iron oxide melt and the ensuing hydrothermal processes dominated by alkali metasomatism were both involved to different degrees in the formation of Choghart and other similar deposits in Central Iran.

Keywords: Kiruna-type iron oxide deposits; Geochemistry; Choghart; Bafq; Central Iran; REE

1. Introduction

The origin of massive iron oxide deposits related to igneous rocks has been the subject of a long-standing and heated debate for the last hundred years. Despite the voluminous published literature, the origin remains uncertain and controversial [2,8,18]. These deposits are usually composed of magnetite-hematite-fluorapatite with varying amounts of alkali amphiboles. They occur worldwide and range in size from large high-grade orebodies to small dikes and veinlets. They are usually found in volcanic-plutonic terrains and range in age from Proterozoic to Cenozoic. Among these deposits, the so-called Kiruna-type ores have attracted the most attention. Several genetic models have been proposed for this specific type of massive iron oxide deposits [14], but in the main, they are considered to be magmatic segregation deposits [9].

The Choghart apatite-bearing iron oxide deposit (55°28'2"E, 31°42'00"N) occurs in the Bafq mining

district of Central Iran, 12 km northeast of Bafq town and 125 km southeast of Yazd city (Fig. 1). There are more than 80 identified magnetic anomalies in the Bafq mining district, and the region is believed to host over 2 Gt of iron oxide ore [4]. Most of the deposits are unexploited or only partially mined. Choghart is the first deposit of its kind exploited in the Bafq mining district. The remaining total reserve of Choghart is estimated to be 200 Mt. The first apatite-rich iron oxide ore was shipped to Isfahan steel mill (the largest mill in Iran) in 1971, and since then, Choghart has remained the main supplier of iron ore to this mill.

The origin of Choghart iron deposit and other similar iron oxide deposits in the Bafq mining district, like their counterparts in the rest of the world, has been the subject of continuing controversy for local geologists with the difference that the controversy has been fueled by the lack of absolute age determinations, accurate isotopic and fluid inclusion studies, and reliable analytical data.

* E-mail: moore@geology.susc.ac.ir

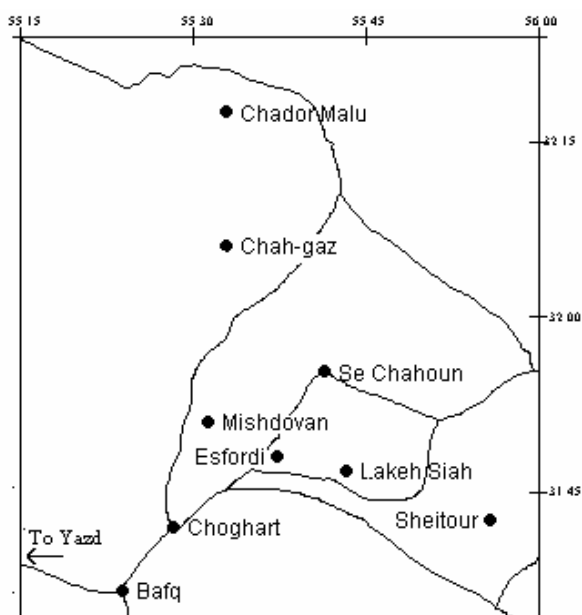


Figure 1. Geographic map showing the location of Choghart iron oxide deposit in the Bafq mining district of Iran.

In general two main groups of apatite-bearing iron oxide deposits occur in the Bafq mining district. The first smaller group, represented by the Mishdovan iron deposit and the Narigan manganese iron deposit, is believed to be exhalative jaspilite composed of synsedimentary iron ore interstratified with Infracambrian volcano-sedimentary rocks [3,7]. The second larger group is represented by Choghart, Chador Malu, Chah Gaz, Se Chahoun and many other similar occurrences. There is no general consensus regarding the origin of this group of iron oxide deposits. Some authors believe that these have been formed directly from magmas filling volcanic diatremes or flowing as lavas [5,6,20], while others suggest metasomatic replacement of preexisting rocks by hydrothermal (deuteric) solutions charged with iron leached from cooling felsic plutons [4,10].

The main scope of this study is the determination of the origin of the Choghart iron oxide deposit in the light of new REE and oxygen isotope data and to study the geochemistry of Choghart's magnetite and apatite.

2. Geologic Setting of the Choghart Deposit

The Choghart deposit occurs in the Bafq mining district, which is part of the narrow N-S trending Pan-African rift zone at the eastern margin of the so-called Lut block. Berberian and King [1] suggested that the

development of this rift zone was the result of stretching of the Arabo-Iranian continental crust during an Infracambrian extensional phase. Forster and Jafarzadeh [6] suggested that the centers of magmatic activity and maximum crustal thinning coincided with the axis of this assumed rift.

The main orebody at Choghart is in the form of a roughly vertical, discordant, pipe-shaped body plunging 73° NNW and has been explored to a depth of 600 m, where it appears to interfinger with intrusive metasomatized and fragmental wall-rock. The thickness of the metasomatic aureole differs widely. The orebody is hosted by volcanic members (intrusive and extrusive alkali rhyolites) of the epicontinental to continental Infracambrian Esfordi Formation. Samani [21] suggested that the Esfordi Formation is a taphrogenic productive zone, that hosts not only the iron deposits, but also a number of Pb-Zn, Mn, Th, U, P and REE occurrences in the region.

Before the commencement of mining activity, Choghart was a prominent black hill measuring 800×300 m, standing 150m above the surrounding plain and 1257 m above sea level. Current mining levels are at 1050 m above sea level.

Drilling and the surface observations at Choghart show that the basement consists of highly metamorphosed Precambrian continental Chapedony Complex and Morad Series, covered with volcano-sedimentary units of Infracambrian Esfordi Formation. There is no outcrop of Precambrian and Infracambrian rocks at Choghart deposit. However, altered fragments of Esfordi Formation dolomites are found as xenoliths of varying size and shape in the immediate intrusive country rock. The intrusive rocks are mainly syenitic, but pyroxenite, gabbro and even granitic patches are also identified. The intrusive assemblage is enveloped by alkali rhyolites. All these rocks display extensive mineralogical, textural and compositional diversity, with varying degrees of hydrothermal alteration. The grade of the alteration is reflected by extensive development of alkali amphiboles. Russian geologists working for the National Iranian Steel Company (NISCO) originally identified the intrusive envelope as metamorphosed sedimentary conglomerates and breccias, whereas Forster and Jafarzadeh [6] refer to them as "intrusive breccia", and Daliran [4] called them "apatites" due to their high apatite content. The orebody and the metamorphosed country rock are cut by several diabasic dikes. Detailed petrographic descriptions of the Choghart orebody and country rock were given by Mousavinasab (1997, unpublished M.S. thesis, Shiraz university).

The plain that surrounds the Choghart orebody and

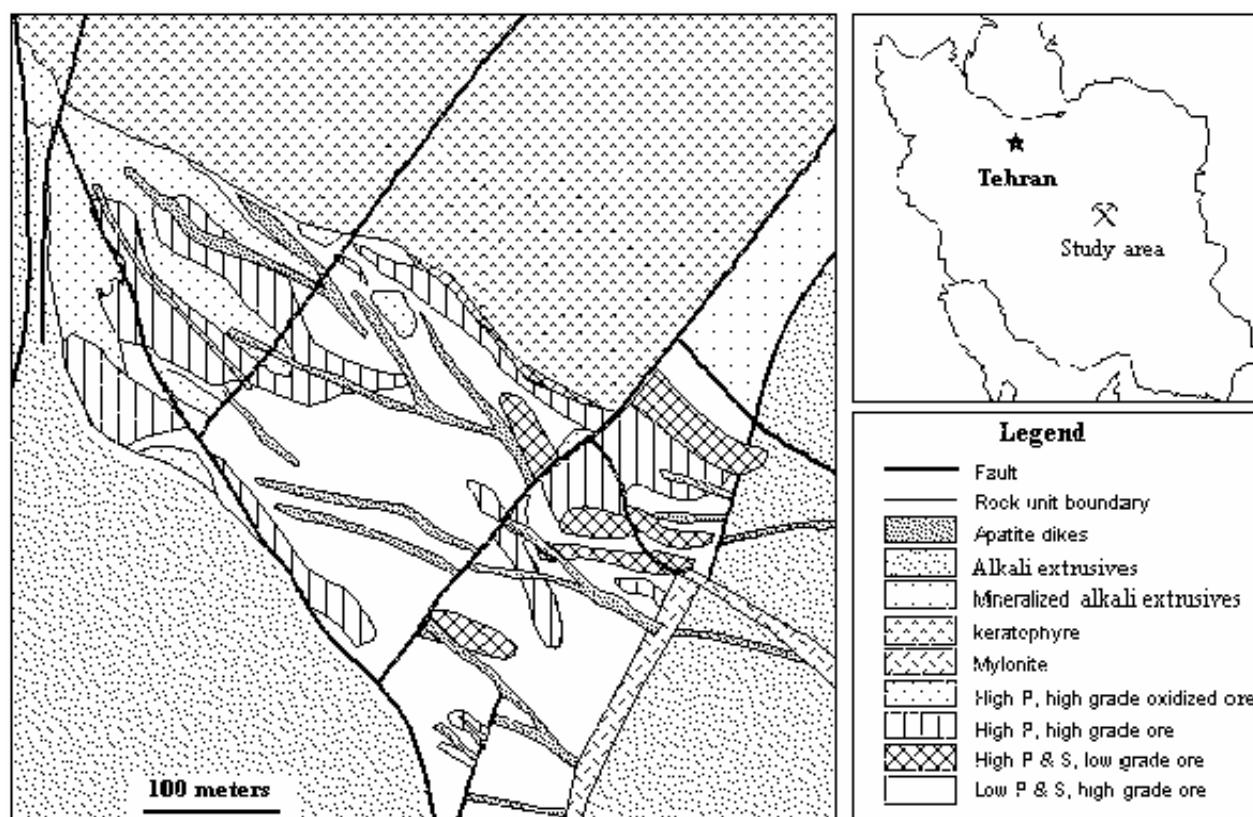


Figure 2. Geological map of Choghart deposit.

its metamorphosed intrusive and volcanic country rocks are composed of 150 m of Quaternary formations and recent alluvium, of fine grained sand and gravel, magnetite boulders, gypsum and intrusive fragments. Six kilometers to the west, the Posht-Badam fault separates the Choghart iron deposit and the surrounding plain from a thick sequence (400 to 700 m) of Mesozoic rocks. A geological map and cross section of Choghart deposit are presented in Figures 2 and 3.

3. Mineralogy and Geochemistry of the Choghart Orebody

Primary ore in the lower part of the Choghart orebody consists largely of massive magnetite. Accessory minerals include apatite, pyrite, alkali amphiboles mainly actinolite and tremolite, calcite, talc, quartz, monazite, davidite and allanite. Forster and Jafarzadeh [6] have distinguished six types of ore on the basis of the main associated gangue. Accordingly, the magnetite-apatite and magnetite-silicate ores are the most and least abundant ore types, respectively. Primary sulfides (mostly pyrite) occur as microscopic inclusions

in the magnetite grains and also in small crosscutting veins.

The oxidation zone reaches down to 150 m depth and varies from incipient martitization to complete replacement of magnetite by martite near the surface. Hematite is the second ubiquitous mineral after magnetite. Although some primary hematite is also found in the drill cores, most of hematite is secondary in origin. Some goethite and hydrous iron oxide occur on the surface, but disappear rapidly with increasing depth.

Primary magnetite ranges in size from fine to coarse-grained crystals. The crystals commonly show intimate intergrowths with sharp 120° contacts typical for crystallization from a melt. Large grains of magnetite occasionally contain lamellae of exsolved ilmenite and some are zoned or twinned. In reflected light, Choghart magnetite displays a moderate reflectivity, a grey color with variable brownish tints and distinct isotropism. Some crystals show signs of recrystallization.

Apatite is the most abundant gangue at Choghart. It is a distinctive, transparent, yellow-green fluor-apatite. Fine and coarse-grained apatite occur in varying proportions with magnetite, and apatite-bearing

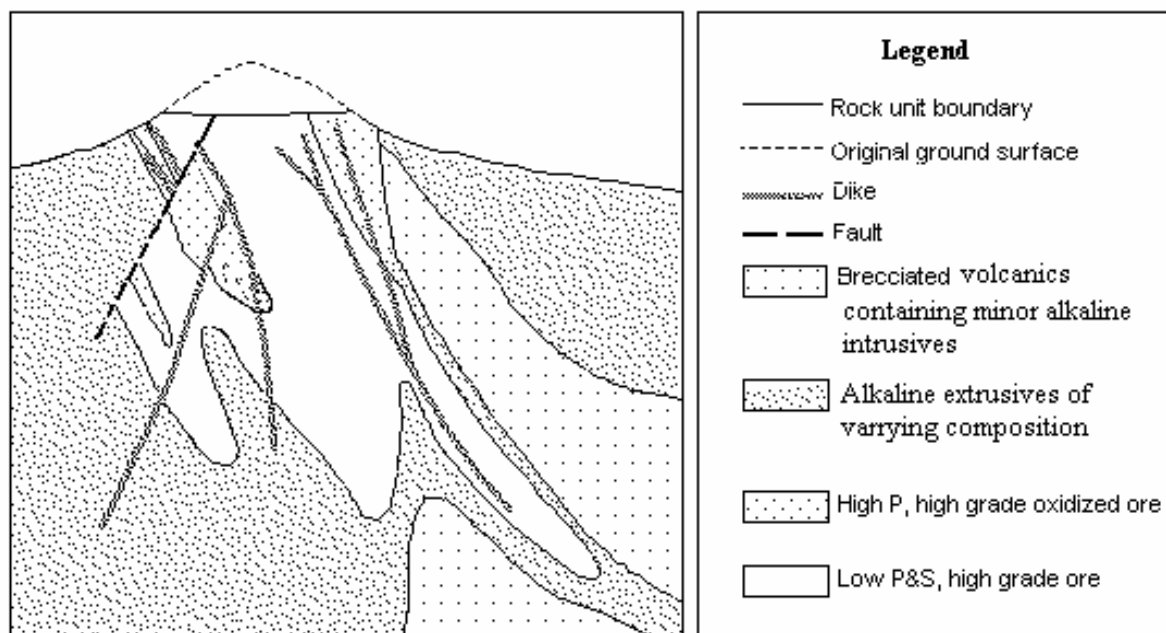


Figure 3. Schematic cross section through Choghart deposit.

magnetite is the most abundant ore type at Choghart. At least two generations of apatite are discernible. The first, which is contemporaneous with the main phase of iron oxide formation, displays euhedral crystals ranging in size from a few millimeters to a few centimeters in diameter. It is intimately intergrown with magnetite. The second generation occurs as subhedral to anhedral crystals in lenses, dikes, and veinlets of varying size and thickness, which cut the magnetite-apatite ore.

A study of ten doubly polished wafers of apatite at Shiraz University by the authors, and several more at Michigan University by Dr. S. Kesler, failed to find primary fluid inclusions worthy of microthermometric determinations in apatites. The main reason is the intense crushing of apatite by post-mineralization deformation. The regional tectonic pressure is also recorded as undulating extinction in apatite and some quartz crystals.

Pyrite and quartz are distributed quite evenly in the orebody, either as solid inclusions in primary magnetite grains or as well-developed crystals in the orebody and the adjacent country rock. Some magnetite crystals are cemented by quartz and vice versa, indicating alternation of magnetite and quartz mineralization. Calcite, dolomite, secondary hematite and talc occur throughout the orebody as veinlets and cementing material of oxidized ore. Rutile and goethite are probably the result of total transformation of the earlier-formed martite.

3.1. Magnetite Geochemistry

In order to study the major, trace and REE compositions of Choghart magnetite, twenty samples were collected from surficial exposures, drill cores and the stockpiled ore. The emphasis during sampling was on ores with primary texture, so as to avoid possible influence on the chemistry by recrystallization or metasomatic changes during hydrothermal alteration. The samples weighted about 2 kg each, half of which was crushed and washed in distilled water. Magnetite was then separated by means of heavy liquids and magnetic separation. However, despite these efforts, a few samples appeared to be mildly martitized or recrystallized, and a few microscopic grains of intimately intergrown apatite also remained in the purified samples. An aliquot of 0.5 g of each sample was dissolved in aqua regia. The drawbacks of this method of dissolution is the length of time needed for magnetite to dissolve and the yellow color of the resultant solution which makes it impossible to determine titanium by conventional spectrophotometric techniques. The dissolved samples were analyzed for various major and trace elements except Ti at the Department of Geology, Shiraz University, using standard wet chemical methods. Ti and REE were analyzed by instrumental neutron activation methods at Isfahan Bureau of Atomic Energy of Iran. The major and trace elements of Choghart magnetites are presented

Table 1. Chemical compositions of Choghart magnetites. Major elements in wt% and trace elements in ppm)

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
SiO ₂	0.11	0.06	0.02	0.09	0.13	0.03	0.07	0.13	0.01	0.25	0.16	0.05	0.11	0.07	0.09	0.13	0.17	0.08	0.11	0.04
TiO ₂	1.02	0.69	0.72	1	0.55	1.13	0.25	0.59	0.57	0.63	0.47	1.12	0.68	0.7	0.54	0.5	0.98	0.78	0.51	0.69
Al ₂ O ₃	0.1	0.11	0.09	0.1	0.12	0.14	0.11	0.06	0.12	0.15	0.15	0.07	0.28	0.14	0.12	0.24	0.34	0.08	0.12	0.11
V ₂ O ₅	0.12	0.8	0.53	0.26	0.64	0.48	0.39	0.48	0.46	0.23	0.08	0.57	0.2	0.53	0.41	0.21	0.16	0.32	0.44	0.29
Fe ₂ O ₃	66	64.65	68.21	66.25	68.62	66.22	66	66.4	65.51	65.8	66.3	65.87	66.24	65.48	66.54	67.05	65.86	66.1	65.4	66.2
FeO	29.5	29.33	27.61	29.37	26.81	28.42	30.2	28.7	29	28.57	27.9	28.94	28.72	28.29	28.64	28.04	28.27	26.8	28	28.1
MgO	0.63	1.5	1.15	0.91	0.63	1.3	1.05	0.85	1.16	2.2	1.67	1	0.46	1.09	0.87	1.52	1.06	0.74	1.39	1.12
CaO	2.43	1.98	1.24	1.25	2.16	2.56	1.45	2.27	2.37	2.09	2.95	2.57	2.04	3.07	2.86	1.66	2.72	4.15	3.72	2.69
MnO	0.1	0.22	0.41	0.11	0.22	0.18	0.27	0.19	0.04	0.23	0.09	0.17	0.31	0.17	0.12	0.23	0.31	0.22	0.09	0.16
P ₂ O ₅	0.01	0.02	0	0.01	0.04	0	0	0.01	0.03	0	0	0	0.01	0	0	0.02	0.09	0	0	0
Total	100	99.36	99.98	99.35	99.92	100.5	99.8	99.7	99.27	100.15	99.7	100.4	99.05	99.54	100.2	99.6	99.96	99.3	99.8	99.4
Co	104	70	117	128	135	130	89	110	96	123	137	117	103	118	117	96	115	143	182	126
Cr	20	17	24	15	21	12	18	13	9	25	11	16	29	8	19	21	15	14	14	5
Ni	104	62	106	136	126	149	62	115	105	151	170	83	36	114	98	34	74	139	86	178
Cu	5	5	2	9	8	12	4	3	42	11	10	11	3	9	6	7	4	2	4	9
Zn	36	38	312	47	50	53	225	7	281	47	11	26	456	51	9	3	7	29	16	162

in Table 1.

According to Palache *et al*'s [19] classification, Choghart magnetites fall in the field of "ordinary magnetites". The low Fe²⁺ content is well reflected in the rather high Ca, Mg, and Mn contents. Co and Ni also substitute for Fe²⁺. Elements like Cu and Zn are probably mostly present as microscopic solid inclusions of sulfides in the magnetite. Nyström and Henriquez [18] suggested that magnetites of apatite-bearing iron ores are characterized by very low Cr and relatively high V content. This is well demonstrated in the composition of Choghart magnetites in which the V values range from 816 to 5438 ppm. Ti and Si are also mostly present in small solid inclusions, for inspection of polished thin sections at high magnification reveals that some Choghart magnetites contain microscopic inclusions of rutile and quartz. Thin exsolution lamellae of ilmenite were also observed in few magnetites. The scattered high values of Ti (1499 to 6714 ppm) are attributed to the exsolved ilmenite and rutile inclusions. However, some Ti also exists as substitution solid solution in magnetite, where it substitutes in the Al³⁺ site. The microscopic solid inclusions, the exsolution lamellae, and the presence of various small amounts of apatite in some samples do not seem to considerably

modify the chemistry of Choghart magnetites.

When the ferride elements (Fe, Ni, V, Ti) of Choghart magnetites are plotted on Lohberg and Horndhal diagrams [17], they plot in the field of apatite-iron ores (Fig. 4), indicating chemical similarity with Kiruna-type iron-oxide deposits.

Figure 5 presents the chondrite normalized REE distribution pattern of Choghart magnetite. In normalization, Wakita *et al*'s values [24] were used. The analyzed samples (Table 2) display similar patterns. The average (La/Lu)_{cn} ratio of 8.3 indicates a high degree of fractionation. The fractionation is more pronounced in HREE part of diagram, where the average (Gd/Lu)_{cn} ratio is 45, whereas the average (La/Sm)_{cn} ratio in the LREE part of the diagram is only 2. This indicates that the REE content in Choghart magnetite is not affected by hydrothermal alteration.

The ΣREE content varies between 148 and 210 ppm with an average of 172 ppm (<100 times chondritic values). These REE values are much higher than those reported for the type locality of Kiruna-type iron deposits [9]. Other features include pronounced negative Eu and Ce and positive Pr and Gd anomalies.

Six purified magnetite samples were sent to Michigan University and Center for Isotope Studies,

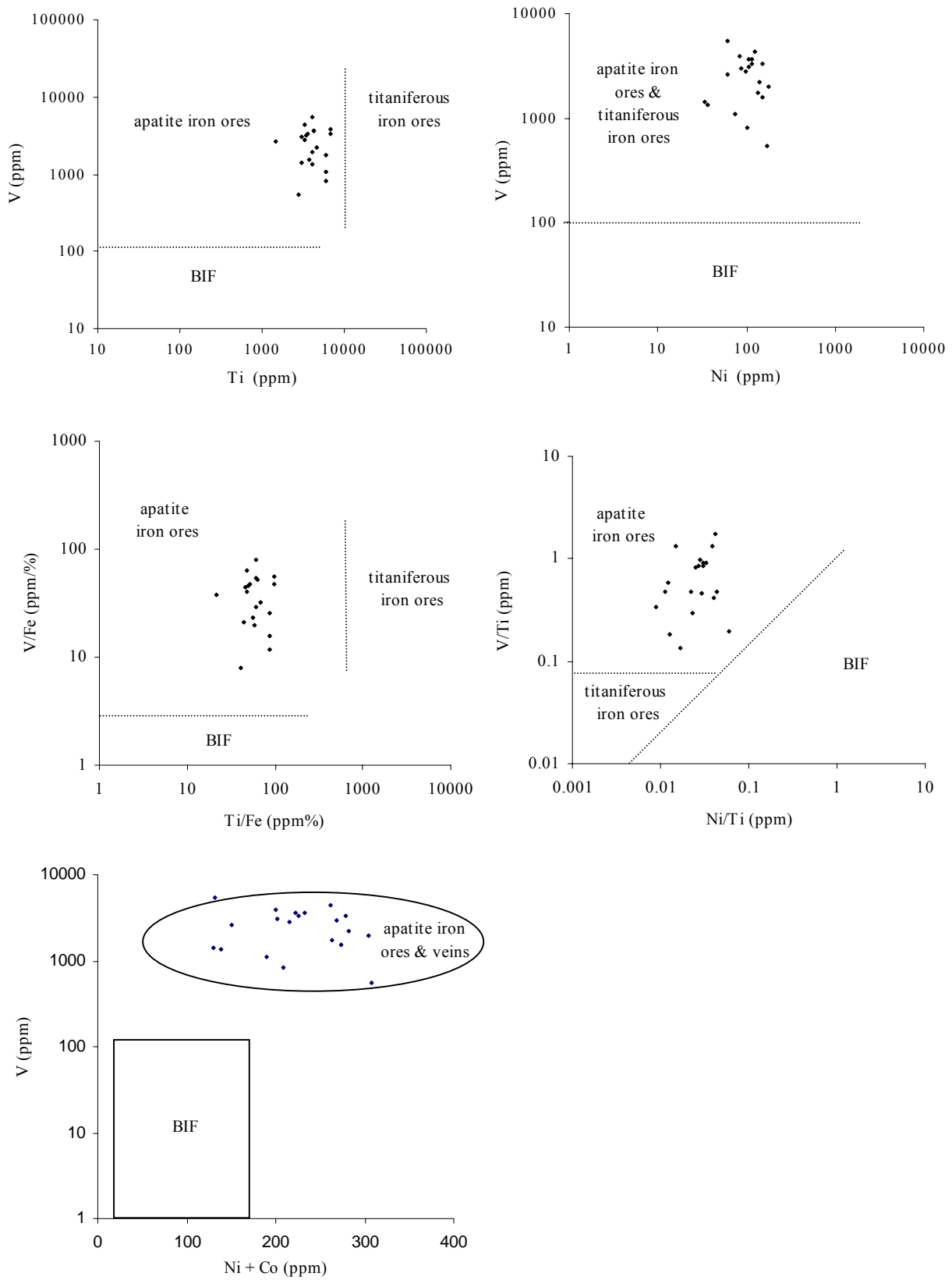


Figure 4. Ferride elements (Fe, Ni, V, Ti) of Choghart magnetites plotted on Lohberg and Horndhal [17] diagrams.

Table 2. REE concentration of Choghart magnetites

No.	1	2	3	4	Chond ^a
La	19	7	12	15	0.34
Ce	26	13	23	28	0.91
Pr	35	33	50	40	0.121
Nd	39	45	24	15	0.64
Sm	5	3	17	2	0.195
Eu	0.3	0.5	0.6	0.4	0.073
Gd	52	44	80	44	0.26
Tb	0.7	1	0.5	1	0.047
Dy	2	2	2	2	0.3
Yb	0.7	0.9	1.5	1.2	0.22
Lu	0.14	0.13	0.18	0.2	0.034
ΣREE	179.84	149.53	210.78	148.8	
(La/Lu) _{cn}	13.57	5.38	6.67	7.5	
(La/Sm) _{cn}	2.18	1.34	0.40	4.30	
(Gd/Lu) _{cn}	48.57	44.26	58.12	28.77	
[Eu]/[Eu*]	0.04	0.07	0.04	0.06	
[Ce]/[Ce*]	0.2	0.1	0.1	0.2	
Eu/Sm	0.06	0.17	0.04	0.2	

^a Chondrite values from Wakita *et al.* [24]

Table 3. The δ¹⁸O values for Choghart magnetites in relation to SMOW. CH-1 to CH-4 were analyzed at the Center of Isotope Studies, North Ryde, Australia, and CH-5 and CH-6 were analyzed at Michigan University

No.	CH-1	CH-2	CH-3	CH-4	CH-5	CH-6
δ ¹⁸ O (‰)VSMOW	9.5	8.5	10.2	10.4	8.0	9.0
δ ¹⁸ O SMOW	3.66	3.73	4.12	4.38		

Table 4. Chemical compositions of Choghart apatites. (Major elements in wt% and trace elements in ppm)

No.	1	2	3	4	5	6	7
Al ₂ O ₃	0.18	0.09	0.13	0.17	0.18	0.11	0.15
FeO	0.25	0.13	0.27	0.18	0.22	0.14	0.23
MnO	0.12	0.25	0.09	0.13	0.11	0.17	0.14
MgO	0.13	0.25	0.21	0.19	0.12	0.23	0.24
CaO	53.80	53.48	53.41	54.01	53.57	54.16	53.73
SrO	0.24	0.20	0.26	0.19	0.12	0.15	0.13
Na ₂ O	0.36	0.28	0.22	0.17	0.26	0.23	0.19
K ₂ O	0.01	0.08	0.06	0.05	0.02	0.03	0.07
P ₂ O ₅	42.51	42.48	42.71	42.64	42.77	42.12	42.61
F	3.07	3.22	3.19	3.20	3.41	3.14	3.17
Cl	0.09	0.06	0.07	0.12	0.07	0.06	0.08
H ₂ O ⁺	0.15	0.08	0.12	0.05	0.08	0.10	0.14
	100.91	100.58	100.74	101.10	100.93	100.54	100.48
O=F	1.29	1.35	1.34	1.34	1.34	1.32	1.33
Total	99.62	99.25	99.40	99.76	99.50	99.32	99.55
Trace elements							
As	220	298	278	234	363	211	359
Ba	72	61	69	55	53	64	50
Co	19	17	16	16	12	14	13
Cr	10	32	12	24	17	12	11
Rb	15	9	11	11	7	13	8
Th	65	98	83	96	82	67	79
U	4	7	6	3	8	2	7
V	62	53	58	57	90	77	63
W	4	7	3	2	2	8	3
Zr	692	817	546	714	769	832	854
Zn	92	90	79	85	61	74	69
Pb	5	3	3	4	6	2	3

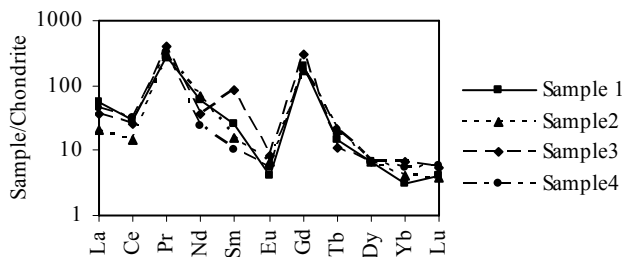


Figure 5. Chondrite normalized REE distribution pattern of Choghart magnetites.

North Ryde, Australia, for measurement of their $^{18}\text{O}/^{16}\text{O}$ ratios. The results are reported in Table 3 in units of per mil (‰) relative to VSMOW for oxygen. Considering that the magnetites formed at about 500°C, which is a reasonable guess, bearing in mind that they are associated with alkali intrusive and extrusive granitoids, then the fluid from which they formed, would yield $\delta^{18}\text{O}$ values that range from 8.5 to 10.4‰ which will fall in the magmatic water box and hence provide further support for a magmatic origin of Choghart magnetite (Fig. 6).

3.2. Apatite Geochemistry

Seven apatite samples were carefully separated from Choghart ore using combined hand-picking and heavy liquid and magnetic separation methods. The purity of the apatite was controlled by a binocular microscope. The elemental compositions were determined by INAA, ICP, and standard wet chemical analysis. CO_2 , although present in small amounts could not be determined quantitatively.

The results are presented in Table 4 and show that Choghart apatite is a fluorapatite with some minor solid solution substitution of Cl and OH for F, and Sr, Mn, Mg and Fe^{2+} for Ca. Trace elements are not present in appreciable amounts. Of the 12 trace elements determined, only As (211-363 ppm) and Zr (546-854 ppm) are present in significant concentrations, while Pb, W and U concentrations are very close to the detection limits and must be considered negligible. The concentrations of Ba, Th, V and Zn range between 50-100 ppm, while those of Co, Cr, and Rb range between 10-50 ppm.

The chondrite-normalized REE patterns of four Choghart apatites are shown in Figure 7. All four analyzed samples display similar distribution patterns, with strong LREE/HREE ratios, a pronounced negative Eu anomaly and a slightly negative Ce anomaly. The ΣREE content ranges between 9854 and 13,604 ppm (Table 5). The average $(\text{La}/\text{Lu})_{\text{cn}}$ ratio of 31.4 (compared with 8.3 for magnetites) is indicative of strong fractionation. Strong LREE/HREE fractionation is probably related to the source and composition of the enclosing host rocks and the closely associated magnetite. Wilson [26] has shown that strong LREE/HREE enrichments are characteristic of alkaline rocks similar to those found in Choghart. The strong negative Eu anomaly probably indicates near-surface fractionation of alkali rhyolites involving feldspars, while the slight Ce depletion may be the result of late-stage metasomatic alteration. When compared with Kiruna apatites, Choghart apatites prove to be at least

one order of magnitude richer in REE. The other difference is the aforementioned Ce depletion at Choghart. However, the overall trend of REE distribution in Choghart apatites is very similar to that of Kirunavaara (Fig. 8).

4. Discussion and Conclusion

The Choghart apatite-iron oxide deposit and indeed the whole Bafq mining district of Iran, is a fragment of Gondwana with a Precambrian basement. The ore district is part of a Pan-African Late-Proterozoic extensional volcano-tectonic province. The spatial association of the Choghart orebody with alkaline intrusive and extrusive igneous rocks clearly indicates a genetic relationship between alkaline magmatism and iron-oxide ore formation. Hauck [13] states that alkaline magma is the ultimate source of iron-rich melts, which he suggests to have been derived from it by liquid immiscibility. The field relationships and the overall geological evidence at Choghart indicate that the

Table 5. REE concentration in Choghart apatites

No.	1	2	3	4	Chond ^a
La	2800	2000	2500	2200	0.34
Ce	5900	4300	4900	4100	0.91
Pr	930	754	777	750	0.121
Nd	2900	2300	3500	2000	0.64
Sm	274	276	278	266	0.195
Eu	46	43	46	41	0.073
Gd	456	265	276	250	0.26
Tb	40	38	36	33	0.047
Dy	180	156	179	149	0.3
Yb	70	64	65	58	0.22
Lu	8	8	7.5	6.8	0.034
ΣREE	13604	10204	12564.5	9853.8	
$(\text{La}/\text{Lu})_{\text{cn}}$	35	25	33.33	32.35	
$(\text{La}/\text{Sm})_{\text{cn}}$	5.86	4.16	5.16	4.74	
$(\text{Gd}/\text{Lu})_{\text{cn}}$	7.45	4.33	4.81	4.81	
$[\text{Eu}]/[\text{Eu}^*]$	0.04	0.5	0.5	0.5	
$[\text{Ce}]/[\text{Ce}^*]$	0.8	0.8	0.8	0.8	
Eu/Sm	0.17	0.16	0.16	0.15	

^a Chondrite values from Wakita *et al.* [24]

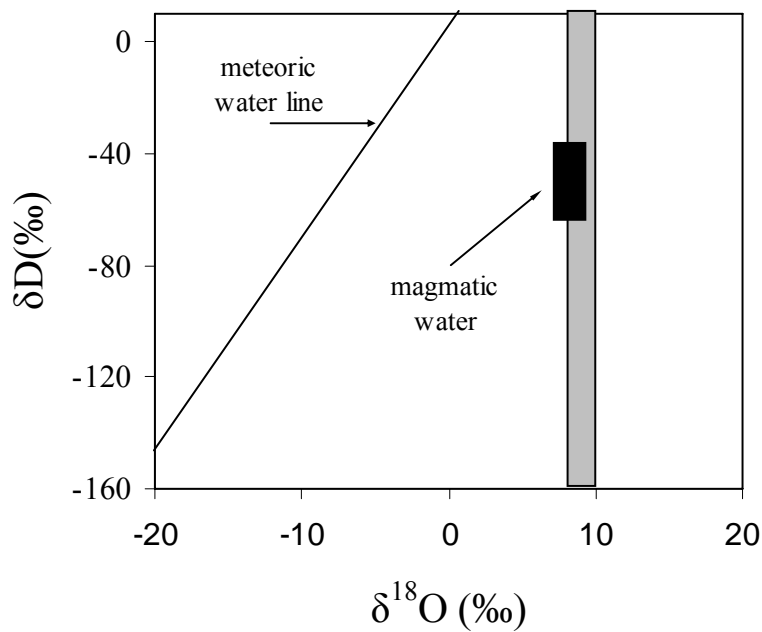


Figure 6. $\delta^{18}\text{O}$ values of Choghart magnetite showing a band overlapping the range given for magmatic water.

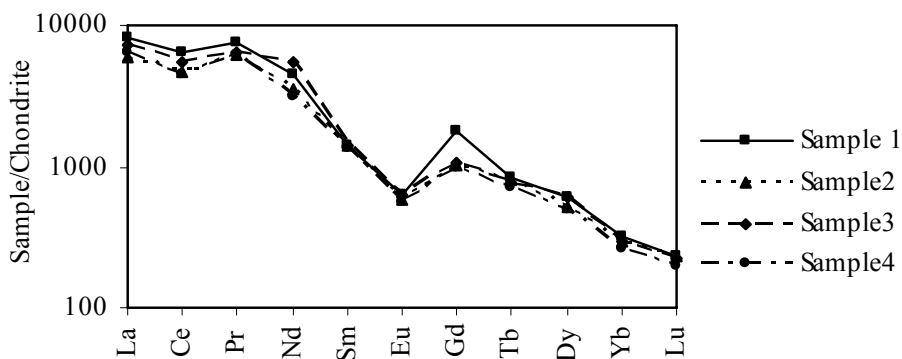


Figure 7. Chondrite normalized REE distribution pattern of Choghart apatites.

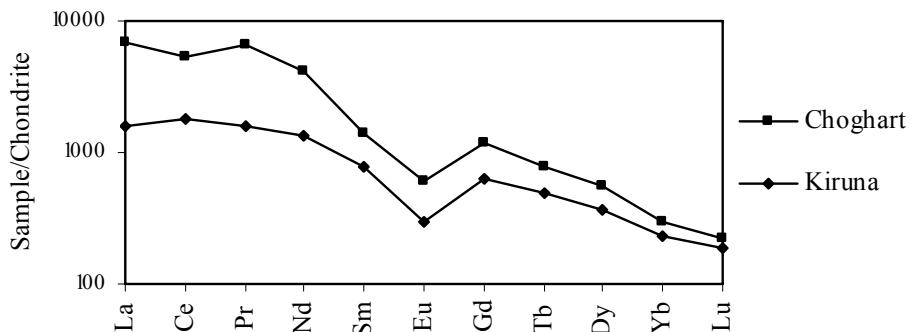


Figure 8. Comparison of Choghart REE pattern with Kirunavaara.

ryholitic to syenitic host rocks, the products of intracratonic plutonism and a tensional geological setting (rifting), were roughly synchronous and coeval with mineralization. The magnetite-apatite ores of Choghart were probably formed by magmatic differentiation of the alkaline magma. The high phosphorous and alkali content probably led to the formation of a Fe-F, CO₂-H₂O-P-Na dominated immiscible melt which separated from a silica-rich melt. The high phosphorous content and the so-called alkali-iron effect [12] fluxed the immiscible melt and kept iron in solution at temperatures significantly lower than the melting point of magnetite at rather shallow depth. The role of other volatile constituents such as CO₂ and F is also important in this process [25]. The PCO₂ at Choghart may have been raised by the assimilation of Esfordi dolomite, as evidenced by the presence of dolomitic xenoliths in the volcanic hosts. The presence of fluor-apatite and hydrous minerals (amphiboles) also suggest high F and H₂O content. Both experimental and theoretical analysis of the behavior of volatile-rich magma systems stress the important role liquid immiscibility may play [16]. The breakdown of this late immiscible phase has resulted in the formation of magnetite-apatite melt, which behaved intrusively at Choghart and similar deposits, and probably extrusively in occurrences such as Se Chahun in the Bafq mining district. The intrusion or extrusion of the separated iron-oxide melt depends upon depth of separation, volatile content of iron-rich melt, and finally presence or absence of favorable tectonic and structural conditions. Structural control of Choghart orebody is particularly evident in the discordant pipe-shaped mass.

Most of the high concentration of REEs was probably partitioned as F-REE complexes in the fluorine-dominated fluid generated during volatile exsolution. The majority of the REEs are contained in apatite, and to date, it is the only identified phase with high REE. However, some of the REE in apatite is probably contributed by REE-bearing microscopic solid inclusions such as monazite and xenotime in apatite. According to Taylor and McLennan [23], REE distribution patterns depend on the bulk REE composition in the parent magma. When the REE content of Choghart deposit is compared with that of the Kiruna ores, it displays a stronger LREE/HREE fractionation and a large Eu depletion, probably indicating a relationship to alkaline parent magma, in turn suggestive of a rifting environment. Taylor and Fryer [22] suggest that LREEs are preferentially mobilized in Cl-rich fluids, whereas F and CO₂-bearing fluids are rich in HREE. Thus, it is likely that HREE were selectively leached from Choghart apatite by F

and CO₂-rich late fluids, giving rise to the observed high LREE/HREE ratio.

The alkaline plutonic and volcanic host rocks are crushed and hydrothermally altered to an extent that the original chemistry of the host rocks is only roughly known. However, the alteration assemblages associated with the Choghart deposit, the pyroclastic texture, and the fact that alkaline intrusive and extrusive hosts are impregnated with magnetite or dissected by magnetite veins of limited extent is evidence of a metasomatic component late in the ore-forming process and the hydrothermal origin for some of the ore.

The distribution and origin of sulfides (magmatic vs. hydrothermal) are not well-documented at Choghart. Pyrite appears to be widely distributed as disseminations in the magnetite. Chalcopyrite is the sole copper sulfide observed, and occurs as solid inclusions within the magnetite or as microveinlets cutting it, suggesting that chalcopyrite precipitation accompanied or post-dated magnetite formation. According to Hitzman *et al.* [15] iron and/or copper sulfides are especially common in the magnetite-rich iron-oxide deposits. Grip [11] also reported sulfides in the magnetites of northern and central Sweden. The very low sulfide to iron oxide ratio at Choghart, suggests low concentration of sulfur in the original immiscible melt and the late hydrothermal fluids.

In summary, it may be concluded that following the establishment of late Proterozoic extensional tectonic regime in the Bafq mining district and the onset of alkaline magmatism, iron oxide mineralization occurred at Choghart. In view of the enormous size of the orebody, the large volume of melt or high temperature hydrothermal fluid needed for the formation of Choghart, and the conflicting evidence for and against liquid immiscibility or hydrothermal origin, neither of the two hypotheses can be held responsible alone for the formation of Choghart deposit. It is suggested here that the separation of an iron oxide melt and the ensuing hydrothermal processes dominated by alkali metasomatism were both involved to different degrees in the formation of Choghart deposit.

Acknowledgments

The authors would like to thank the research council of Shiraz University for grant No. 78-SC-1274-670 for providing the financial support needed for this study. Oxygen isotope results were provided by Dr. Edraki (CSIRO), Australia, and Dr. Kesler (Michigan University), to whom we are indebted. Thanks are also extended to Dr J. Richards of Alberta University for critically reading the manuscript.

References

- Berberian M. and King G.C.P. Towards a paleogeography and tectonic evolution of Iran. *Canadian Journal of Earth Science*, **18**: 210-265 (1981).
- Borook D.M., Kesler S.E., Boer R.H. and Essene E.J. The Vergenoeg magnetite-fluorite deposit, South Africa: support for a hydrothermal model for massive iron oxide deposits. *Economic Geology*, **93**: 564-586 (1998).
- Daliran F. The magnetite-apatite deposit of Mishdovan, East Central Iran. An alkali rhyolite hosted, "Kiruna type" occurrence in the Infracambrian Bafq metallotect. Heidelberg Geowissenschaftliche Abhandlungen, Ph.D. thesis, 37, 248 (1990).
- Daliran F. REE geochemistry of Bafq apatites, Iran; implication for the genesis of Kiruna-type iron ores. In: Stanclly *et al.* (Eds.) *Mineral Deposits; Processes to Processing*. Balkema, Rotterdam, pp. 631-634 (1999).
- Förster H. and Borumandi H. Jungpräkambrische magnetit-lava und magnetit-tuffe aus dem Zentraliran. *Die Naturwissenschaften*, **58**: 524-525 (1971).
- Förster H. and Jafarzadeh A. The Bafq mining district in Central Iran: A highly mineralized Infracambrian volcanic field. *Economic Geology*, **89**: 1697-1721 (1994).
- Förster H. and Knittel U. Petrographic observation on a magnetite deposit at Mishdovan, Central Iran. *Ibid.*, **74**: 1485-1510 (1979).
- Frietsch R. On the magmatic origin of the iron ores of the Kiruna-type. *Ibid.*, **73**: 478-485 (1978).
- Frietsch R. and Predhal J.A. Rare earth elements in apatite and magnetite in Kiruna-type iron ores and some other iron ore types. *Ore Geology Reviews*, **9**: 489-510 (1995).
- Gerasimovsky V.V. and Minjeev D.A. Redkozemelyne elementy v apatitach izapatit-magnetiovykh. *Rud Geochimija*, **1**: 99-104 (1981).
- Grip E. Sweden. In: Bowie A., Kvalheim A. and Haslam H.W. (Eds.) *Mineral Deposits of Europe*. Inst Min Metall, **1**: 93-198 (1979).
- Guilbert J.M. and Park C.F. *The Geology of Ore Deposits*. WH Freeman & Company, 985 p. (1997).
- Hauck S.A. Petrogenesis and tectonic setting of middle Proterozoic iron oxide-rich ore deposits: an ore deposit model for Olympic Dam-type mineralization. In: Pratt W.P. and Sims P.K. (Eds.) *The Mid-continent: Permissive Terrain for an Olympic Dam Deposit?* USGS Bull, **1932**: 4-39 (1990).
- Hildebrand R.S. Kiruna type deposits: their origin and relationship to intermediate subvolcanic plutons in the Great Bear magmatic zone, northwest Canada. *Economic Geology*, **81**: 640-659 (1986).
- Hitzman M.W., Oreskes N. and Einaudi M.T. Geological characteristics and tectonic setting of Proterozoic iron oxide (Cu-U-Au-REE) deposits. *Precambrian Research*, **58**: 241-287 (1992).
- Kolker A. Mineralogy and geochemistry of Fe-Ti oxide and apatite (nelsonite) deposits and evolution of the liquid immiscibility hypothesis. *Economic Geology*, **77**: 1146-1158 (1982).
- Lohberg B.E.H. and Horndhal A.K. Ferride geochemistry of Swedish Precambrian iron ores. *Mineralium Deposita*, **48**: 487-504 (1983).
- Nyström J.O. and Henriquez F. Magmatic features of iron ores of the Kiruna type in Chile and Sweden: ore textures and magnetite geochemistry. *Economic Geology*, **89**: 820-839 (1994).
- Pallache C., Beramn H. and Frondel C. *The System of Mineralogy*. John Wiley & Sons, Vol. 1834 p. (1963).
- Samani B.A. Metallogeny of the Precambrian in Iran. *Precambrian Research*, **39**: 85-106 (1988).
- Samani B.A. Sagand formation, a riftogenic unit of Upper Precambrian in Central Iran. *Geosciences, Scientific Quarterly Journal of the Geological Survey of Iran* (in Farsi with English abstract), **2**(6): 32-45 (1993).
- Taylor R.P. and Fryer B.J. Rare earth element geochemistry of granitoid mineral deposits. *Canadian Inst Min Metall Bull*, **76**: 74-84 (1983).
- Taylor R.P. and McLennan S.M. *The Continental Crust: Its Composition and Evolution*. Blackwell, Oxford, 312 p. (1985).
- Wakita H., Ray P. and Schmitt R.A. Abundances of the 14 rare earth elements and 12 other trace elements in Apollo12 samples: five igneous and one breccia rocks and four soils. *Proc 2nd Lunar Sciences Conf.*, pp. 139-1329 (1971).
- Weidner R.Jr. Iron oxide magmas in the system F-C-O. *Canadian Mineralogist*, **20**: 555-666 (1982).
- Wilson M. *Igneous Petrogenesis*. Harper Collins Academic, London, 499 p. (1991).