Iraqi Bulletin of Geology and Mining *Vol.17, No.1, 2021* *p 43 – 58*

CHARACTERISTICS AND ORIGIN OF IRON MINERALIZATION IN NORTHERN SANANDAJ – SIRJAN ZONE (IRAN – IRAQ)

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Received: 09/ 03/ 2020, Accepted: 14/ 07/ 2020
Key words: Iron mineralization; Magnetite; Magmatic exhalations; Skarn iron; Stratiform deposits

ABSTRACT

The studied iron mineralization is located in the northwestern parts of the Sanandaj – Sirjan Zone (SaSZ) of Iran and extends inside Iraq. This zone is bordered by the Urumieh – Dokhtar magmatic arc and the Zagros Thrust Zone, which is the boundary between the Arabian and Iranian plates. The SaSZ is very important for its iron, manganese and gold mineralizations. The main iron ore localities and mining sites in the area are studied in this work. The study included field characterization, petrologic and geochemical analysis. The aim of the present work is to study the genesis and paragenetic history of the Fe mineralization in this zone. The results indicate a two-phase formation process with two different paragenesis of iron mineralization in most of the localities studied in the region of the northern Sanandaj – Sirjan Zone; one of low temperature and the other formed at high temperature. The first phase represents sedimentary exhalative iron oxides layers. The second phase is metamorphogenic, following orogenesis, metamorphism, and plutonism. High-temperature fluids released from the solidification of a large plutonic body remobilized iron oxides of the first phase and caused deposition as magnetite and high-temperature silicate veins within higher stratigraphic levels.

خصائص وأصل تمعدن الحديد في نطاق سنندج – سرجان الشمالي (إيران – العراق)

حسين مونوزيري و تؤله احمد ميرزا

المستخلص

تقع مواقع تمعدن الحديد التي تمت دراستها في الجزء الشمالي الغربي من نطاق سنندج – سيرجان في إيران ويمتد داخل العراق. يحد هذه المنطقة قوس أوروميا – دوختار الصهاري ونطاق دسر زاغروس وهو الحد الفاصل بين الصفيحتين العربية والإيرانية. تمت دراسة مواقع تمعدن الحديد والمناجم الرئيسية في هذه المنطقة وشملت الدراسة التوصيف الحقلي والفحوصات الصخارية المجهرية والتحليلات الجيوكيميائية وتهدف الى تحديد العوامل المنشأية لرواسب الحديد بمختلف أطوارها وعلاقتها بالتاريخ الجيولوجي للمنطقة. تشير نتائج هذه الدراسه الى ان معظم تمعدنات الحديد في منطقة شمال سنندج – سيرجان تشكلت بمرحلتين، إحداهما في درجة حرارة منخفضة والأخرى في درجة حرارة عالية. تمثل المرحلة الأولى تكوين طبقات أكاسيد الحديد الزفير الترسباتية والمرحلة الثانية هي مرحله التحول بسبب الحركات الأوروجينية والبلوتونية حيث عملت السوائل ذات درجة الحرارة العالية المنبعثة من تصلب جسم بلوتوني كبير فى إعادة انتشار أكاسيد الحديد المتكونة في المرحلة الأولى وإعادة ترسيبها في المستويات الطباقية الأعلى كعروق من المغنيتيت والسيليكات ذات درجات الحرارة العالية.

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INTRODUCTION

The studied iron mineralizations are located in the northwestern part of Sanandaj – Sirjan Zone (SaSZ) (Figs.1A and 1B), which has had a particular geologic history since the Triassic (Stöcklin, 1974). The Zagros Thrust Zone, with a northwest – southeast trend, which represents the tectonic boundary between the Arabian and Iranian plates, passes to the southwest of northern part of the Sanandaj – Sirjan Zone (Fig.1B). The SaSZ is a major metallogenic zone that has been deformed significantly due to plate tectonics and that has passed through almost the same geological history as central Iran. Iron mineralization in the northern Sanandaj – Sirjan Zone ranges in age from Precambrian to Permian, Jurassic and Cretaceous, and then Miocene (Zahedi and Hajian, 1985; Kholghi-Khasraghi, 1999).

In most of the ore deposits of the region, the iron mineralization has a stratiform character due to its sedimentary exhalative origin. The age of the host rock is within the time span from Permian to Early Mesozoic, as is the associated stratiform magnetite mineralization (Nabatiana *et al*., 2015; Eslamizadeh, 2016). In places, it is associated with volcano-sedimentary sequences and sometimes calcsilicate veins. The iron mineralization often occurs as interlayers within volcano-sedimentary formations. In cases where intrusive igneous masses are present, the magnetite veins are tens of meters away from the intrusive masses and the limestone formations.

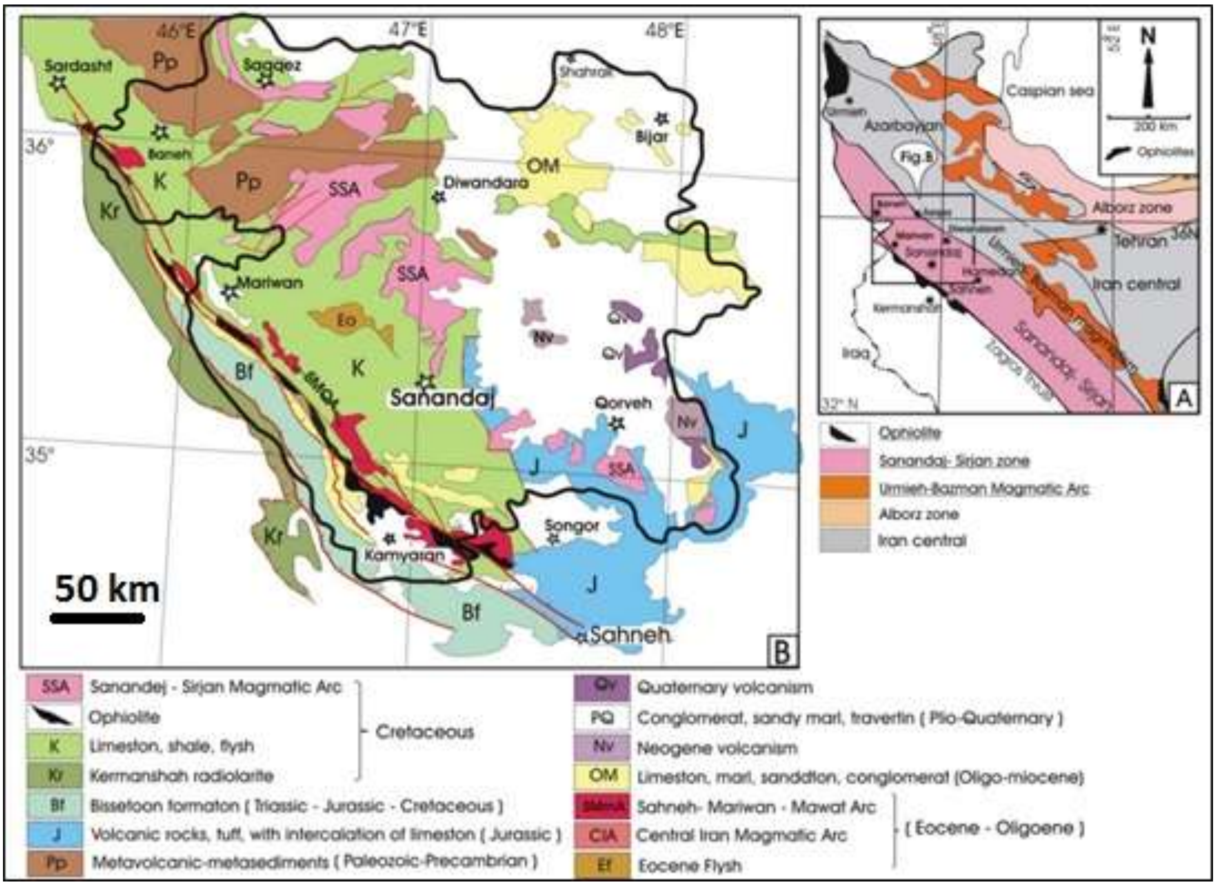

Fig.1: **A)** Simplified structural map of Iran (Stocklin, 1968). **B)** Simplified geological map of northwestern part of Iran, modified from 1/ 250,000 and 1/ 100,000 geological maps (Zahedi and Hajian, 1985; Sartipi *et al*., 2006) Geological Survey and Mineral Exploration of Iran

GEOLOGICAL SETTING

The SaSZ, a Triassic and Jurassic sedimentary basin parallel to the Zagros Thrust Zone, consists of pelite, calcilutite, graywacke, and volcanic rocks (Braud, and Bellon, 1974, Berberian, and Berberian, 1981; Berthier *et al*., 1974). Sediments were folded during the Late Jurassic orogenic phase by a weak regional metamorphic event (Mohajjel *et al*., 2003). A chain of intrusive masses with a calc-alkaline signature, including diorites, quartz diorites to granodiorites and granites, and sporadic gabbros, was intruded into the sedimentary sequence in the Late Jurassic and Cretaceous (Fig.1B), causing an increase of the geothermal gradients in the area and distinctive metamorphism around the intrusive masses (Ahmadi-Khalaj *et al*., 2007; Baharifar *et al*., 2004; Massoudi *et al*., 2002; Berthier *et al*., 1974; Shahbazi *et al*., 2010: Sepahi *et al*., 2014). Multiphase plutonic activity affected the region from Late Jurassic to the Paleocene, as reported by Ahmadi-Khalaj *et al*. (2007), Masoudi *et al*. (2002), Valizadeh and Cantagrel (1975), Baharifar *et al*. (2004), Shahbazi *et al*. (2010), Azizi *et al*. (2011), and Sepahi *et al*. (2014).

The Triassic – Jurassic sequence endured a new metamorphic event related to the Laramide Orogeny at the end of the Cretaceous. Additionally, a range of calc-alkaline intrusive masses, including gabbros, diorites, and granites, intruded in the Zagros Thrust Zone (Sahneh – Marivan – Mawat magmatic arc) in the Early Cretaceous – Early Oligocene age (Moinevaziri *et al*., 2008; Azizi *et al*., 2011). The region underwent compression phases, with faulting and thrusting, during the Tertiary. In the Northern Sanandaj Sirjan Zone, numerous iron mineralizations (Fig.2), including the Saghez (Araboghli, Hassansalarn, Saheb), West Marivan (Asnawa), West Divandareh (Nargestala, Allijan, Tawakalan, Kanisepid, Zafarawa), North Bijar (Shahrak, Gharakand), South Dehgolan (Meymoonawa), and East Qorveh (Galalli, Khosroawa, Charmalah, Hezarkhani, Meymanat-awa and Baba-Ali) are mined and others are under exploration.

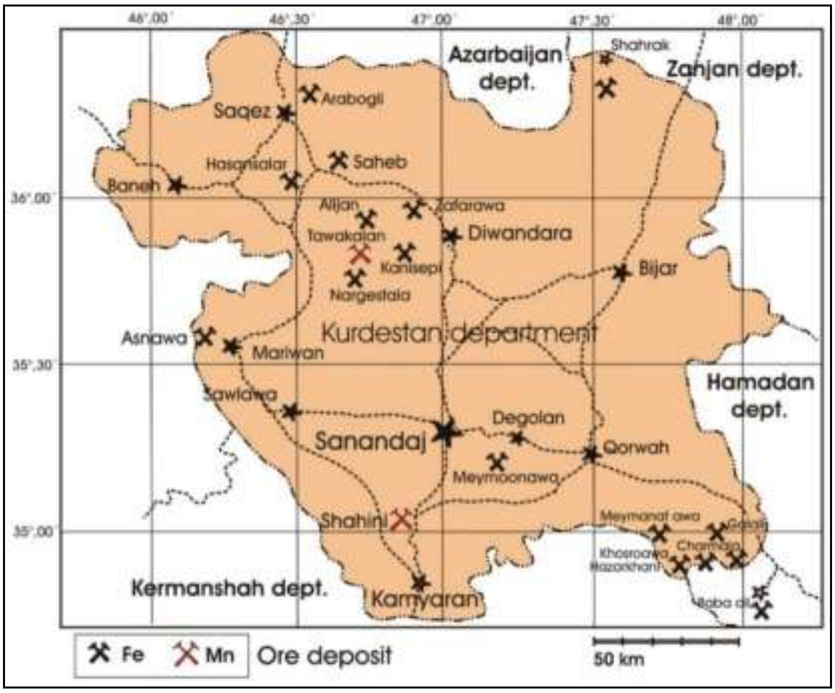

Fig.2: Location map of iron and manganese mineralization in the northern Sanandaj – Sirjan Zone

METHODOLOGY

This study relied mainly on field observations carried out in main iron ore occurrences and deposits, accompanied by optical microscopy and geochemical analysis. All samples were collected during field trips to different iron ore mineralization units. Sampling for this study included the ore and host rocks. Fourteen ore samples and 45 samples from the host rocks were collected. The mineral components of the samples were studied by polarized transmitted-light microscope and reflected-light microscope. Thin and polished sections were prepared for the petrographic study. Several samples were selected and analysed by X-ray fluorescence (XRF) for major and trace elements concentration. The petrologic work and geochemical analysis were done in the Faculty of Earth Sciences, Kharazmi University, Tehran, Iran, Kansaran Binaloud Company, and Research Laboratory of the Department of Geology, College of Science, University of Sulaimani.

FIELD CHARACTERISTICS

Hematite iron mineralization in the northeast of northern Sanandaj – Sirjan Zone (Araboghli, northeast of Saghez; Nargestala, west of Divandareh) occurs as interbeds in Permian or Cretaceous volcano-sedimentary formations (Zahedi and Hajian, 1985; Kholghi-Khasraghi, 1999; Hitzman *et al*., 1992). Attaining economic value in faults and fractures, the hematite ore type has lateritic characteristics (Fig.3a). The region of Saghez (Hasansalarn and Saheb) also accommodates skarn magnetite mineralization (Zandi *et al*., 2018). The magnetite iron ore is associated with calcsilicates within Precambrian or Permian formations. It exists as small outcrops scattered regionally on the surface in the Diwandareh region **(**Zafarawa, Alijan, Tawakalan, and Kanisepid; Fig.3b).

– **Asnawa magnetite iron ore** is located in Iraq near Iran border, about 3 Km to the southeast of the town of Penjween and west of Mariwan. The iron mineralization is located at the top of a massive granodiorite and within Cretaceous volcano-sedimentary rocks. The magnetite iron ore occurs within the folds and schistosity of the host rocks (Figs.3c and d). The schistose rocks of Asnawa represent the lower part of the Qandil Series, which was regionally metamorphosed to greenschist and epidote-amphibolite grades during the Laramide orogenic phase (Abdwon, 2011; and Karim *et al*., 2015). The Asnawa ore body is about 250 m long and 50 m wide at maximum. It has as a fine-grained texture and massive structure. Grains are euhedral, subhedral, and anhedral (Fig.3e). Gangue minerals include hornblende, clinopyroxene, andradite, and chlorite (Karim *et al*., 2015).

– **North of Bijar**, several magnetite ore deposits occur in the villages of Shahrak and Gharakand. In this area, tonalite, diorite, and granodiorite masses were intruded into Oligocene – Miocene formations. The Oligo – Miocene formations in the valleys accommodate tuff, andesitic and trachy andesitic lava, calcareous beds, and magnetite ore. The magnetite ore is associated with pyrite and gangue minerals including quartz, dolomite, siderite, epidote, garnet, actinolite, and chlorite.

– **East of Sanandaj**, there are a large number of dispersed outcrops of iron ore deposits. The host lavas and pyroclastic rocks are often accompanied by thin layers of Jurassic limestone. The Jurassic limestone is covered unconformably by calcareous and volcanic rocks of the Late Cretaceous (Moinevaziri *et al*., 2015). The host rocks of the iron ore in the Khosroawa, Takyayebala, Charmalah, Hezarkhani, and Baba-ali are also pyroclastics, volcanic lavas, and thin dislocated layers of Jurassic limestone. In these areas, the gangue is epidosite and amphibolite, and the iron ore deposits are associated with sulfide minerals (Tavakoli. 2004;

Motavali *et al*., 2005). In the Galali locality, the magnetite mineralization occurs in volcanic rocks (rhyolitic, dacitic, and andesitic tuff) far from the granitic mass (Fig.4).

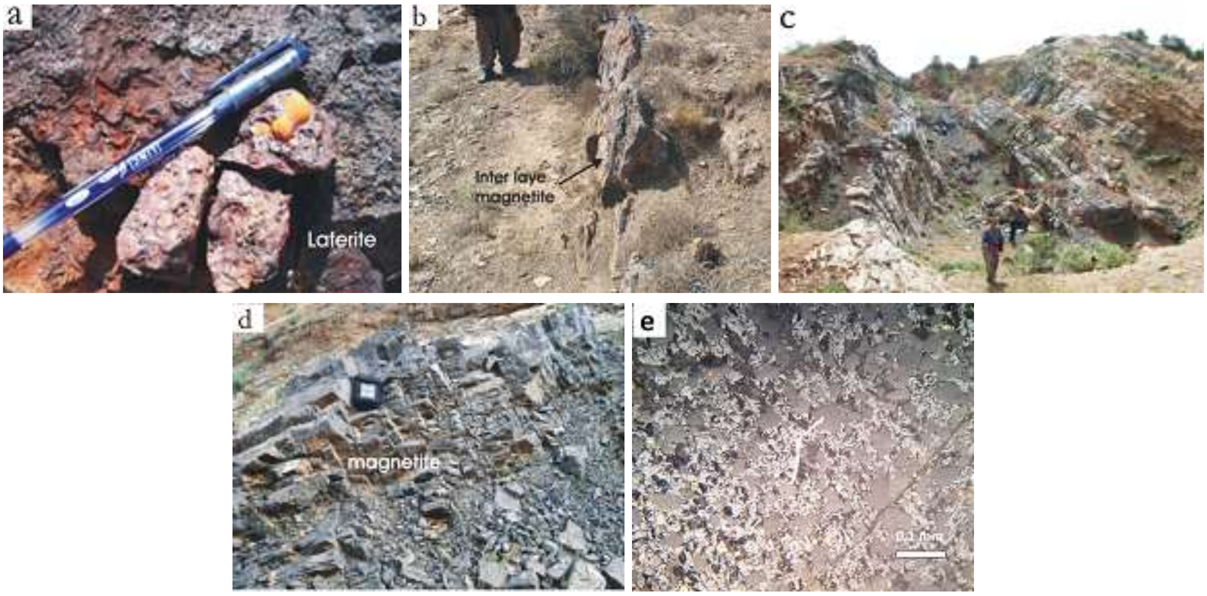

Fig.3: **a)** Nargestala lateritic ore, **b)** Iron ore (magnetite and hematite) in the Kanisepid village (west Diwandareh), **c)** Asnawa iron mineralization in west Mariwan, **d)** Asnawa ore body has formed schistosity in three spatial directions as its host rocks. **e)** Magnetite of Asnawa under reflected-light microscope characterized by fine grained texture and massive structure

Fig.4: One of Galali iron mines: the mineralization occurs in volcanic rocks without contact with limestone and intrusive body

MINERALOGY AND CHEMICAL COMPOSITION OF THE IRON ORE

To determine the mineral composition of the iron ore deposits, transmitted and reflected light microscopy are used. The results of the microscopic study show that the iron mineralization in the northern Sanandaj – Sirjan Zone is mainly magnetite, occasionally with hematite and often without apatite (Fig.5). In the Permian formations, the mineralization consists mainly of interstratified laterite and hematite as fracture filling. Iron ore deposits, such as the Hassansalarn, Shahrak, Galali, Baba-Ali, Khosroawa, Charmalah, Hezarkhani, and Takyebala, are associated with sulfides. Gangue minerals in these deposits are quartz, calcite, actinolite, chlorite, epidote, rarely dolomite, siderite, and garnet.

The $Fe_2O_3^t$ content in the iron ores of the northern Sanandaj – Sirjan Zone is between 45.9 and 91.26 wt.%, SiO_2 ranges from 5.47 to 40.6 wt.%, TiO_2 ranges from 0.03 to 0.46 wt.%, and P_2O_5 ranges from 0.03 to 0.77 wt. %; only a Shahrak sample contained high P_2O_5 of 2.22 wt. % (Table 1). The chemical composition of the iron ores from most of the ore deposits in the northern Sanandaj – Sirjan Zone shows a relative richness in V and Ti in the magmatic magnetite and magnetite skarn. The relationship between the elements V, Ni, and Ti (Lohberg and Horndahl, 1983) and the variation of Ca+Al+Mn vs. Ti+V (Dupuis and Beaudoin, 2011) indicate a hydrothermal origin for Maymoonawa, Galali, Zafarawa, and Asnawa but a magmatic origin for the others (Fig.6).

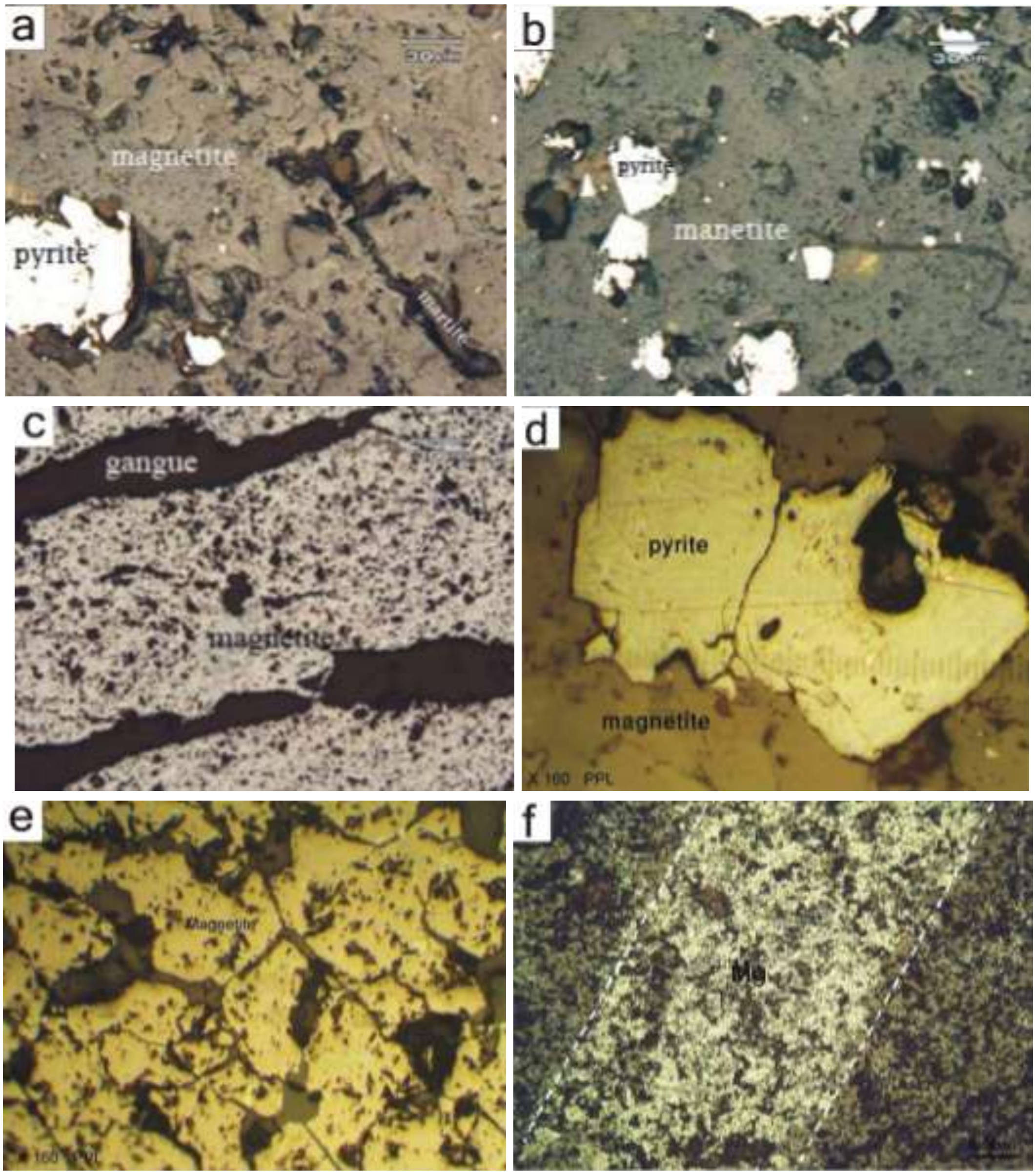

Fig.5: Iron ore study with reflective light; **a**, **b** and **c)** samples from Galali mine (east Qorveh), includes magnetite and minor inclusion of pyrite; **d** and **e)** samples from Kanisefid mine; **f)** sample from Zafarawa mine (west Divandareh)

Table 1: Chemical analysis of iron ores in northern Sanandaj – Sirjan Zone; Khosroawa, Charmalah, Hezarkhani samples from Tavakoli *et al*. (2004); Takye 4 from Motavali *et al*. (2005), Takye 1, 2, 3 samples from Barati *et al*.(2018), and Asnawa R1, R2, R4M, R5M samples from Karim *et al*. (2015).

Sample	**Mymoo 1**	**Mymoo 2**	**Mymoo 3**	**Khosr.**	**Takyeh**	**Charm**	**Hezar.**	**Alijan**	**Zfarawa**	**Nargs.**
SiO_2	26.29	12.99	5.47	10.9	7.39	12.7	40.6	17.39	12.59	21.70
Al_2O_3	3.38	3.6	1.56	0.77	1.51	2.41	4.16	0.3	1.71	3.45
$Fe_2O_3^t$	49.6	53.5	91.26	78.6	87.1	79.7	45.9	81.58	81.77	62.34
CaO	11.43	23.2	0.62	1.48	0.28	1.92	1.19	0.21	0.98	0.70
MgO	8.49	4.13	0	3.37	0.65	0.78	1.22	0.01	0.57	0.66
Na_2O	0.07	0.05	0.15	0.04	0.19	0.19	0.04	0.03	0.05	0.08
K_2O	0.14	0.08	0.12	0.07	0.06	0.35	0.41	0.05	0.05	0.80
MnO	0.11	0.15	0	0.05	0.02	0.05	0.03	0.02	0.14	0.03
TiO_2	0.19	0.15	n.d	0.03	0.46	0.39	0.45	0.06	0.09	0
P_2O_5	0.09	0.07	n.d	0.06	0.13	0.17	0.39	0.00	0.06	0
Total	99.97	97.92	99.56	95.37	97.79	98.66	94.39	99.65	98.01	89.76
V_{ppm}	17.7	27.7	n.d	29	1504	734	194	110	22.2	n.d
Ni_{ppm}	37.4	36.4	n.d	n.d.	n.d.	n,d.	n.d.	28	54	n.d
Ti_{ppm}	1140	900	n.d	180	2760	2340	2700	360	540	n.d
V/Ti	0.015	0.03	n.d	0.16	0.54	0.31	0.07	0.3	0.04	n.d
Ni/Ti	0.03	0.04	n.d	--	--	--	--	0.07	0.01	n.d

Table 1 Continue

Sample	**Shahr.1**	**Shah.2**	**Shah.3**	**Shah.4**	**Shahr.5**	**Glali 1**	**Glali. 2**	**Takye 1**	**Takye 2**	**Takye 3**
SiO_2	5.65	18.92	22.11	23.1	31.57	19.68	22.36	-	-	-
Al_2O_3	2.42	3.85	10.12	5.64	11.25	7.21	5.98	-	-	-
$Fe_2O_3^t$	87.68	64.32	56.07	64.85	49.7	58.63	62.86	-	-	-
CaO	0.75	4.04	3.98	3.93	5.39	12.68	4.86	-	-	-
MgO	0.74	2.2	2.72	0.94	4.35	1.18	1.52	-	-	-
K_2O	0.02	0.03	0.01	0.02	0.03	0.03	0.09	-	-	-
MnO	0.04	0.08	0.03	0.09	0.11	0.32	0.09	-	-	-
TiO_2	0.07	0.16	0.29	0.13	0.38	0.16	0.34	-	-	-
P_2O_5	0.03	0.37	2.22	0.77	0.51	0.12	0.01	-	-	-
Total	97.58	93.7	97.52	99.38	103.18	99.95	100.26	-	-	-
V_{ppm}	80	113	268	359	161	94	30	1219	2210	1019
Ni_{ppm}	46	43	43	36	37	32	131	106	91	105
Ti_{ppm}	420	960	1740	780	2280	960	2040	782	858	731
V/Ti	0.19	0.118	0.15	0.46	0.07	0.09	0.01	1.58	2.57	1.39
Ni/Ti	0.11	0.04	0.02	0.04	0.01	0.03	0.06	0.13	0.1	0.14

Table 1 Continue

Sample	Asnawa	Asnawa R.1	Asnawa R.2	Asnawa R.4M	Asnawa R.5M
SiO_2	21.16	18.23	13.51	4.73	9.20
Al_2O_3	4.23	3.89	2.22	1.37	2.30
$Fe_2O_3^t$	63.26	70.18	77.25	91.98	83.74
CaO	9.28	6.51	5.61	1.66	2.97
MgO	1.51	1.16	1.47	0.28	0.56
Na_2O	--	0.46	0.12	0.13	0.21
K_2O	0.24	0.45	0.12	0.15	0.21
MnO	0.17	0.151	0.125	0.08	0.116
TiO_2	0.23	0.127	0.186	o.174	0.177
P_2O_5	0.31	0.09	0.10	0.02	0.05
L.O.I.	---	1.61	1.37	1.70	1.40
Total	100.39	102.86	102.08	102.27	100.93
V_{ppm}	83	27	97	36	33
Ni_{ppm}	431	440	578	347	212
Ti_{ppm}	1379	762	1116	1044	1062
V/Ti	0.06	0.03	0.08	0.03	0.03
Ni/Ti	0.31	o.58	0.51	0.33	0.2

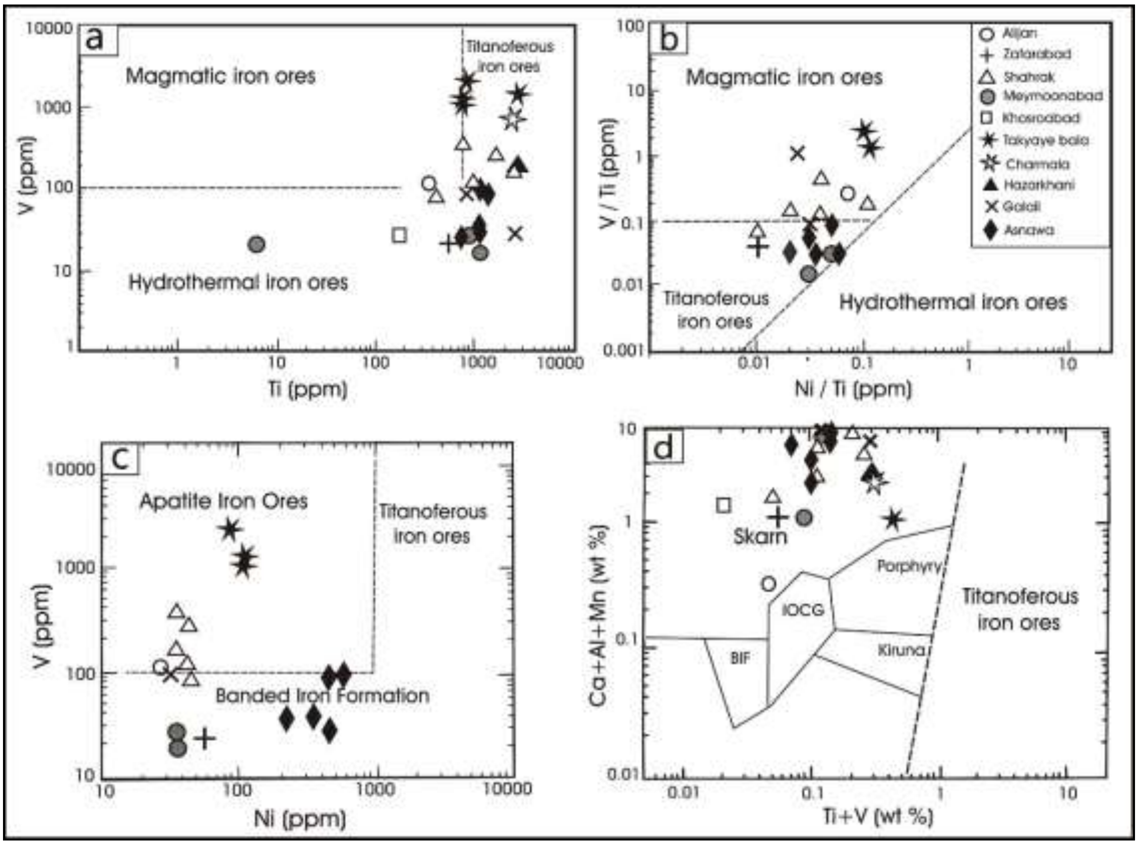

Fig.6: **a, b** and **c)** Diagrams show the relationship between the elements V, Ni and Ti (Loberg, and Horndahl, 1983); **d)** diagram show the variation of Ca + Al + Mn vs. Ti+V (Dupuis and Beaudoin, 2011)

AGE OF THE IRON MINERALIZATIONS

In northwestern Sanandaj Sirjan Zone, magnetite and hematite occur in the Permian and the Mesozoic volcano-sedimentary rocks. These minerals are also interstratified within the sedimentary formations, and for this reason, mineralization must have occurred in the Paleozoic and Mesozoic. In the west and east of Qorveh (eastern part of the northern Sanandaj – Sirjan Zone), iron ore deposits bear magnetite and the host rocks are Jurassic. In this region, granitoid intrusions with age of 144 to 155 Ma (Azizi *et al.*, 2011 and 2015) and 109 Ma (Mahmoudi *et al*., 2011) are intruded into Jurassic sequences.

In Asnawa, west Mariwan, the iron ore is interlayered with Cretaceous volcano-sedimentary rocks. Large granite intrusions with age of 36 to 39 Ma to 37.5 Ma (Sepahi *et al.*, 2014; Karim *et al.*, 2015) intruded into the Cretaceous sequence, and it seems that the plutonism gave rise to iron mineralization. Abdwon (2011) performed $^{40}Ar/^{39}Ar$ analysis of hydrothermal magnesio-hastingsite separated from iron ore samples from the Asnawa area and distinguished a plateau age of 40.8 ± 0.6 Ma, while the age of the magnesio-hastingsite from the country rock samples is of age 37.5 ± 0.8 Ma, suggesting that the magnesio-hastingsite and magnetite in the iron ore were formed contemporaneously or that the magnesio-hastingsite formed slightly earlier. In the north of Bijar, magnetite mineralization developed due to granitoid intrusion into Oligo – Miocene formations, and the age of the mineralization should be Late Miocene.

In the west of Diwandareh, iron mineralization is present in the Paleozoic and Mesozoic volcano-sedimentary formations. Occasionally it i accompanied by calcsilicate veins, which sometimes cross the stratigraphy of sedimentary formations. In this case, the mineralization shows two different stages, a sedimentary stage in the Permian – Jurassic and a hydrothermal stage, which is therefore relatively younger.

The mining area of the Meymoonawa iron mineralization is within an anticline consists of Jurassic and Cretaceous rocks whose eastern part is eroded so that the granite mass is exposed at the base of the formations (Fig.7). The igneous body caused metasomatism in the basal part of the Jurassic formations (Fig.8a). The Meymoonawa iron ore does not have direct contact with the limestone rocks, but it is intimately associated with the Jurassic volcanic rocks in the form of intercalations (Figs.8b and c). Magnetite is sometimes present as void fillings (Fig.8d). It is ordinarily associated with quartz, actinolite, chlorite, albite, and calcite. In many cases, the Jurassic amphibolites are metasomatised basalts, and they contain fine or coarse magnetite grains (Fig.9). The percentage of $Fe_2O_3^t$ in the iron amphibolites (Fig.8c) varies between 15 wt.% (Fig.9a) and 50 wt. % (Fig.9b).

DISCUSSION

The iron ore deposits are globally divided into five groups: sedimentary, magmatic, hydrothermal, skarn, and volcano-sedimentary (Guilbert and Park, 1986). Another type of ore deposit is known, as “iron oxide, copper, and gold” (IOCG) ore (Hitzman *et al*., 1992). The Fe-apatite and Fe-skarn deposits are part of the IOCG deposits (Barton, 2014). Numerous studies have considered the origin of the Fe-mineralization in the SaSZ and its occurrence has been perpetually controversial. The SaSZ is a major metallogenic zone with known tectonic conditions and grades similar to those of the continent. It was an extensional basin that probably represents an early stage of Neo-Tethys opening from the Late Devonian or earlier, (Azizi *et al*., 2011; Abdulzahra *et al*., 2016; Azizi and Stern, 2019), an active continental margin from the Jurassic to the Late Cretaceous, and then a collision zone between the

Arabian and Iranian plates (Moinevaziri, 1985; Azizi *et al*., 2011; Azizi *et al*., 2013; Ali *et al*., 2013; Sepahi *et al*., 2014; and Abdulzahra *et al*., 2017 and 2018).

This variety of settings is a possible explanation for the different types of Fe mineralization occurring in the extension zone, ocean environments, collision zones, and post-collision sedimentary environments. The iron mineralization in northern Sanandaj – Sirjan Zone, passed through almost the same geological history. Iron mineralization in the region has ages from Permian to Jurassic and Cretaceous and then to Miocene and younger. In most areas, the iron mineralization is accommodated as interlayers within the host rocks (stratiform type); which is related to rifting or back arc setting. However, at some locations, the mineralization intersects the stratigraphy of the formations. The veins of magnetite are sporadically associated with calcsilicates, such as actinolite, epidote, and garnet. The presence of magnetite veins at tens of meters away from the intrusive masses excludes the possibility of direct reaction between the magma and the limestone country rocks. Field observations, textures, and structures of the ore occurrences provide convincing basis for this interpretation.

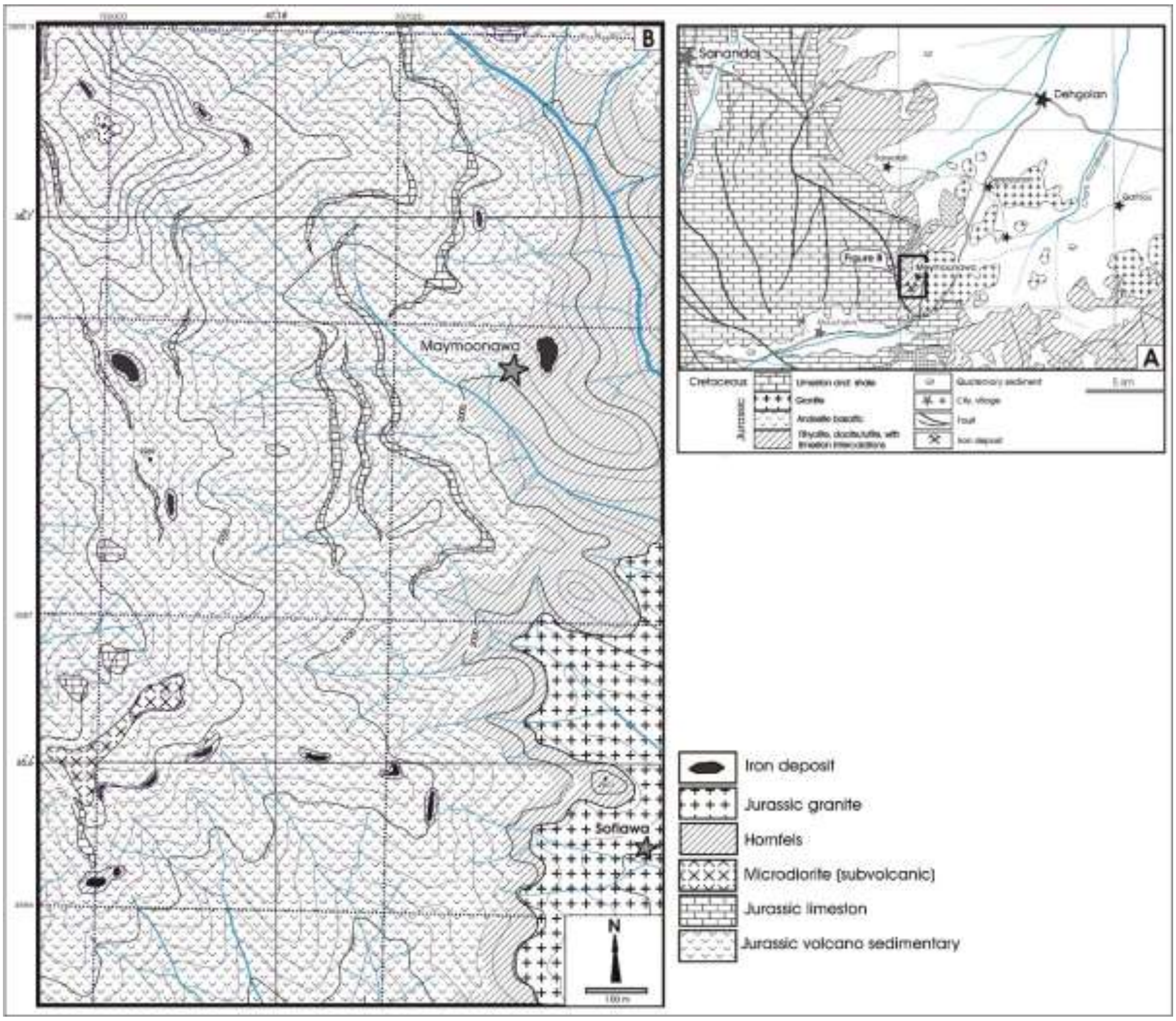

Fig.7: **A)** Geological map of the eastern part of Sanandaj modified from 1/ 100000 geological map (Zahedi and Hajian, 1985); Geological Survey and Mineral Exploration of Iran, **B)** Geological map of Meymounawa area, final report of polymetallic exploration in the Meymoonawa (Moinevaziri, 2005)

Fig.8: **a)** Dacitic and rhyolitic tuffites are metamorphosed into hornfels facies. The white and dark bands consist of pyroxene (with amphibole) and plagioclase respectively; **b)** The magnetite deposits are intruded into volcanic rocks far from limestone and granitic mass; **c)** Meymoonawa magnetite as an interlayer in the Jurassic metabasalt and metatuff; **d)** Dacitic tuff fractures filled with magnetite veins

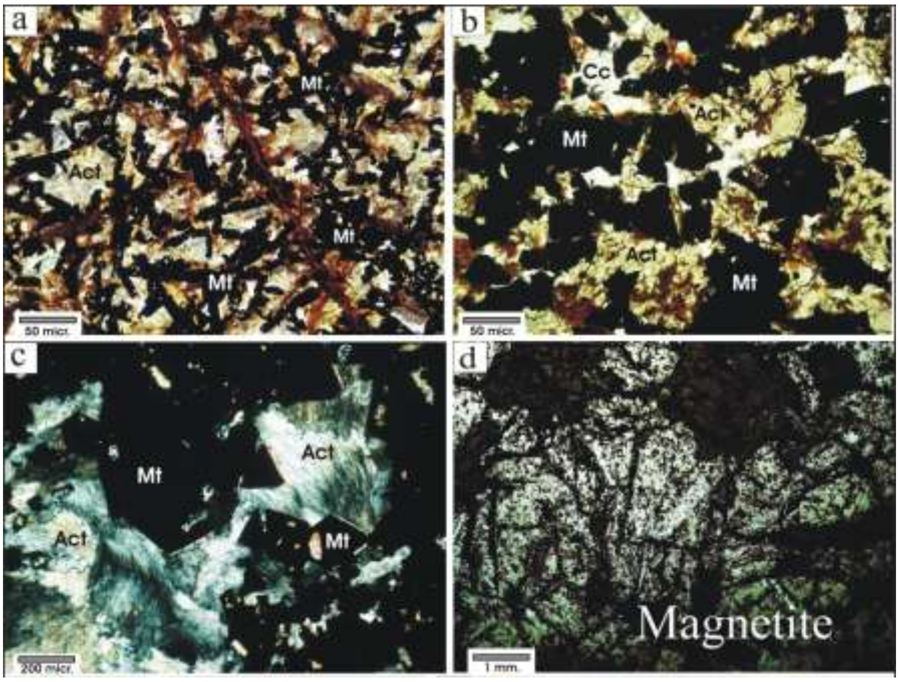

Fig.9: Meymoonawa iron ore studied with transmitted-light **(a, b and c)** and reflected- light (d). **a)** Amphibolite (altered basalt) where the twin and acicular growth of magnetite micro crystals makes overlapping rods; **b** and **c)** iron rich amphibolite; magnetite crystals in advanced growth; and **d)** magnetite ore deposit

In the Meymoonawa region (southwest of Qorveh), the magnetite ore also occurs interstratified with volcanogenic formations. The microscopic characteristics of the iron ores are very different, changing from magnetite amphibolite to almost pure magnetite (Figs.9a and d). The samples with low magnetite content (magnetite amphibolite) include actinolite, albite, and quartz, with some needle-type (acicular) magnetite. The assembly and arrangement of the octahedral microcrysts of magnetite in the magnetite amphibolites (Fig.9a) are reminiscent of those seen today in the fresh basaltic glasses. The magnetite needles are developed in the magnetite-rich amphibolites, which is approximately 80% magnetite and 20% actinolite.

It seems that the pre-existing magnetite microcrysts in the glass of the volcanic rocks grew due to the iron oxide transmitted by hydrothermal fluids and that the crystals of magnetite enlarged to their present form as the hot iron-rich fluids cooled (Fig.9d). In other words, the development of hydrothermal fluids at high temperature involved leaching, transportation, and finally deposition of iron oxide near the surface. Moreover, the granite of Sofiawa in Meymoonawa (Fig.6b), with ages from 149 to 144 Ma (Azizi *et al*., 2011), is a potassium calcalkaline leucogranite and has low iron content ($Fe_2O_3^t$ = 0.53 to 1.75%) it could not have given rise to significant iron mineralization in Meymoonawa. As well as, iron ore deposits of magmatic origin, such as the Kiruna type, include abundant apatite (Williams *et al*., 2005; Groves *et al*., 2010), but apatite is very rare in the iron deposits of this region.

Study of the manganese ores at Tawakalan (west of Divandareh; Fig.2) showed that the manganese mineralization was deposited in two distinct stages (Moinevaziri, 2019). In the first stage, manganese was formed in marine sediments. In the second stage, the sedimentary manganese was dissolved by hot fluids released from deep intrusive masses and then redeposited in the upper horizons. The second stage consists of three sub-stages, in which manganese is first crystallized as high-temperature silicates (spessartite, rhodonite, orientite), then rhodochrosite, and finally pyrolusite.

Based on the field prospecting, microscope study, geochemistry of the ores minerals, and geological history of this area, a two-phase mineralization process for the formation of the iron ores in the Northern Sanandaj Sirjan Zone are suggested in this work (Fig.10):

- Iron ore formed through the Paleozoic and Early Mesozoic in an extensional oceanic basin (Fig.10a).
- Subduction of the Neo-Tethyan oceanic crust (Figure 10b) which occurred from the Early Jurassic to the Late Cretaceous (Moinevaziri, 1985; Agard *et al*., 2005; Moinevaziri *et al*., 2008; Allahyari *et al*., 2010; Moinevaziri *et al*., 2015; and Azizi *et al*., 2015).
- A magmatic arc near the trench and over the northeastern part of the Neo-Tethyan oceanic crust (Figure 10c), called the Sahneh – Marivan Magmatic Belt, formed during the Eocene and Oligocene (Moinevaziri *et al*., 2008; and Azizi and Moinevaziri, 2009).
- At the Late Mesozoic and Tertiary, along with the tectono-magmatic activity, the high temperature fluids released by the crystallization of deep plutonic bodies crossed the iron-rich volcano-sedimentary formations and the iron was leached from the sediments. Iron was then deposited in the highest horizons in the form of magnetite veins accompanied by high-temperature silicates (Fig.10d and e).

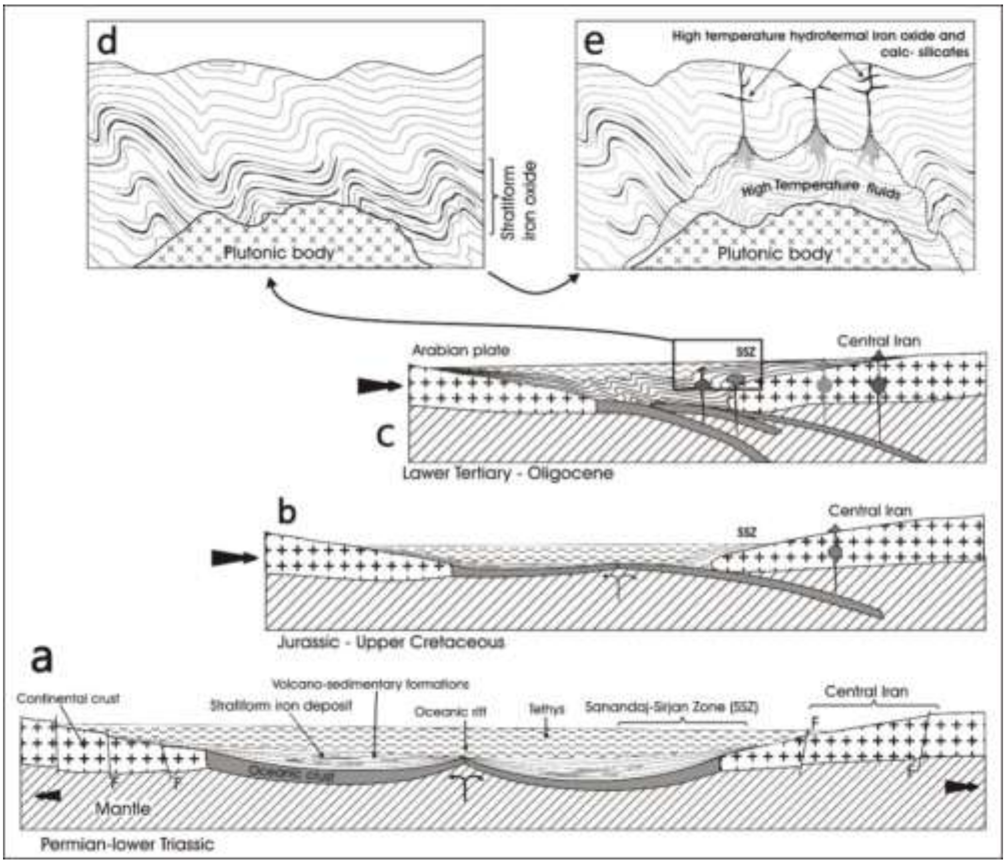

Fig.10: Geological history and iron mineralization process in the studied area. **a)** formation of iron sedimentary ore through the Paleozoic in an extensional basin. **b)** Subduction of Neo-Tethyan oceanic crust from Jurassic to Late Cretaceous time. **c)** During Eocene and Oligocene a magmatic arc is formed near the trench and created an island arc over northeastern part of Neo-Tethyan oceanic crust. **d** and **e)** high temperature fluids released from solidification of the profound plutonic body while passing through the iron rich volcano-sedimentary formations and leached iron from sediments and deposited in the upper horizons again as magnetite accompanied by high temperature silicates

CONCLUSIONS

Field and laboratory studies of iron mineralization in the northern Sanandaj – Sirjan Zone and their comparison with sedimentary, magmatic, hydrothermal, skarn and volcano-sedimentary mineralizations have indicated that, in most cases, the mineralization is not produced by a single process, but two different processes may have been involved. In other words, the Fe did not come directly from magma but came from Fe stored in older sediments. The stratiform iron in the ancient sediments of this province could have been a good source of Fe to supply the hot fluids released from the intrusive masses and then precipitated at higher levels.

ACKNOWLEDGMENTS

The authors would like to thank the Kansaran Binaloud Company and Scientific Research laboratory of Sulaimani University for XRF analysis, as well as grateful thanks for the Faculty of Earth Sciences, Kharazmi University, Tehran, Iran for preparation of thin section and polish section.

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