

Taknar Polymetal (Cu-Zn-Au-Ag-Pb) Deposit: A New Type Magnetite-Rich VMS Deposit, Northeast of Iran

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Abstract

The massive sulfide of Taknar deposits are part of meta volcanic-sedimentary complex (Taknar Formation, Ordovician) and consist of clastic sediments, carbonate, felsic and mafic volcanic and sub-volcanic rocks. The Taknar polymetal deposit shows good layering; therefore it is syngenetic in origin. Taknar zone was affected by low grade metamorphism (Green Schist facies) in the late Paleozoic. As a result, pelitic and subarkosic rocks were changed to sericite or sericite-chlorite schist. Taknar deposit is situated within Taknar zone which is an allochthonous block. This block is situated between two major faults, Drouneh Fault to the south and Rivash (Taknar) Fault to the north. These deposits which are called Tak-I, II, III, and IV, originally were part of one big deposit but due to faulting they are being truncated and moved at least 1 km from each other. Three types of mineralization such as layered, massive and stockwork are present. The layered section is composed of alternating layers of pyrite, chalcopyrite, magnetite, sphalerite, galena and chlorite. The Individual sulphide layers range in thickness from millimeters to 2 cm. Chlorite is the dominate silicate mineral within the layered ore. Massive ore horizons, having >50% magnetite, occur at the stratigraphic top of the mineralized zone. Major minerals are: magnetite + pyrite + chalcopyrite + sphalerite ± galena + chlorite ± quartz ± sericite ± calcite. Pyrite and chalcopyrite content are higher in the lower layers and magnetite, sphalerite and galena are higher within the upper layers. In stockwork mineralization, major minerals are: pyrite + chalcopyrite ± magnetite + quartz + chlorite + sericite ± calcite. Chemical variations of some elements in different deposit are: *Tak-I*: Cu=0.01-5.86%, Zn=269-15600 (ppm), Pb=27-4400 (ppm), Au=0.86-7 (ppm), Ag=2-95 (ppm), Bi=34-2200 (ppm), and Mo=85-1300 (ppm). *Tak-II*: Cu=0.33-2.56%, Zn=0.3-7.7%, Pb=93-5000 (ppm), Au=0.33-11 (ppm), Ag=19-105 (ppm), Bi=79-214 (ppm), and Mo=54-116 (ppm). *Tak-III*: Cu=0.05-5.54%, Zn=62-179 (ppm), Pb=17-47 (ppm), Au=0.06-0.33 (ppm), Ag=2-40 (ppm), and Bi=11-250 (ppm). Based on paragenesis, alteration, style of mineralization, petrography, geochemistry, and structure, Taknar is a new type of magnetite rich polymetal volcanic massive sulfide deposit. Lack of pyrrhotite and high magnetite associated with sulfide minerals make this deposit very different from other VMS deposit. Based on the mineral paragenesis the estimated physiochemical conditions of formation are: Tak-I: $T \text{ } ^\circ\text{C} \geq 250$, $\text{Log } f \text{ O}_2 = (-29) \text{ to } (-30)$, $\text{pH} = 5-7$. Tak-II: $T \text{ } ^\circ\text{C} \leq 250$, $\text{Log } f \text{ S}_2 = (-11) \text{ to } (-12)$, $\text{Log } f \text{ O}_2 = (-36) \text{ to } (-39)$, $5 < \text{pH} < 9$. Tak-III: $T \text{ } ^\circ\text{C} \geq 270$, $\text{Log } f \text{ O}_2 = (-28) \text{ to } (-29)$, $\text{pH} > 5$.

Keywords: Taknar deposit; Polymetal; Massive sulfide; Magnetite

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1. Introduction

Taknar polymetal (Cu-Zn-Au-Ag-Pb) deposit is located in the northeast of Iran (Khorasan province), about 280 km southwest of Mashhad city and 28 km northwest of Bardaskan city (Fig. 1).

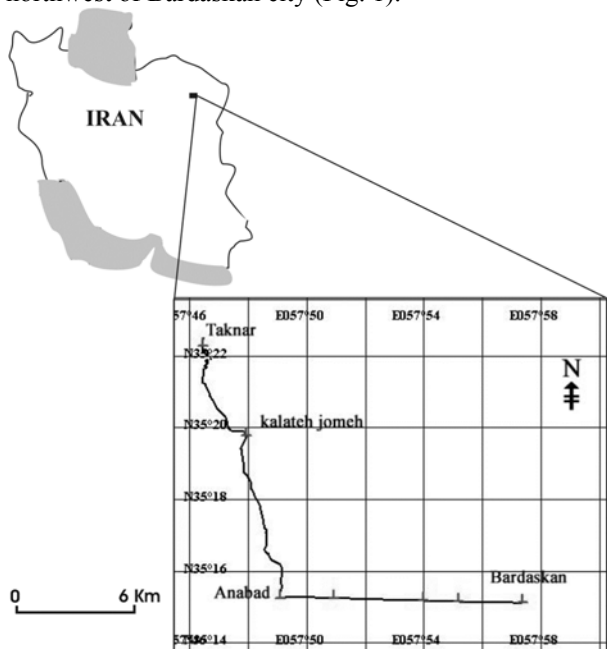


Figure 1. Geographic location of Taknar deposit.

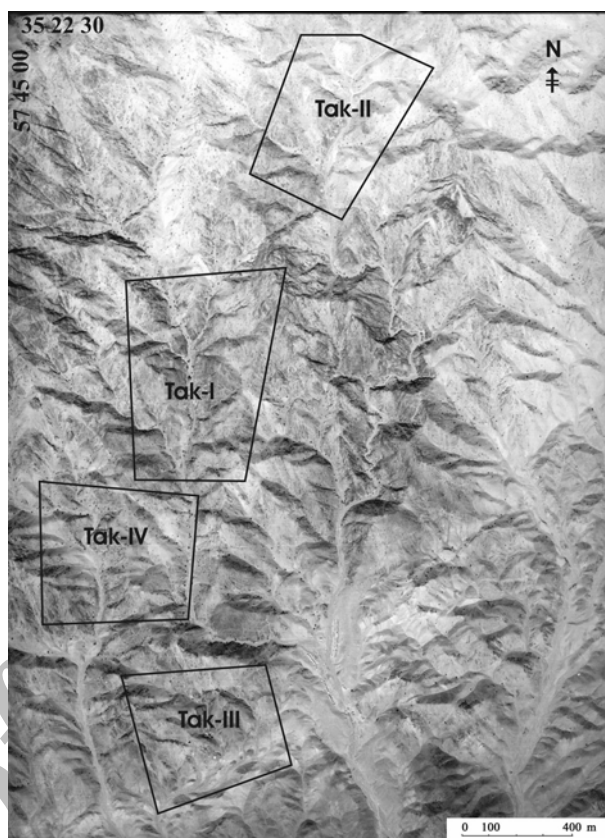


Figure 2. On the air photo the location of Tak-I to Tak-IV mineralized and prospecting areas are shown. The distance between Tak-I and II is about 1 km.

Taknar Deposit is situated in Taknar zone [1]. Taknar zone is uplifted with WSE-ENE trending between Great Kavir fault (Drouneh) in south and Taknar fault in north [1].

Taknar zone consists of Paleozoic, Mesozoic and Tertiary rocks [1]. A complex of intrusive rocks crop out at the center of Taknar zone. Taknar Formation covers a large area within the Taknar zone. Based on the previous studies, age of Taknar Formation was Precambrian [1-4]. However, recent Palynological studies show that the age of Taknar Formation is Ordovician [5-7]. Taknar Formation has been divided into a lower, middle and upper member [1]. The lower member crops out in the central part of Taknar zone and has a thickness of at least 1500 m. It is characterized by an alternative sequence of uniform dark tuff to dark grey rhyolite [1]. The middle member is exposed along the northern and southern margins of the zone. It consists of alternative sequence of carbonates and sandstones and has a thickness ranging from 150 to 350m. The amount of rhyolite is not considerable [1]. The upper member consists of a series of the green shales and sandstones [1].

Taknar Formation was affected by low grade regional metamorphism (probably in the late Paleozoic) and all of the sedimentary rocks were metamorphosed to sericite and sericite-chlorite schist, but Muller and Walter [1] didn't use the appropriate terminology for these rocks. Based on this study, Taknar formation in Taknar mine area is consist of sericite schist, sericite-chlorite schist, meta-volcanic and meta-subvolcanic rocks.

According to Razzagmanesh, the ores of Taknar are "sedimentary sulfide deposits of volcanic origin [8]". Taknar deposit was formed in certain horizon of Taknar Formation and it is syngenetic in origin. This deposit has outcrops in four areas (Tak-I to Tak-IV). Tak-III is located in the most southern part of the deposit. Tak-II is present in the most northern part of the deposit and Tak-IV and Tak-I are between Tak-III and Tak-II (Fig.2).

Ancient workings such as old pits, trenches, and slag are present in the area. This mine was exploited between 1968 to 1977 by Lut Company. Since 1977 until now exploration activities were carried out in the area by different companies, but they have not found a minable reserve so far. The reasons for this are as follow:

1. This old deposit (Ordovician) is being affected by regional metamorphism; therefore secondary chlorite and sericite were formed.
2. Geometry, location and size of deposit have been changed due to the active faulting.
3. Appropriate geological and geophysical methods have not been used in exploration.

The purpose of this paper is to describe the geology, mineralization, alteration, geochemistry and finally to determine the type of mineralization.

Two types of younger mineralization have been recognized in this area: 1) mineralization associated with Post-Paleozoic intrusive and 2) epigenetic mineralization. These two types of mineralization will not be discussed in this paper.

2. Methods of Study

Field and laboratory studies are as follow [9,10]:

1. Surface mapping at the scale of 1:1000 in Tak-I and II and scale of 1:500 in Tak-III (geology, alteration, mineralization and geochemistry)

2. Underground mapping at the scale of 1:100 in Tak-I, Tak-II, and Tak-III

3. Logging of 700 m of core from Tak-III

4. Study of more than 220 thin section, 70 polished-thin section and 50 polished block

5. Collecting more than 40 rock chip samples both from underground and surface and they are analyzed for Cu, Zn, Pb, Au, Ag, Bi, and Mo both in Sarcheshmeh and Ferdowsi University of Mashhad laboratories by Atomic Absorption Spectroscopy (AAS).

3. Geological Setting

The massive sulfide of Taknar deposit is parts of volcanic-sedimentary complex (Taknar Formation) which consists of clastic sediments, carbonate, felsic and mafic volcanic and sub-volcanic rocks. Rocks outcrops in the area of Taknar deposit are portion of Taknar Formation and younger intrusive rocks (Figs. 3-5). Before regional metamorphism, this portion of Taknar Formation was composed of immature quartz-rich pelitic rocks, sub-arkose, and chert, volcanic and subvolcanic rocks in the range of acid-intermediate to occasionally mafic compositions [8,9].

Quartz is the main constituents of the sedimentary rocks (up to 70%) and clay minerals were less than 40%. In some pelitic rocks, clay minerals were rich in iron and magnesium forming montmorillonite. Sub-arkosic rocks contained up to 10% feldspar and minor clays.

Both volcanic and subvolcanic rocks were formed within Taknar Formation. Subvolcanic rocks were mainly diabase-diorite monzonite in composition, but the volcanic rocks were mainly rhyodacite and rhyolite (subvolcanic and volcanic rocks are abundant in Tak-III deposit).

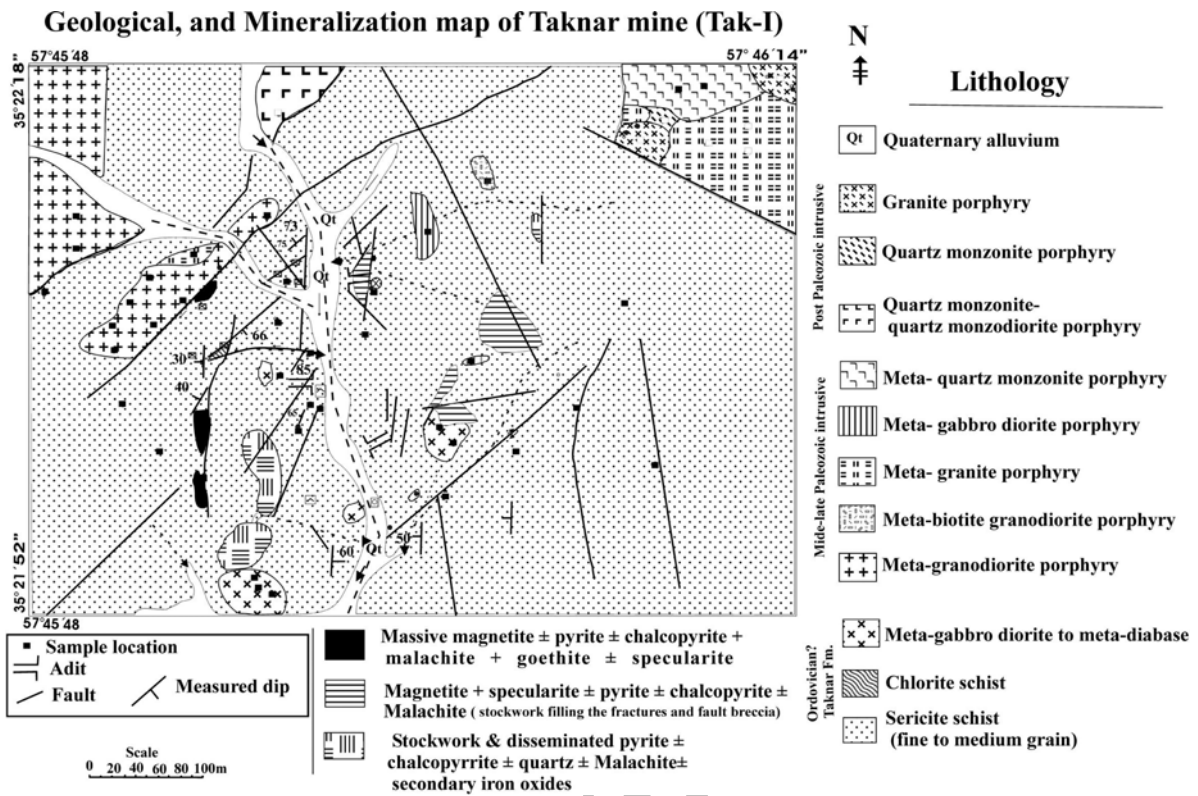


Figure 3. Geological and mineralization map of Tak-I [9].

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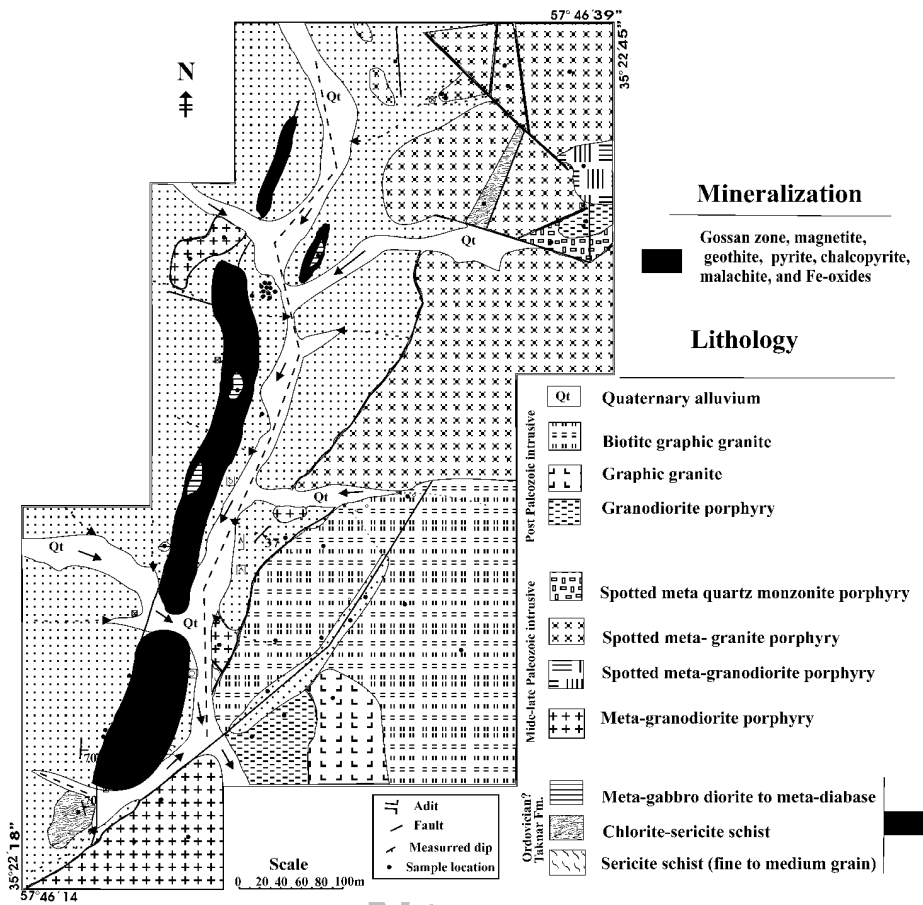


Figure 4. Geological and mineralization map of Tak-II [9].

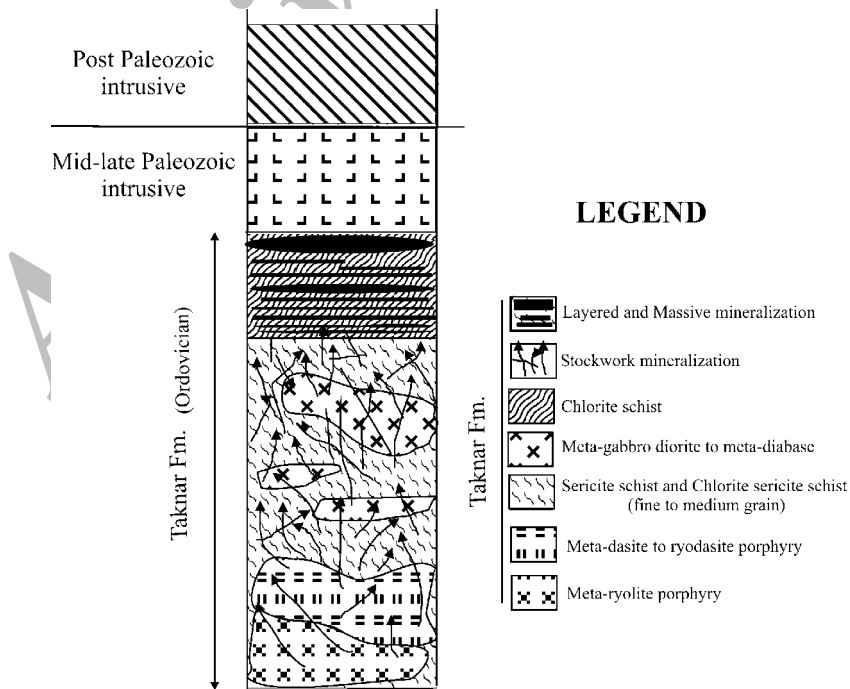


Figure 5. Stratigraphic column for the Taknar area [9].

Mineralization shows good layering. Therefore, it is a syngenetic type deposit and it was formed at certain horizon within the Taknar Formation.

Taknar zone was affected by low grade regional metamorphism (Green Schist facies) in the late Paleozoic. As a result, pelitic and subarkosic rocks were changed to sericite or sericite-chlorite schist (clay minerals are converted to sericite and chlorite).

There are two types of sericite and chlorite within these rocks. Sericite and chlorite which were formed during alteration-mineralization are coarse grain and they are found in mineralized areas. The second type which was formed during regional metamorphism is fine grains and they are present in certain portion of non-mineralized areas.

Subvolcanic and volcanic rocks are also affected at least by two episodes of metamorphism. The early stage of alteration occurred during the mineralization and while the second occurred during to regional metamorphism (Figs. 3-5).

A varied group of post mineralized igneous rocks with a composition ranging from quartz diorite, monzonite, and granite were mapped in the study area (Figs. 3-5). These intrusives rocks consist of small stock, dikes and sills and classified based on the occurrence of regional metamorphism (late Paleozoic) into two groups: 1) the Middle-Late Paleozoic intrusive which shows sign of regional metamorphism and 2) the younger group was not affected by regional metamorphism (Figs. 3-5) [9,10]. Since these intrusive rocks are younger than Taknar polymetal mineralization, therefore they will not be discussed in this paper.

4. Structure

Taknar deposit is a part of Taknar zone which is an allochthonous blocks. Taknar zone is situated between two major faults, Drouneh Fault to the south and Rivash (Taknar) Fault to the north (Fig. 6). Fault movements at different periods, truncated and displaced Taknar deposit, therefore geometry, size and location of Taknar deposit has been changed considerably through time. Deposits which are called Tak-I, II, III, and IV, originally were part of one large deposit, but as a result of faulting they have been truncated and moved at least 1 km from each other.

Drouneh is a major fault located at the northern part of Lut block (Fig. 6). Its movement is mainly strike slip type, but from Kashmar to the east is right-lateral strike slip and from Kashmar to the west is left-lateral strike slip. Rivash Fault is a right-lateral strike slip (Fig. 6) [2,11,12].

Four types of faults are being recognized within Taknar zone, from older to younger are [13]: 1) North-South faults, 2) East-West faults, 3) Northeastern-Southwestern faults, and 4) Northwestern-Southeastern faults.

These faults have formed due to the movements of Drouneh Fault, Rivash Fault, Nehbandan and Naybandan Faults (Fig. 6).

5. Mineralization

Based on surface and subsurface mapping which carried out at Tak-I and Tak-II deposits by Malekzadeh [9] and Tak-III by Ghorchi [10], three types of mineralization such as layered, massive and stockwork were recognized (Figs. 5, 7 & 8).

At Tak-III deposit only stockwork type is present, whereas at Tak-I and II, layered, massive and small scale stockwork are present. At Tak-I and II, small scale stockwork mineralization is found within the eastern part of the deposit and massive mineralization is found mainly to the west and the layered mineralization between these two. The contact between different styles of mineralization is fault controlled (Figs. 7 & 8).

The mineralized bodies at Tak I & II are elongate shaped. Gossan zone with dimension of 520×70 m is well-developed in Tak-II, but in other deposit the gossan zone is small (Figs. 3 & 4), as a result of the small exposure of mineralization.

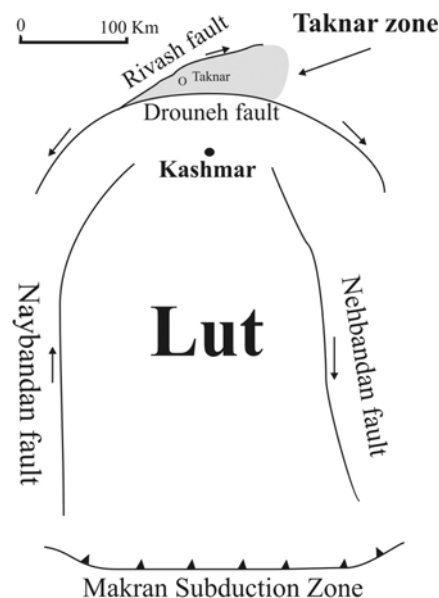


Figure 6. Map showing major faults around Lut Block and location of Taknar deposit [12, with some modification by writers].

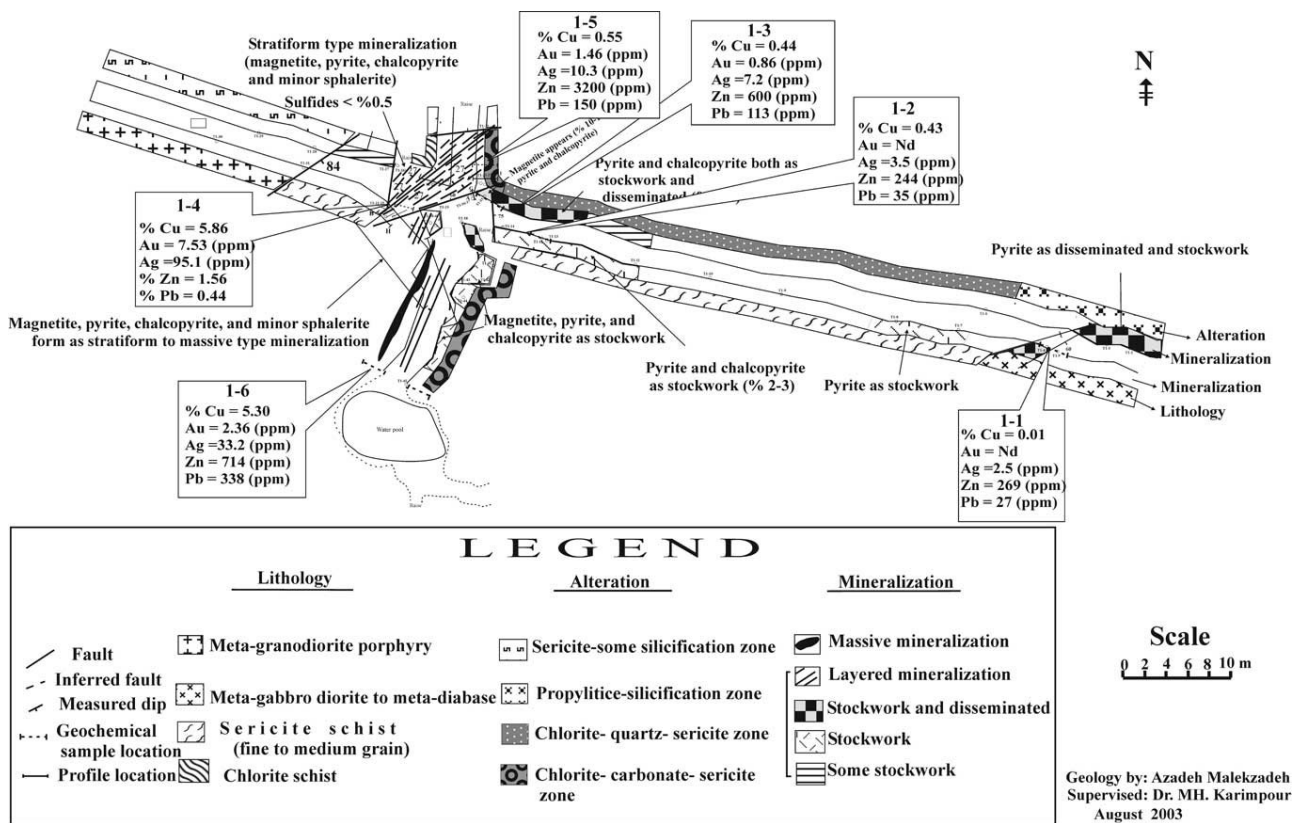


Figure 7. Geological, mineralization, alteration, and geochemical map of Tak-I adit [9].

5.1. Layered Mineralization

The length and the width of layered mineralization at Tak-II deposit is about 400 m and 3-4 m, respectively, whereas at Tak-I deposit is less than 30 m in length and up to 9 m in width.

The massive sulphides are composed of alternating layers of pyrite, chalcopyrite, magnetite, sphalerite and galena. The individual massive sulphide layers range in thickness from millimeters to 2 cm.

Chlorite is the dominate silicate mineral. In areas where chlorite is the dominate mineral, rocks are called chlorite schist. Chlorite schist is mainly present within the lower part of the layered mineralization (Figs. 5&7).

Paragenetic studies carried out simultaneously with mineralogical and textural characterization of the ore. To establish the percentage and mineralogical changes within the layering part, continuous samples were taken from three profiles at Tak-I and II deposit. 25 samples selected from these profiles and polished blocks were made perpendicular to the layers. The size of some blocks was 4×7 cm. Mineral contents and percentage of

each layer were studied. Results are reported in Table 1.

The abundance of magnetite, pyrite, chalcopyrite, sphalerite and galena changes upward within the layered mineralization (Figs. 9 & 10). The result of mineralogical study carried out on all samples from Tak I & II layered mineralization indicates that, pyrite and chalcopyrite content are higher in the lower layers and magnetite, sphalerite and galena are abundant within the upper layers (Table. 1).

Magnetite grains are subhedral and martitized up to 5-6%. Magnetite content is about 1% in the lower part and increases to 60% in the upper part (Fig. 9). Pyrites are mainly euhedral and their sizes are 0.1 to 1.6 mm. Pyrite content is between 25% to 65% within the lower layers and decreases to 1-25% in the upper layers (Fig. 9).

In Tak-I, chalcopyrite is more abundant than Tak-II, whereas sphalerite and galena are more abundant in Tak-II (Table 1).

The result of paragenetic study of the layered mineralization is shown in (Fig. 11).

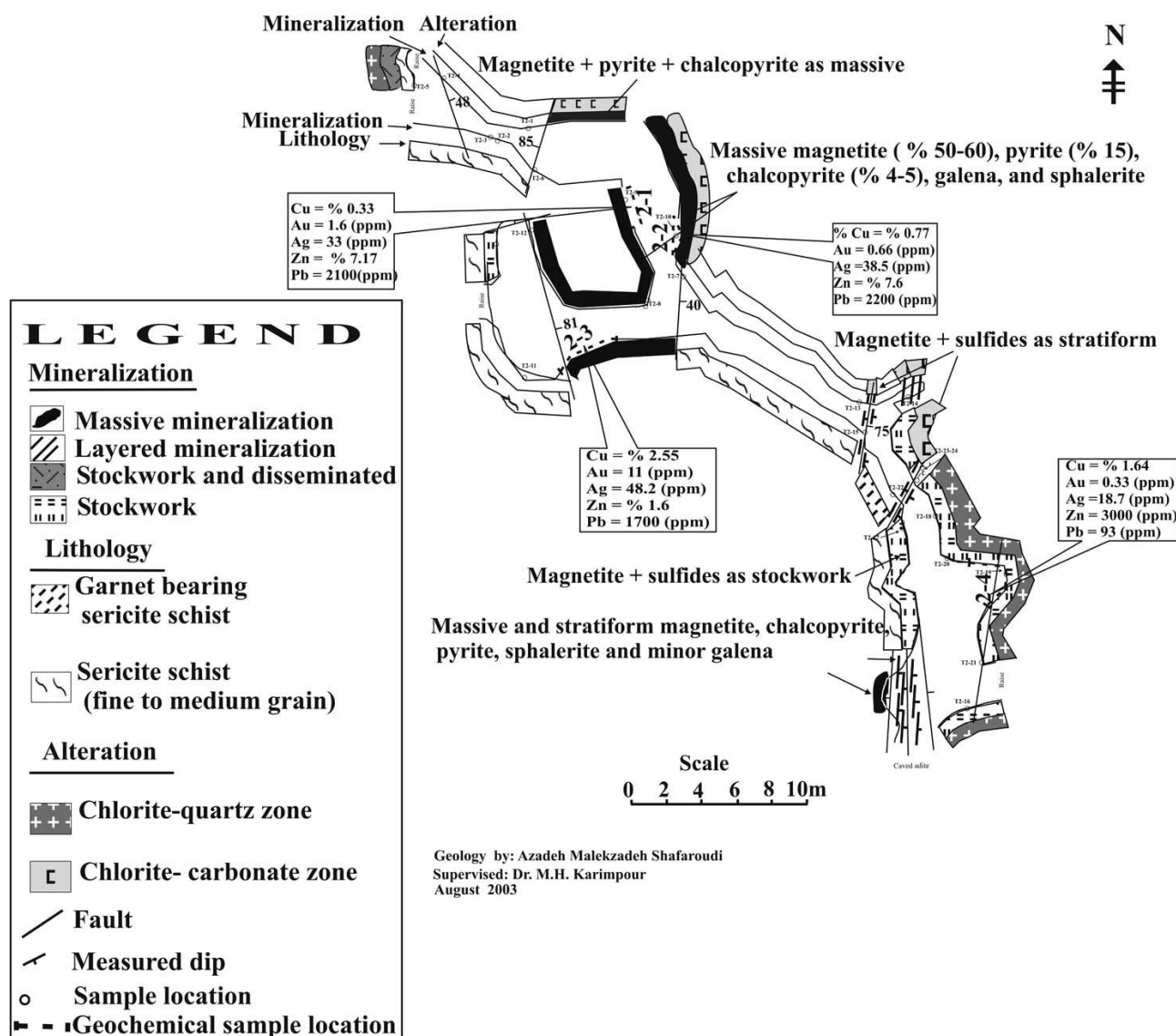


Figure 8. Geological, mineralization, alteration, and geochemical map of Tak-II adit [9].

5.2. Massive Mineralization

Massive ore horizons, having >50% magnetite, occur at the top of the mineralized section. Massive mineralization was formed due to the high magnetite content (Tak-I contain more than 70% and Tak-II more than 85% magnetite). In general, sulfide and chlorite are low and this deposit shows massive appearance.

Mineral paragenesis of massive type mineralization from Tak-I and II deposit is shown in Figure 11. Mineral contents in Tak-I and II deposit are reported in Table 2. Chalcopyrite is more abundant in Tak-I, whereas at Tak-II, sphalerite and galena are present in high quantity. The amount of chlorite and calcite are

very low (Table 2).

Pyrites are euhedral and their size is usually 0.1-0.2 mm and occasionally up to 2 mm. Magnetite is anhedral and highly fractured. They are martitized up to 6%.

5.3. Stockwork Mineralization

Stockwork and disseminated mineralization is well-developed at Tak-III deposit. Since Tak-I and II have been dislocated as a result of faulting, therefore the main stockwork mineralization is missing. Stockwork hosted by sericite schist, chlorite-sericite schist, meta-gabbrodiorite to meta-diabase (Tak-I to IV), meta-rhyolite and meta-rhyodacite (Tak-III) (Figs. 5, 7 & 8).

Table 1. The percentage of minerals in layered mineralization [9]

Mineral	Tak-I		Tak-II	
	Lower	Upper	Lower	Upper
Magnetite	<1-2%	25-60%	<1-2%	15-60%
Pyrite	25-65%	1-25%	25-65%	1-25%
Chalcopyrite	5-25%	7-10%	1-12%	<1%
Sphalerite	0	1-8%	<1-10%	10-40%
Galena	0	0.5-5%	0-5%	3-10%
Chlorite	60-85%	6-20%	60-85%	6-20%
Calcite	7-12%	12-15%	0-10%	15-20%
Sericite	15-30%	1-5%	–	–
Quartz	<3%	0	<1%	0

Table 2. The percentage of minerals in Massive mineralization [9]

Mineral	Average Tak-I	Average Tak-II
Magnetite	60%	65%
Pyrite	10%	25%
Chalcopyrite	5%	3%
Sphalerite	7%	12%
Galena	1%	2%
Chlorite	4%	4%
Calcite	3%	12%
Sericite	0.1%	–
Quartz	0.1%	0.1%

Table 3. The percentage of minerals in Stockwork mineralization [9,10]

Mineral	Average Tak-I	Average Tak-II	Average Tak-III
Magnetite	10%	3%	0.5%
Pyrite	15%	25%	10%
Chalcopyrite	12%	4%	35%
Sphalerite	–	1%	–
Galena	–	1%	–
Chlorite	20%	20%	20%
Calcite	1%	10%	2%
Sericite	5%	–	12%
Quartz	50%	50%	50%

The density of veinlets varies from 4 to 15 veinlets per 1 m² in Tak-III, whereas in Tak-I and II are generally less than 5 veinlets per 1 m². The widths of veinlets are from few millimeters up to centimeter.

The paragenesis of stockwork mineralization is shown in Figure 11. The opaque minerals in order of abundance at Tak-III are chalcopyrite and pyrite, along with minor magnetite, whereas in Tak-I are pyrite, chalcopyrite, and magnetite and at Tak-II are pyrite, chalcopyrite, magnetite, along with minor galena and sphalerite. Mineral contents of different stockwork in Tak-I, II, and III are reported in Table 3.

Pyrites are euhedral and occasionally up to 4 mm in size. Chalcopyrite is usually anhedral and seldom euhedral. The size of euhedral grains are up to 2 mm. Magnetite grains are euhedral to subhedral and their size are up to 3 mm.

6. Alteration

Four types of alteration were recognized at the Taknar deposit as a result of polymetal mineralization (Figs. 7 & 8) [9,10]:

1. Chlorite+Quartz±Sericite±Calcite zone: This zone is associated with stockwork mineralization. Mineralogically, this alteration has been defined by the occurrence of quartz (15-17% of the veinlets), chlorite (10-40% of the veinlets), sericite (5-30% of the veinlets), and calcite (<60% of the veinlets). Calcite is very abundant and sericite is not recognized in Tak-II deposit.

2. Chlorite ± Sericite zone: mineralogically, this zone has been defined by the occurrence of chlorite (up to 30%) and sericite (less than 25%) with minor calcite and quartz.

This type of alteration was formed within special portion of the layered and massive type of deposit in Tak-I and II. Sericite is not present in Tak-II.

3. Chlorite + Calcite ± Sericite zone: The mineral contents of this zone are: 10-70% chlorite, up to 55% calcite, and 7-15% sericite. Sericite is not present within Tak-II but calcite is more.

This alteration is recognized in most part of the layered and massive mineralization in Tak-I and II.

4. Propylitice-Silicification zone: this zone has been defined by the occurrence of chlorite, epidote, calcite, sericite, and quartz. Their abundance is varied considerably. This alteration was formed within metagabbro-diorite to metadiabase rocks.

Later regional metamorphism developed very good foliation and occasionally contacts metamorphism due to occurrence of intrusive rocks. This process has changed chlorite and sericite into biotite and muscovite, respectively.

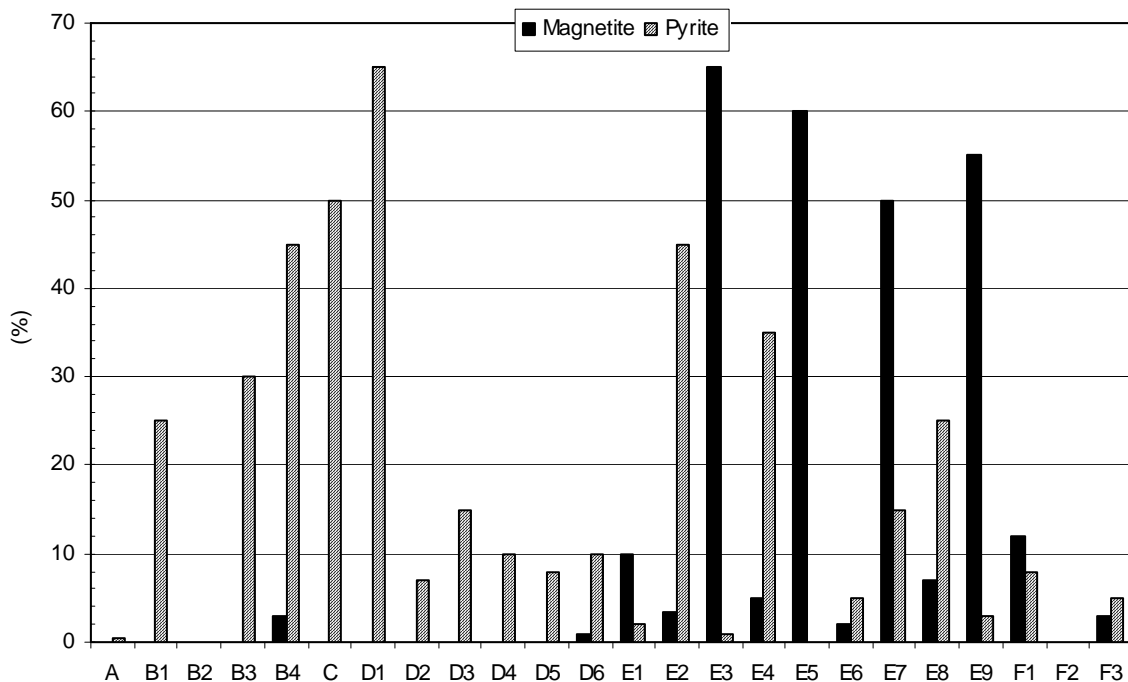


Figure 9. Change in pyrite and magnetite content of the layered mineralized zone from lower part (A) to upper portion (F3) [9].

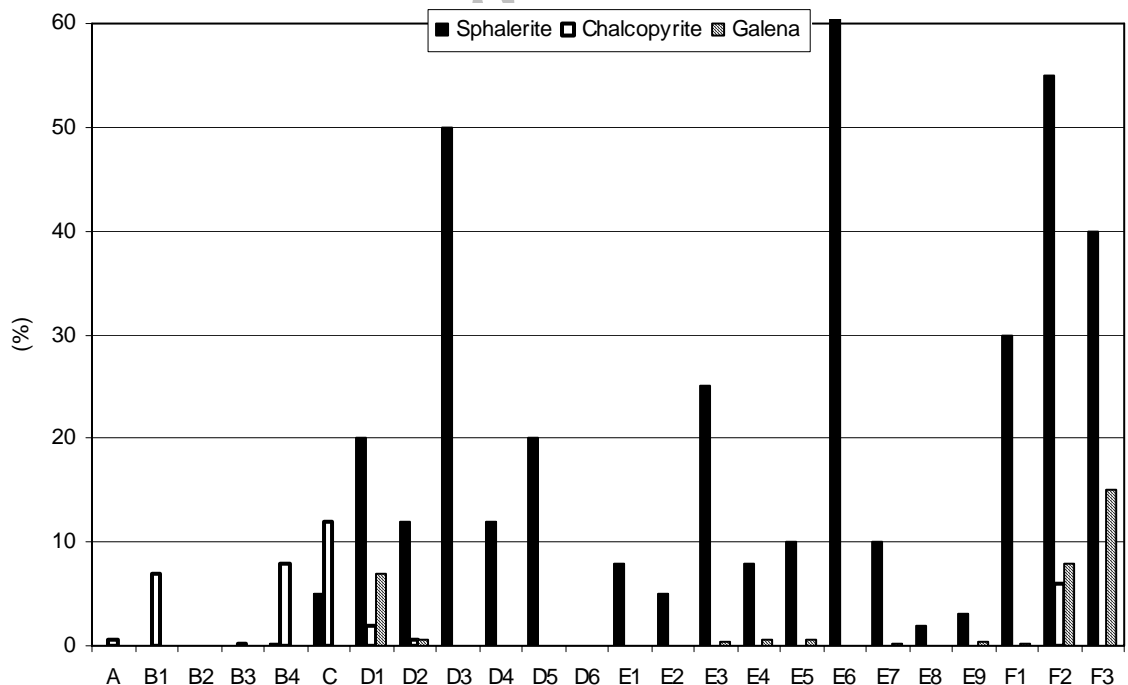


Figure 10. Change in chalcopyrite, sphalerite, and galena content of the layered mineralized zone from lower part (A) to upper portion (F3) [9].

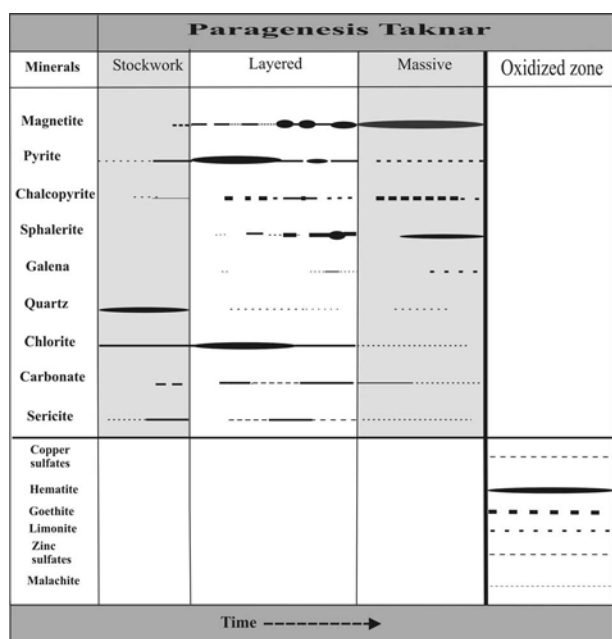


Figure 11. The mineral paragenesis sequence of Taknar deposit [9].

7. Geochemistry

Rock-ore geochemical samples were collected from subsurface and surface by using chip composite method. Some of the sample locations are shown in Figures 7&8.

In the layered part of the mineralization, samples taken from a channel perpendicular to the strike of the layers, but within the massive and stockwork mineralization, samples were taken from an area of the mineralization [9,10].

Chemical variations of some elements in different deposit are:

Tak-I: Cu = 0.01-5.86%, Zn = 269-15600 (ppm), Pb=27-4400(ppm), Au=0.86-7.53 (ppm), Ag=2.4-95.1(ppm), Bi=34-2200 (ppm), and Mo=85-1300 (ppm).

Tak-II: Cu=0.33-2.56%, Zn=0.3-7.68%, Pb=93-5000 (ppm), Au=0.33-11 (ppm), Ag=18.7-105 (ppm), Bi=79-214 (ppm), and Mo=54-116 (ppm).

Tak-III: Cu=0.05-5.54%, Zn=62-179 (ppm), Pb=17-47 (ppm), Au=0.06-0.33 (ppm), Ag=1.6-40 (ppm), and Bi=11-250 (ppm).

Tak-IV: Cu=0.1%, Zn=0.23%, Pb=0.12%, Ag=1.7 (ppm), and Bi=31 (ppm).

The Cu, Zn, and Pb content from the stockwork mineralization at Tak-I, II and III were compared (Figs. 12-14). Stockwork mineralization at Tak-III has higher Cu content, but Tak-I and II has higher Pb and Zn content.

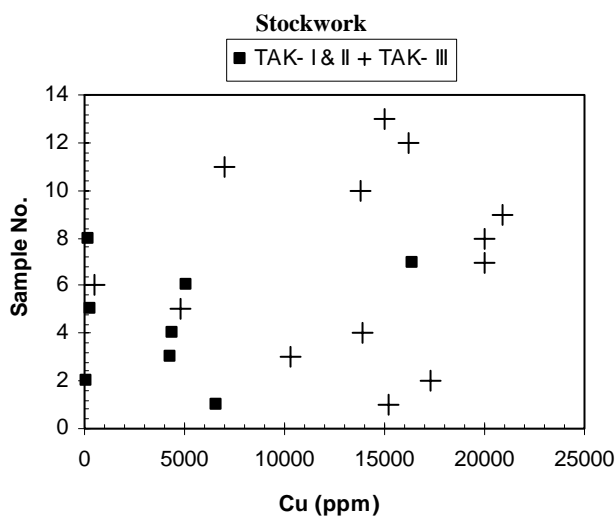


Figure 12. Comparison of Cu content within stockwork mineralization at Tak-I to III [9].

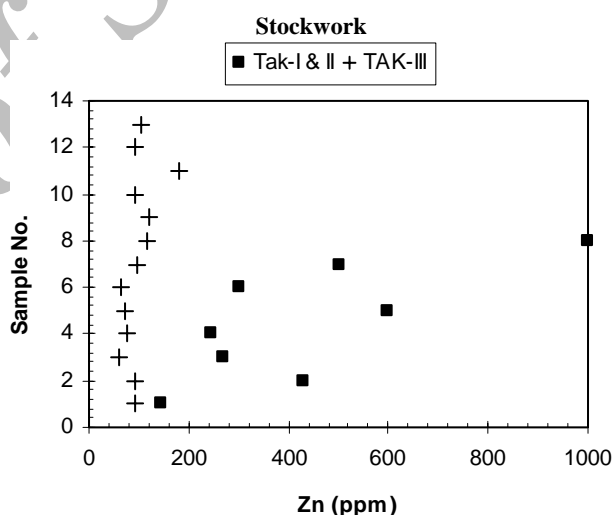


Figure 13. Comparison of Zn content within stockwork mineralization at Tak-I to III [9].

The variation of Cu, Zn, Pb, and Au content of layered and massive type of mineralization from Tak-I and II deposit are plotted in Figures 15-18. As it appear in Figure 15, the copper content of Tak-I is higher in comparison with Tak-II whereas at Tak-II, Zn and Pb are higher (Figs. 16 & 17).

Gold content is relatively higher in both Tak-I and II deposit (Fig. 18).

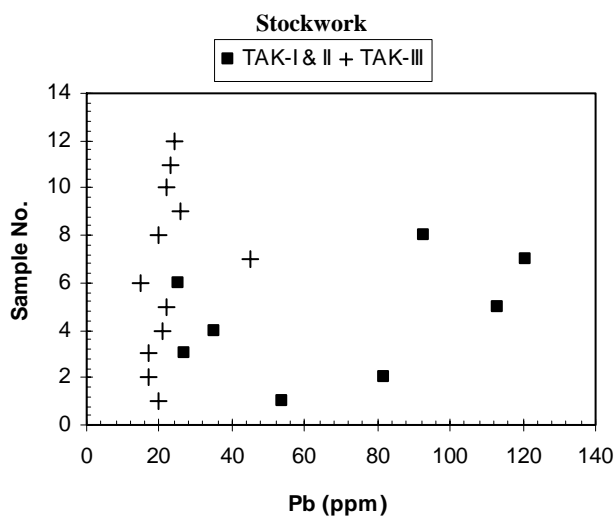


Figure 14. Comparison of Pb content within stockwork mineralization at Tak-I to III [9].

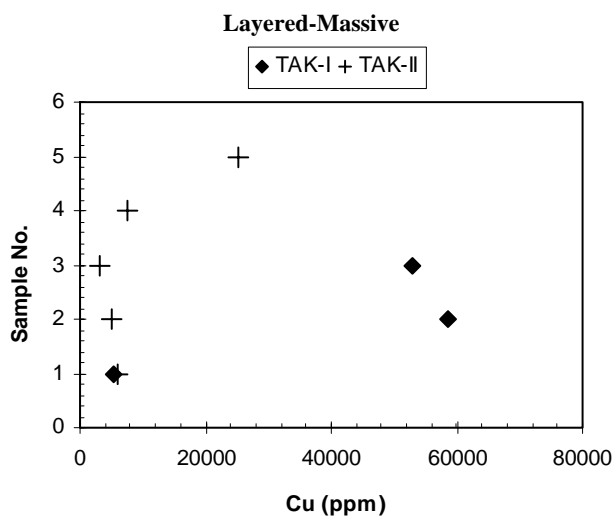


Figure 15. Comparison of Cu content within layered-massive mineralization at Tak-I & II [9].

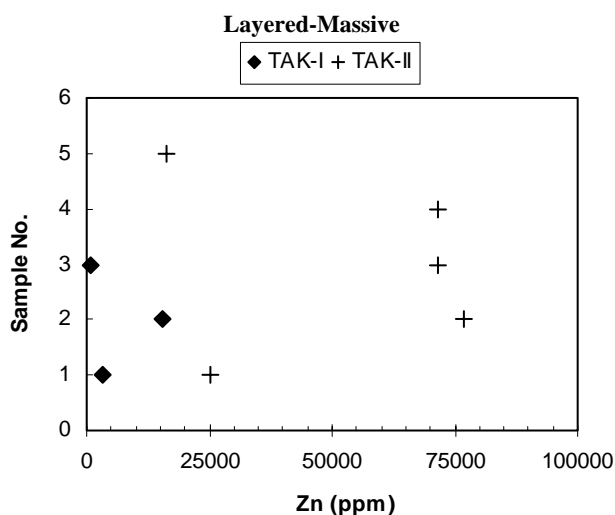


Figure 16. Comparison of Zn content within layered-massive mineralization at Tak-I & II [9].

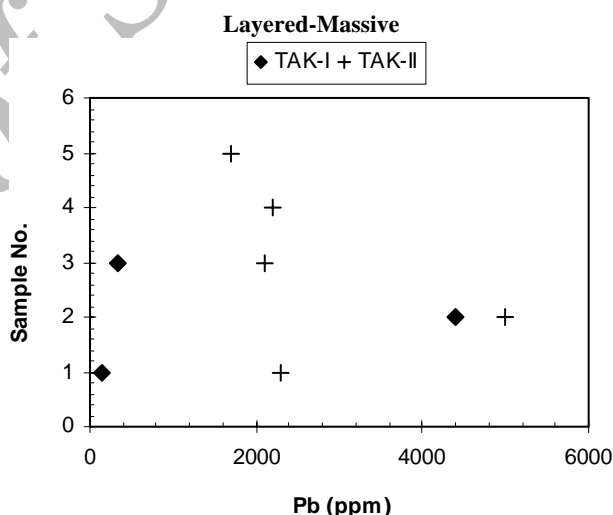


Figure 17. Comparison of Pb content within layered-massive mineralization at Tak-I & II [9].

8. Type of Mineralization

Based on the styles of mineralization (stockwork, layered, and massive), alteration types, mineral paragenesis and lithology, Taknar is a polymetal massive sulfide deposit.

Taknar deposit was compared with different massive sulfide deposits around the world such as Cyprus [14-17], Kuroko [15-18], Besshi [17,19,20], Archean [15-17] and the massive sulfide deposits in Australia (Zn-rich, Cu-rich, and Au-rich deposits) [16,21-32] (Table 4) [8].

Taknar is different with all the VMS deposits, due to high magnetite content.

Taknar deposit was compared with magnetite-rich massive sulfide deposits such as Balcooma [33-38] and Gossan Hill [39-42] in Australia and Matabi [40,43,44], Mattagami [45,46], Millenbach [43,47,48], and Orchean [43,45] in Canada.

Taknar deposit shows similarity in terms of lithology, alteration and mineralogy with Balcooma deposit, but has major differences with other magnetite-rich VMS deposits.

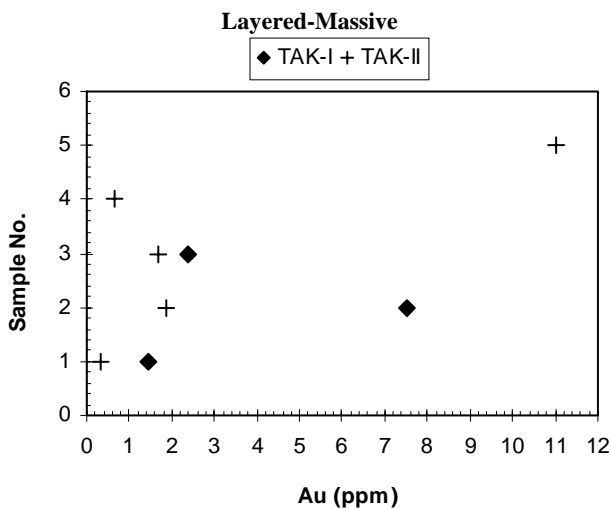


Figure 18. Comparison of Au content within layered-massive mineralization at Tak-I & II [9].

Among the differences, two items are considered to be important: 1) absence of pyrrhotite in Taknar deposit, and 2) the magnetite content and its relation with sulfide occurrences.

The magnetite content in the Taknar deposit increases from about 1% in stockwork mineralization to more than 80% in the massive portion of the deposit, whereas in other deposits, the magnetite content is mostly associated within the lower part of deposit and the total magnetite content is lower.

9. Chemistry of the Ore-Forming Fluids

Solubility-temperature plot for the major ore minerals under conditions of $\text{pH} = 4$, 1m NaCl , $a_{\text{H}_2\text{S}} = 10^{-3}$ and $\text{SO}_4/\text{H}_2\text{S} = 10^{-1}$ are shown in Figure 19a [49]. At high temperature and low pH, fluids will transport both copper and gold as chloride complexes (Fig. 19a). In the temperature range $250\text{-}330^\circ\text{C}$ significant quantity copper and gold was precipitated in the stringer and lower section of the massive sulfide (Figs. 19a & 19b). Sphalerite and galena were precipitated at low temperature ($250\text{-}150^\circ\text{C}$) (Figs. 19a & 19b).

At Tak-III, mineralization is dominantly stockwork (stringer zone). Major minerals were pyrite and chalcopyrite. Based on paragenesis and geochemical, temperature of deposition was more than 270°C (Fig. 19a).

At Tak-I, mineralization was dominantly layered and massive. Based on the geochemical and high content of magnetite, pyrite, chalcopyrite and minor amount of sphalerite and galena, the temperature of formation was more than 250°C (Fig. 19a).

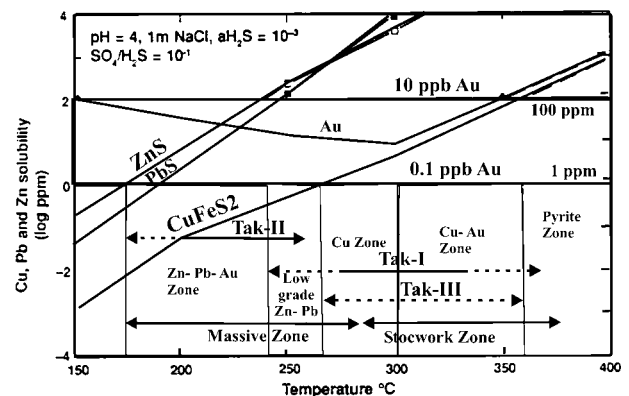


Figure 19a. Metal solubility temperature plot showing the temperature intervals for zone developed in VMS deposit from [49]. Stockwork zone is usually formed in high temperature ($> 270^\circ\text{C}$) and massive zone is usually formed in range of $300\text{-}150^\circ\text{C}$ T. Based on geochemical and paragenesis, Tak-III was formed in $\geq 270^\circ\text{C}$, Tak-I was formed in $\geq 250^\circ\text{C}$ and Tak-II was formed in $< 250^\circ\text{C}$ [9].

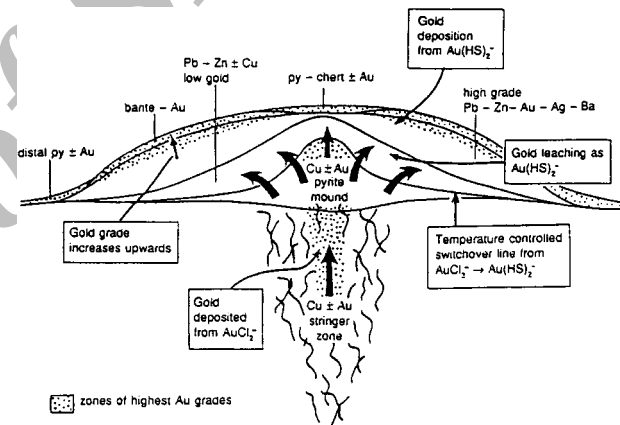


Figure 19b. Zonation showing in VMS deposit and distribution of Cu, Au, Pb, & Zn [50].

At Tak-II deposit, the presence of high sphalerite and galena indicates that the temperature of fluid was less than 250°C (Fig. 19a).

Based on the style of mineralization, paragenetic mineralization and relative temperature of formation, Tak-I, II and III deposits were originally formed together at the different parts of the massive sulfide deposit (Fig. 20). Tak-III is stringer zone mineralization, Tak-I is lower part of the massive sulfide and Tak-II is upper and lateral portion of massive sulfide deposit (Fig. 20). As a result of faulting, they had been dislocated to their present position.

Some of the chemical parameters such as pH , $\text{Log } f \text{ O}_2$ and $\text{Log } f \text{ S}_2$ are determined by plotting the paragenetic minerals in Figures 21-23. Their values are [9,10]:

Table 4. Comparison of Taknar deposit with VMS deposits around the world [9,10,14-32]

	Lithology		Alteration		Mineralization	
	Rock type	Differences	Type of alteration	Differences	Mineralogy	Differences
Taknar	Metasediment (Sericitic schist & Chlorite sericitic schist), Chlorite schist, Metasubvolcanic rocks (metagabbro-diorite to metadiabase), & Metavolcanic (Rhyolite, Dacite, ...)	–	Associated with stockwork mineralization: 1) Chlorite+Quartz±Sericitic ± Calcite, 2) propylitic + silicification. Associated with layered and massive mineralization 3) Chlorite±Calcite±Sericitic ± Quartz.	–	Magnetite, Pyrite, Chalcocopyrite, Sphalerite, and galena	–
Kuroko	Andesite-Dacite and calc-alkaline Rhyolite	Abundant volcanic	Quartz-Sericite-Chlorite zone with orebody and Zeolite-Carbonate-Clay minerals zone farther away	Different zoning+Zeolite-Carbonate-Clay zone	Quartz, Chalcocopyrite, Pyrite, Sphalerite, Galena, and Barite	No magnetite, high barite
Cyprus	Tholeiitic basalt of upper part of Ophiolites	Abundant volcanic+mafic	Chlorite, Talc, Carbonate, and minor Sericitic with orebody, Quartz within stockwork zone	Different zoning	Pyrite, Chalcocopyrite, Magnetite, Sphalerite, Marcasite, Pyrrhotite, minor Galena, Hematite and Cubanite	Low magnetite, abundant pyrrhotite
Archean	Submarine volcanic as basalt-andesite, dacite and minor rhyolite	Abundant volcanic	Chlorite zone associated with orebody, and Quartz zone associated with stockwork zone. Sericitic zone and Zeolite-Carbonate-Clay minerals farther away	Different zoning	Pyrite, Chalcocopyrite, Quartz, and minor Pyrrhotite and Sphalerite	No magnetite & galena, minor pyrrhotite
Besshi	Clastic sediment and volcanic rocks	Similar	Calcite, Ankerite, Albite, Tourmaline, Siderite, and Biotite	Different alteration	Pyrite, Pyrrhotite, Chalcocopyrite, Sphalerite, Cobaltite, Galena, Bornite, Tetrahedrite, Molybdenite, Arsenopyrite, Marcasite.	No magnetite, present Pyrrhotite, Cobaltite, Bornite, Tetrahedrite, Molybdenite, Arsenopyrite, Marcasite.
Zn-rich deposit	Felsic or mafic-intermediate volcanic centers dominated by lavas and/or volcanoclastic facies	Abundant volcanic	Chlorite Quartz-rich alteration immediately below the ore lenses, Sericitic-rich alteration farther away. Carbonate within Chlorite or sericitic zone	Minor different	Pyrite, Sphalerite, Chalcocopyrite, Arsenopyrite, Tetrahedrite, Argantite, Acantite ± Pyrrhotite, and Magnetite	Low magnetite, present Arsenopyrite, Tetrahedrite, Argantite, Acantite ± Pyrrhotite
Cu-rich deposit	Felsic volcanic centers dominated by subvolcanic intrusions	Abundant volcanic	Chlorite Quartz zone close to the ore within footwall and hangingwall Sericitic zone	Different zoning	Pyrite, Chalcocopyrite, (Magnetite), Sphalerite, Galena, Hematite, Molybdenite, and Cassiterite	Low magnetite, present Molybdenite, and Cassiterite
Au-rich deposit	Volcanoclastic facies, Limestone and Ignimbrite	Volcanoclastic, Limestone and Ignimbrite	A core of massive microcrystalline Silica surrounded by an intermediate Silica-Sericite zone followed by an outer zone of Silica-Sericite-Pyrite-Chlorite. Carbonate zone within volcanoclastic facies	A core of massive microcrystalline silica surrounded by an intermediate Silica-Sericite zone	A core of Gold-Ag-Te-rich surrounded by Cu-Pb-Bi zone-rich followed by an outer zone of Zn-rich	A core of Gold-Ag-Te-rich surrounded by Cu-Pb-Bi zone-rich

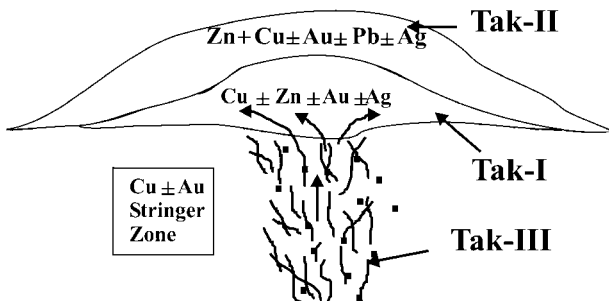


Figure 20. Original Location of Tak-I, II, & III deposits based on type of mineralization and mineral paragenesis [9].

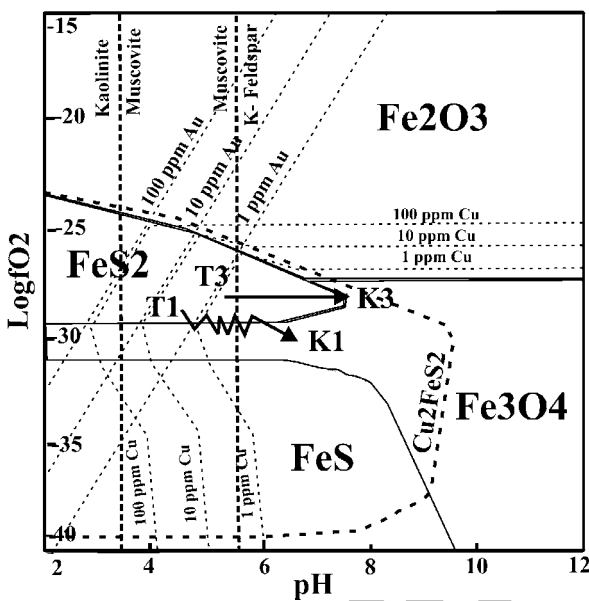


Figure 21. Log fO₂ - pH diagram constructed by [51] for temperature 350°C, ΣS=10^{-2.5} m, ΣCl=3.5 m, ΣNa=3.0 m, ΣK=0.3 m, ΣCa=0.10 m. Line T1-K1 represent possible conditions for formation of layered & massive mineralization at Tak-I and line T3-K3 is the possible condition for stockwork mineralization at Tak-III, based on mineral paragenesis [9,10].

Tak-I: T°C ≥ 250°C, pH=5-7, Log fO₂=(-29) to (-30).
 Tak-II: T°C ≤ 250°C, Log fS₂=(-11) to (-12), Log fO₂=(-36) to (-39), pH=>5 to >9.

Tak-III: T°C ≥ 270°C, pH>5, Log fO₂=(-28) to (-29).

Lack of sericite (formed due to alteration) in Tak-II deposit indicates that the pH of solution at Tak-II is higher than Tak-I.

10. Conclusion

Based on the style and shape of mineralization, type of alteration, mineral paragenesis, host-source rocks and

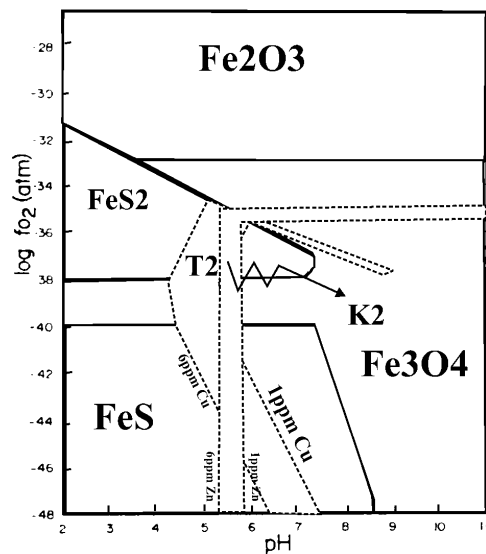


Figure 22. Log fO₂-pH diagram constructed by [52] for temperature 250°C, ΣS=10⁻³ m & 1 M NaCl. Line T2-K2 represents possible conditions for formation of layered & massive mineralization at Tak-II based on mineral paragenesis [9].

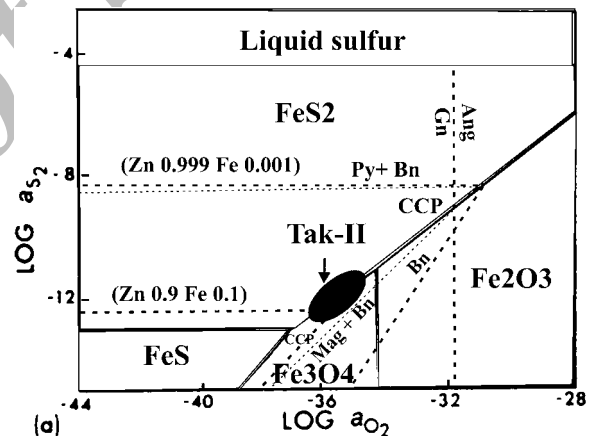


Figure 23. Log aO₂-Log aS₂ diagram at 250°C, ΣS=2×10⁻² m constructed by [53]. Based on mineral paragenesis [9], possible conditions of formation for layered & massive mineralization at Tak-II is shown.

geochemistry, Taknar is a polymetal massive sulfide deposit. Mineralization shows good layering. Therefore, it is a syngenetic type deposit and it was formed at certain horizon within Taknar Formation (Ordovician age). Fault movements at different periods, truncated and displaced Taknar deposit, therefore geometry, size and location of Taknar deposit has been changed considerably through time. Deposits which are called Tak-I, II, III, and IV, originally were part of one large deposit.

Low grade regional metamorphism (Green Schist facies) was affected Taknar zone in late Paleozoic. As a result, pelitic and subarkosic rocks of Taknar Formation

were changed to sericite or sericite-chlorite schist (clay minerals were converted to sericite and chlorite).

Tak-III deposit is only part of stringer zone of massive sulfide, whereas Tak-I and II are the massive portion of the massive sulfide. They have been cut and displaced more than a kilometer from each other.

Massive sulfide deposits with high magnetite are generally rare. Taknar deposit was compared with magnetite-rich VMS deposit such as Balcooma, Gossan Hill (Australia) and some Archean deposit in Canada.

The major differences between these deposits are 1) lack of pyrrhotite indicating that ore bearing fluid at Taknar was more oxidizing, 2) in most deposit, magnetite found at the lower part of the deposit, whereas in Taknar magnetite is associated with sulfide minerals and gradually increases upward. Magnetite content riches up to 80% in the upper portion of the system, and 3) it carries high content of Cu, Zn, Au, Ag, & Pb.

In summery, Taknar is a magnetite-rich polymetal (Cu, Zn, Au, Ag, and Pb) massive sulfide deposit (Taknar type).

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References

- Muller R. and Walter R. Geology of the Precambrian-Paleozoic Taknar inliers northwest of Kashmar, Khorasan province, NE Iran. GSI. Rep. No. 51, p. 165-183 (1983).
- Lindenberg H.G. and Jacobshagen V. Post-Paleozoic geology of the Taknar zone and adjacent area, NE Iran, Khorasan, GSI. Rep. No. 51, p. 145-163 (1983).
- Eftekharnjad J., Aghanabati A., Baroyant V., and Hamzehpour B. Geological Map of Kashmar, 1: 250000. GSI, Tehran (1976).
- Forster H. Associations of volcanic rocks in the mountains South of Sabzevar (NE-Iran). 23, IGK. 2. p. 197-212 (1968).
- Personal Conversation with Dr Ghavidel, M concerning the age of Taknar Formation using Palinology (2003).
- Sepahigerow A.A. Petrology of granitoides in Taknar-Sarborj area (northwest of Kashmar). M.Sc. Thesis, University of Esfahan, 201 p (1992).
- Homam S.M. Geology and petrology of Taknar Formation, northwest of Kashmar, Khorasan province. M.Sc. Thesis, University of Esfahan, 126 p (1992).
- Razzaghmanesh B. Die Kupfer-Blei-Zink-Erzlagerstätten von Taknar und ihr geologischer Rahmen (NE-Iran). Diss. Aachen, 131 p, Aachen (1968).
- Malekzadeh A. Geology, mineralogy and geochemistry of Taknar polymetal (Cu-Zn-Au-Ag-Pb) deposit (Tak-I & II) and determining type of mineralization. M.Sc. Thesis, Ferdowsi University of Mashhad, 287 p (2004).
- Ghorchi M. Geology, mineralogy and geochemistry of Taknar deposit (Tak-III & IV), Bardaskan: M.Sc. Thesis, Ferdowsi University of Mashhad, 219 p (2004).
- Mohajer-Ashjai A. Recent and contemporary crustal deformation in eastern Iran. Ph.D. Thesis, Imperial College London (1975).
- Khatib M.M. Structure geology report of Kuh-e-Zar, Torbet-Heydarieh (Zarmehr Gold company) (2002).
- Bazin D. and Hubner H. Copper Deposits in Iran, Geological survey of Iran, Report. No. 13, p. 87-93 (1969).
- Hoy T. Cyprus massive sulphide Cu (Zn). In: Lefebure D.V. and Ray G.E. (Eds.), *Selected British Columbia Mineral Deposit Profiles*, Volume 1-Metallic and Coal. British Columbia Ministry of Energy of Employment and Investment, Open File 1995-20, p 51-52 (1995a).
- Cox D.P. and Singer D.A. Mineral Deposit Models, U. S. Geological survey, Bulletin 1693, 379 p (1986).
- Franklin J.M., Lydon J.W., and Sangster D.F. Volcanic associated massive sulfide deposits: *Economic Geology*, 75th Ann, volume, p. 485-627 (1981).
- Karimpour M.H. and Saadat S. *Applied Economic Geology*. 2nd Edition, Ferdowsi University of Mashhad, 535 p (2002).
- Hoy T. Noranda/Kuroko, Massive sulphide Cu-Pb-Zn. In: Lefebure, D.V. and Hoy T. (Eds.), *Selected British Columbia Mineral Deposit Profiles*, Volume 1-Metallic and Coal. British Columbia Ministry of Energy of Employment and Investment, Open File 1995-20, p 53-54 (1995b).
- Hoy T. Besshi massive sulphide, In: Selected British Columbia mineral deposit profiles, volume 1-Metallic and Coal, Lefebure, D.V. and Ray G.E. (Eds.), British Hoy T. (1991), Volcanogenic Massive Sulfide Deposits in British Columbia: in Ore Deposits, Tectonic and Metallogeny in the Canadian Cordillera, W.J. McMillan, Coordinator, British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1991-4, p. 89-123 (1995c).
- Urabe T., Scott S.D., and Hatttri K. A Comparison of footwall-rock alteration and geothermal systems beneath some Japanese and Canadian volcanogenic massive sulfide deposits. *Economic Geology*, Mono. 5, p. 345-364 (1983).
- Gemmell J.B. and Large R.R. Stringer system and alteration zones underlying the Hellyer volcanogenic massive sulfide deposit, Tasmania, Australia. *Ibid.*, 87: 620-649 (1992).
- Gemmell J.B. and Fulton R. Geology, genesis, and exploration implications of the footwall and hanging-wall alteration associated with the Hellyer volcanic-hosted massive sulfide deposit, Tasmania, Australia. *Ibid.*, 96: 1003-1035 (2001).
- Large R., McPhie J., Gemmell J.B., Herrmann W., and Davidson G.J. The spectrum of ore deposit types, volcanic environments, alteration halos, and related

- exploration vectors in submarine volcanic successions, some examples from Australia. *Ibid.*, **96**: 913-938 (2001a).
24. Large R.R., Allen R.L., Blake M.D., and Herrmann W. Hydrothermal alteration and volatile element halos for the Rosebery K lens volcanic-hosted massive sulfide deposit, western Tasmania. *Ibid.*, **96**: 1055-1072 (2001b).
 25. Khin Z. and Large R.R. The precious metal-rich South Hercules mineralization, western Tasmania: A possible subsea-floor replacement volcanic-hosted massive sulfide deposit. *Ibid.*, **87**: 931-952 (1992).
 26. Herrmann W. and Hill A.P. The origin of chlorite-tremolite-carbonate rocks associated with the Thalanga volcanic-hosted massive sulfide deposit, North Queensland, Australia. *Ibid.*, **96**: 1149-1173 (2001).
 27. Paulic H., Herrmann W., and Gemmell J.B., Alteration of felsic volcanic hosting the Thalanga massive sulfide deposit, North Queensland, Australia: geochemical proximity indicators to ore. *Ibid.*, **96**: 1175-1200 (2001).
 28. Huston D.L. and Kamprad J. Zonation of alteration facies at western Tharsis: Implications for the genesis of Cu-Au deposits in the Mount Lyell field, western Tasmania. *Ibid.*, **96**: 1123-1132 (2001).
 29. Herrmann W., Blake M., Doyle M., Huston D., Kamprad J., Merry N., and Pontual S. Short wavelength infrared (SWIR) spectral analysis of hydrothermal alteration zones associated with base metal sulfide deposits at Rosebery and Western Tharsis, Tasmania, and Highway-Reward, Queensland. *Ibid.*, **96**: 930-955 (2001).
 30. Doyle, M. G., Volcanic influences on hydrothermal and digenetic alteration: Evidence from the Highway-Reward deposit, Mount Windsor subprovince, Australia. *Ibid.*, **96**: 1133-1148 (2001).
 31. Halley S.W. and Roberts R.H. Henty: A shallow-water gold-rich volcanogenic massive sulfide deposit in western Tasmania. *Ibid.*, **92**: 438-447 (1997).
 32. Callaghan T. Geology and alteration of the Mount Julia deposit, Henty gold mine, Tasmania: Unpublished Masters Thesis in *Ibid.*, Hobart, Tasmania, University of Tasmania, 78 p (1998).
 33. Huston D.L., Taylor T., Fabray J., and Patterson D.J. A comparison of the geology and mineralization of the Balcooma and Dry River South Volcanic-Hosted Massive sulfide Deposits, Northern Queensland. *Ibid.*, **87**: 785-811 (1992).
 34. Harvey K.J. The discovery of the Balcooma massive sulfide deposit [abc.]. *Geol. Soc. Australia Abstracts*, **12**: 218-219 (1984a).
 35. Harvey K.J. The geology of the Balcooma massive sulfide deposit, north-east Queensland: *Unpub. M.Sc. Thesis*, James Cook University, 92 p (1984b).
 36. Huston D.L. The stratigraphic and structural setting of the Balcooma volcanogenic massive sulphide lenses, northern Queensland. *Australian Journal of Earth Sciences*, **37**: 423-440 (1990).
 37. Van der hor F. Structural geology of the Balcooma-Dry River area, Northeast Australia with emphasis on the interrelation between deformation and metamorphism: *Unpub. Ph.D. Thesis*, James Cook University (1990).
 38. Withnall I.W., Black L.P., and Harvey K.J. Geology and geochronology of the Balcooma area: Part of an early Paleozoic magmatic belt in North Queensland. *Australian Journal of Earth Sciences*, **38**: 15-29 (1990).
 39. Barley M.E. A review of Archean volcanic-hosted massive sulfide and sulphate mineralization in western Australia. *Economic Geology*, **87**: 855-872 (1992).
 40. Franklin J.M., Kasarda J., and Poulsen K.H. Petrology and chemistry of the alteration zone of the Mattabi massive sulfide deposit. *Ibid.*, **70**: 63-73 (1975).
 41. Sharpe R. Alteration characteristics of the Archean Golden Grove Formation at the Gossan Hill deposit: Indurations as a focusing mechanism for mineralizing hydrothermal fluids. *Ibid.*, **96**: 1239-1262 (2001).
 42. Sharpe R. and Gemmell J.B. The Archean Cu-Zn Magnetite-Rich Gossan Hill Volcanic-Hosted Massive Sulfide Deposit, Western Australia; Genesis of a Multistage Hydrothermal System. *Ibid.*, **97**: 517-539 (2002).
 43. Morton R.L. and Franklin J.M. Two-fold classification of Archean volcanic-associated massive sulfide deposits. *Ibid.*, **82**: 1057-1063 (1987).
 44. Fyon *et al.*, OGS special volume **4**, Internet, p. 1097 (1992).
 45. Lacroix *et al.*, Internet, In: Rive *et al.* (Eds.), CIMM Special volume **43**, p. 322 (1990).
 46. Costa U.R., Banett R.L., and Kerrich R. The Mattagami Lake mine Archean Zn-Cu sulfide deposit, Quebec: Hydrothermal co-precipitation of talc and sulfides in a sea-floor brine pool-evidence from geochemistry, $^{18}\text{O}/^{16}\text{O}$, and mineral chemistry. *Economic Geology*, **78**: 1144-1203 (1983).
 47. Knockey M.J., Comba C.D.A., and Riverin G. Structure, metal zoning and alteration at the Millenbach deposit, Noranda, Quebec: Geological Association of Canada, special paper, Spec. Paper 25, p. 255-297 (1982).
 48. Kerr and Gibson, Internet. *Economic Geology*, **88**(6): 1421 (1993).
 49. Large R. Australian volcanic-hosted massive sulfide deposits: features, styles, and genetic models, *Ibid.*, **87**: 471-510 (1992).
 50. Huston D.L. and Large R.R. The distribution, mineralogy and geochemistry of gold and silver in the north end orebody, Rosebery mine, Tasmania. *Ibid.*, **83**: 1181-1192 (1988).
 51. Huston D.L., Bolger C., and Cozens G., A comparison of mineral deposits at the Gecko and White Devil deposits: implications for ore genesis in the Tennant Creek district, Northern Territory, Australia. *Ibid.*, **88**: 1198-1225 (1993).
 52. Large R. Chemical Evolution and Zonation of Massive Sulfide Deposits in Volcanic Terrains, *Ibid.*, **72**: 549-572 (1977).
 53. Barton H.L. and Skinner B.J. Sulfide mineral stabilities: in *Geochemistry of Hydrothermal Ore Deposits*, Barnes, H. L. 2nd edition, New York: Holt, Rinehart, and Winston, p. 278-403 (1979).