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Sediment-Hosted Copper Mineralization in Bavanat Region, Southern Sanandaj-Sirjan, Iran

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Abstract

Sedimentary Copper mineralization has been observed in Monj and Jolany locations in Bavanat (Sanandaj – Sirjan metamorphic belt). According to current study, the host rocks for copper mineralization in this area are green sandstones, generally in subarkose and arkose groups. Age of these sandstones is middle Jurassic. Copper mineralization is observed in two forms, sulfides form including chalcopyrite, chalcocite, covellite and also non-sulfide form including malachite, azurite and chrysocolla. Sedimentary Copper deposit of Bavanat is very similar to redbed type of sedimentary deposits such as Nacimiento deposit in USA for many reasons, including the host rock (green sandstone), concomitant rocks (habitual accompaniment with purple siltstone), age of forming, geological environment and the type of mineralization. These similarities can be useful in supplementary studies. Studied sedimentary copper deposits are different from the Jian copper mine in terms of attributes such as host rock, age of formation, upper and lower rocks and also the type of copper mineralization. Based on chemical analysis results, the average amount of copper concentration in the samples was 15509 ppm, which confirms the need for additional studies.

Keywords: Bavanat; Sedimentary Copper Mineralization; Redbed.

Introduction

Sedimentary hosted copper deposits are the second largest group of copper deposits which include 23% of copper production and global reserves and also are known as an important source of silver and cobalt [1,2]. Moreover, some of these deposits as by- product contain valuable elements such as gold, uranium and platinum group elements [2-4]. In terms of age range, sedimentary copper deposits are not known in archean, but in other geologic periods are seen. In the meantime, deposits of proterozoic age (about 900 million years ago) such as Zambia copper belt have been the most frequent ones [5]. Geographically, the majority of host rocks for these deposits are located within the range of 30 degree latitudes in relation to the bygone equator [2].

Sedimentary Copper deposits have been studied and classified by different researchers. Cox et al.,[5]classify these deposits in three groups. The first group are called reduced facies and cited as the RF group. An important example of this group is Kupferschiefer copper deposits in Europe [5] where the host rock is shale. The second group, large deposits with dispersed reducing compounds and abundant in sandstone host are called Revett (RV). Spar Lake deposit in Montana, US is an example of this group. The third group of sedimentary

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copper deposits, are seen along with the redbeds and so called the Redbed Copper Deposits. They have been named by Emance,[6] for the first time. As our study reveals, the target deposits here fall into the third category or redbed type of deposits. The host rock in redbed deposits may be concordant or as interbeded with rocks such as sandstone, siltstone, and red, brown and purple conglomerates. These rocks generally contain hematite and were formed in the deltaic, fluvial and aeolian origin environments [5]. Nacimiento deposit in America is a benchmark of the redbed deposits and has been studied by various researchers including Woodward et al., [7], Talbott [8] , Kirkham [2] and also Cox et al., [5].Cabral [1] has studied redbed copper deposits of the Quebec Appalachians and based on geochemical, petrographical and geological data suggestes two copper mineralization stages in this area. Zhao et al., [9] have examined late paleoproterozoic sedimentary rock-hosted stratiform copper deposits in south China and have concluded that sedimentary rock-hosted stratiform copper deposits commonly occur in rift environments, temporally coincident with the breakup of the Rodinia and Pangea supercontinents. Geological research in the different area of Iran proved that redbed copper deposite has formed in various conditions. Aghazadeh and Badrzadeh [10] have shown four different horizons for sediment-hosted copper mineralization in Iran. Karimi [11] has studied mineralogy, geochemistry and genesis of Chehrabad copper deposit (Zanjan province).

Geological studies on the sedimentary deposits in Bavanat at the southern part of Sanandaj – Sirjan metamorphic belt in Iran has recently been done by some researchers, including Noori and Karimi[12], Vahid [13] and Chamanara [14]. The current study evaluates results of the latest field and laboratory researches on sedimentary copper mineralization in Bavanat area.

The geological environment

Bavanat, is a part of the Sanandaj - Sirjan metamorphic belt[15] which is located in the west and south-west of Iran (Fig. 1). According to Noori et al., [16] three important geological units are observed along the Bavanat valley which has a NW-SE trend (Fig. 2). The oldest unit is Tootak metamorphic complex (TMC) that outcrops on the 2-C map and includes devono-carboniferous marble. The Tootak complex is overlain by Surian series of metamorphic rocks (SMC unit). Based on geological settings, Jian copper mine has occurred in SMC unit.

This metamorphic complex is covered by the non-metamorphosed purple siltstones (PSS unit, Fig. 3). The

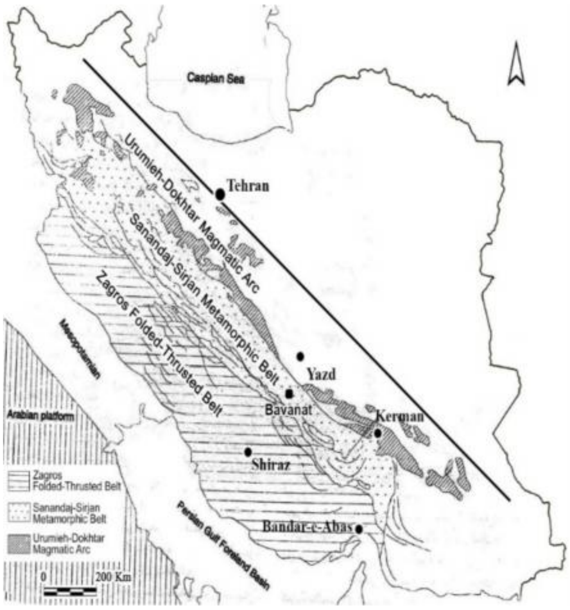


Figure 1. The location of Bavanat area in Sanandaj-Sirjan metamorphic belt in the structural provinces map of Iran,Based map of Ghorbani, [15]

importance of PPS unit is that it locally has intrabeds of green sandstone (unit GS) and this sandstone has acted as the host for copper mineralization (Figs. 5 and 6) .In fact, current studies are focused on this unit. According to the studies, age of PSS and GS is middle Jurassic. JKL unit (upper Jurassic – early Cretaceous) has non metamorphic limestone that covers the PSS units (Fig. 4).

According to the structural geology, Juye Sefid normal fault is observed in Juye Sefid area. Its length is 5.3 Km and the strike is N55E. In Monj area, Monj main fault with the length of 8.5 Km and the strike of N58E is observed. Also, based on field studies and geological map of Bavanat, the region did not have any magmatic activities in Jurassic period. The other important point is that sedimentary basin of Cu host rocks in the area of interest is like a shallow and detrital environment. In all of the studied areas, Cu deposits are generally seen in Jurassic sandstone and arkose.

Mineralization conceptual model

According to above subject, green sandstone is the host rock of copper mineralization in Bavanat which is accompanied by purple sandstone and siltstone. The age of these sedimentary rocks is middle Jurassic. The reason for purple color in these rocks is the presence of iron oxides and hydroxides. This is proved in other redbed deposits, for example Cox et al., [5] emphasized that redbed copper deposits are associated with red, brown and purple sandstone, siltstone and

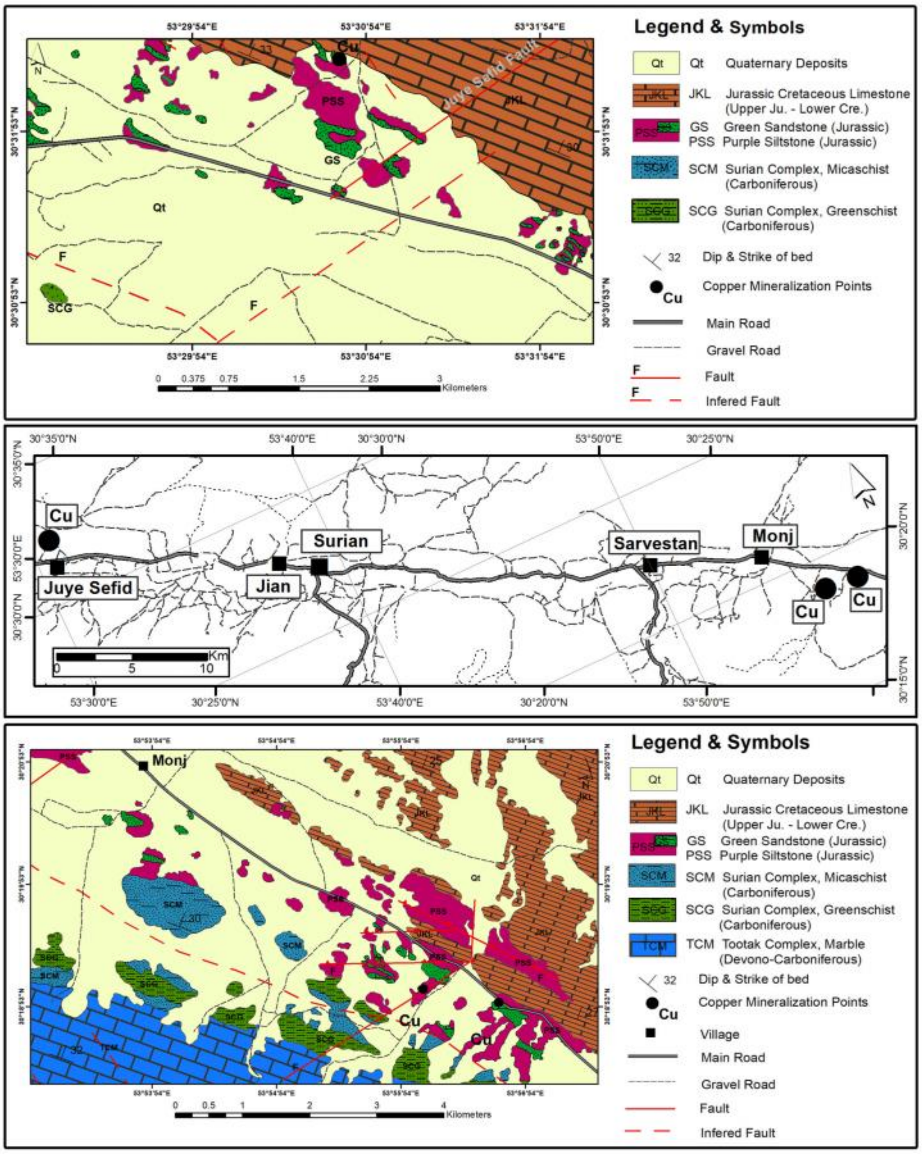


Figure 2. A and C, the Simplified geological map areas of Monj and Jolany, Noori et al., [16] and B, access road map

conglomerate.

Therefore, sedimentary basin of middle Jurassic units as copper host rock, has acted like a shallow and clastic basin. This idea is correlated with previous studies for example Aqanabati [17], according to him Sanandaj-Sirjan sedimentary basin in middle Jurassic had the condition of a shallow and platform basin. This issue is consistent with the results of Zhao et al., [9]. Based on his studies, redbed copper deposits formed in the continental shallow rift zone. Comparison study of geological environment in Jian copper mine and sedimentary copper deposits in Bavanat region can be useful in identifying the differences and analyzing the geological settings.

Many theories are presented about the origin of Jian copper mine. Some researchers [18 ,19] believed that Jian copper mine belongs to the VMS group. However, Moore et al., [20] and Asadi and Moore [21] classified its origin in metamorphosed group.

Despite different ideas, all of these researches emphasized that the host rock of copper mineralization is surian metamorphic complex metabasit with the age of carboniferous. Having this in mind, there are major differences between Jian copper mine and sedimentary copper deposits in Monj and Jolani. Based on Table 1 the host rocks of studied deposits are Jurassic sandstone and siltstone. Also, the host rock of Jian copper mine is metamorphosed, while the studied sandstone in the

Figure 3. Field relation between Jurassic–Cretaceous limestone (JKL) with purple siltstone (PSS), Surian complex (SC) and Tootak complex (TC) along the Bavanat plains, east village of Monj (view to the west)

Figure 4. The position of purple siltstone (PSS) and green sandstone (GS) at the bottom of JKL unit, North Monj (view to the north)

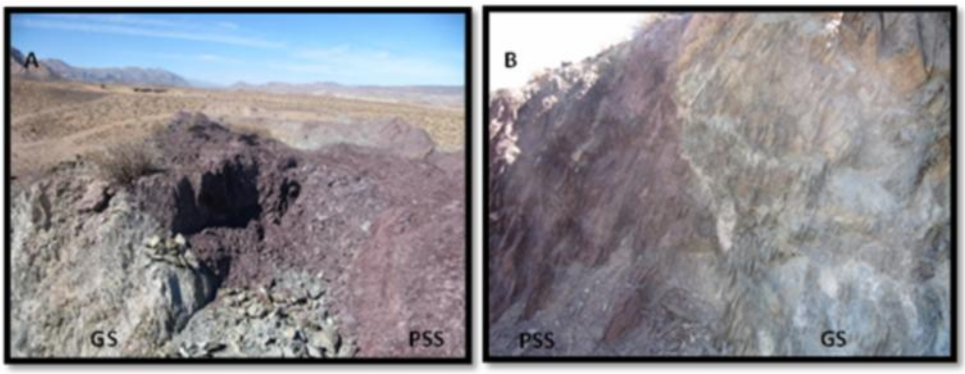


Figure 5. (A and B), close-ups of purple siltstone (PSS) and green sandstone (GS) outcrops in Monj copper deposit, In this two pictures it should be noted the bedding structure in both units confirms sedimentary origin. Purple siltstone abundance in Bavanat area and in the vicinity of the Monj and Jolany copper deposits, embody the redbed and one can compare the type of copper deposit of Bavanat area with sedimentary copper deposit of Nacimiento in USA.Cox et al., [5] believe that host rocks of redbed copper deposit are reduced facies marine or lacustrine rocks such as green, black, or gray sandstone, siltstone ,conglomerate and shale(85% of redbed deposits observed in sandstone or conglomerate).

current research is non-metamorphosed.

As we continue, lithology of GS unit and some parts of PSS unit are studied.

Materials and Methods

Field studying focused at two region: Monj and Jolany. The host rock of copper mineralization in these region are sandstone, so at first, samples prepared and then, supplied thin and polished sections. Microscopic studying done in earth science deportment in the Islamic Azad University in Shiraz by Nicon microscope. Suitable samples selected and dispatched to Kansaran

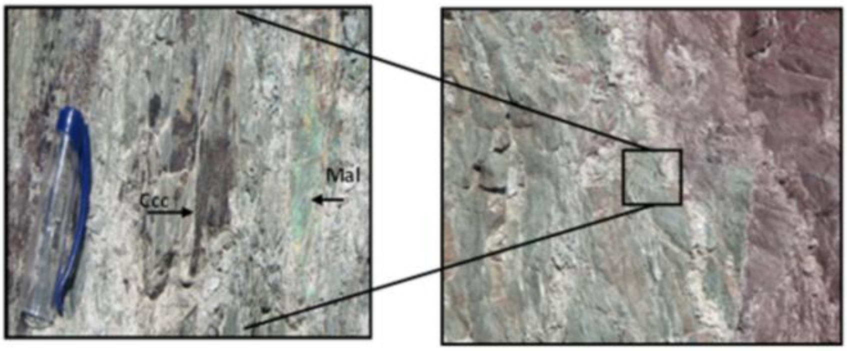


Figure 6. The copper mineralization as malachite (Mal) in green sandstone, Monj copper deposit, Bavanat ,polished section studies, have identified the dark minerals associated with Malachite as chalcocite (Ccc).

Table 1. Comparison check between studied sedimentary copper deposit with Jian copper mine

Deposit	Host rock	Age	Metamorphism
Sedimentary copper deposit, Bavanat	Sandstone	Jurassic	not seen
Jian copper mine, Bavanat	Surian metabasit	Carboniferous	seen

Binalood laboratory (Tehran, Iran) for XRF, ICP-OES and ICP-MS analysis. For data processing, minpet and GCDkit software were used.

Results

1-Results of petrological studies

Table 2 shows the Modal mineralogical composition of sandstone host copper mineralization of Bavanat in

Table 2. Modal mineralogical composition of copper-bearing sandstone, Bavanat area

Min. / Sam.	Qtz	Ab	Or	Bt	Ms	Cal	Chl	Mal	Op	Total	Location	Rock Name
M121	54	5	6	3	1	20	1	5	5	100	Monj	Subarkose
M122	50	8	7	2	2	19	2	6	4	100	Monj	Arkose
M11	56	5	8	1	2	17	1	5	5	100	Monj	Subarkose
M10	53	6	5	1	3	16	2	7	7	100	Monj	Lithicarkose
J101	50	6	9	2	2	18	2	5	6	100	Jolany	Arkose
J102	52	7	7	3	1	17	1	5	7	100	Jolany	Arkose
J103	55	8	6	1	3	19	1	3	4	100	Jolany	Subarkose
J104	57	6	5	1	2	16	1	7	5	100	Jolany	Subarkose
J105	54	8	5	2	2	17	1	6	5	100	Jolany	Subarkose

Qtz: Quartz, Ab: Albite, Or: Orthoclase, Bt: Biotite, Ms: muscovite, Cal: Calcite, Chl:Chlorite, Mal: Malachite, Op: Opaque minerals

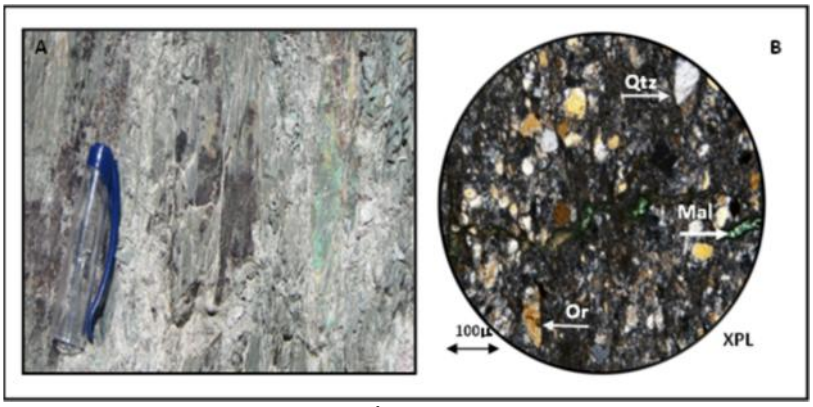


Figure 7. Field outcrop (a) and photomicrograph image (b) of copper mineralization with host sandstone in the Monj area, quartz (Qtz), Orthoclase (Or) and malachite (Mal) are rock-forming minerals.

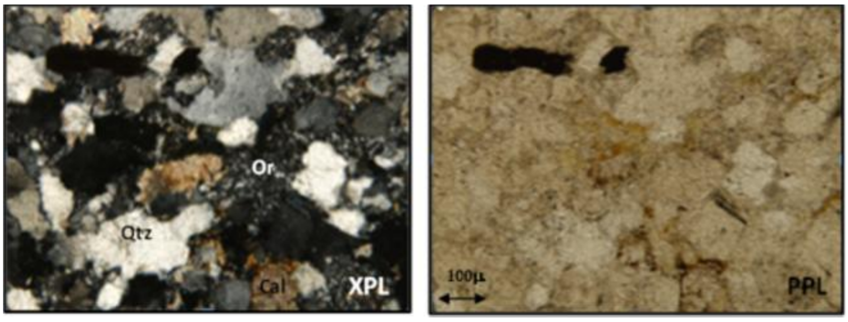


Figure 8. Photomicrograph image of copper mineralization host rock (sandstone) in the Jolany area, quartz (Qtz), Orthoclase (Or) and calcite (Cal) are rock-forming minerals.

Monj and Jolany regions. To display the minerals index is shown using Kretz [22]. According to this table, quartz, feldspar and calcite are the three main rock forming minerals in these rocks (Figs. 7 and 8) accompanied with other minerals such as muscovite, biotite, chlorite, malachite, azurite and opaque minerals. The grain size analysis in these rocks showed that detrital grain size is in the range of 0.06-2 mm. therefore, based on the grain size, copper minerals host rock of Bavanat, were recognized as sandstone. Folk chart [23] was used to classify the sandstone host of copper mineralization in Bavanat area (Fig. 9). As the diagram shows the majority of sandstone rocks were in subarkose category, three samples in arkose and one sample placed in lithic arkose range.

Another important rock accompanying green copper bearing sandstone of Bavanat is a purple sedimentary rock which based on current studies its grain size is in the range of 0.004 - 0.062mm and in fact is recognized as siltstone group (Fig. 10). Quartz, feldspar, sericite and iron oxides are the main minerals forming this siltstone. Presence of iron oxides in the siltstone creates a characteristic color and that's where the name of purple siltstone comes from.

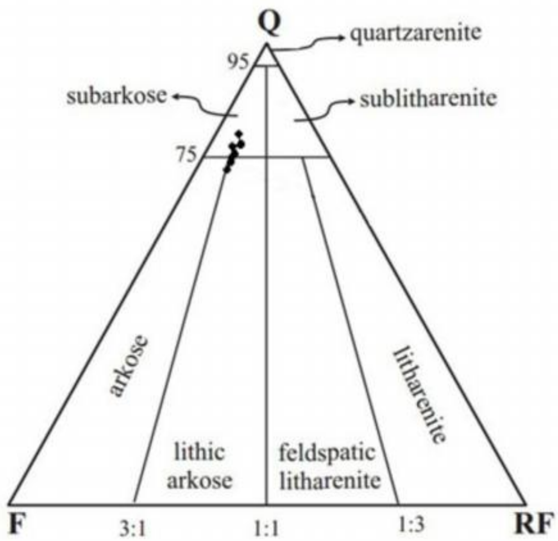


Figure 9. The position of copper mineralization host rock (sandstone) in Bavanat area in the Folk chart [23]

2-Results of Mineralization studies

In the Bavanat studied area, copper mineralization is generally seen as chalcopyrite, chalcocite, malachite and azurite hosted in the green sandstone (Fig. 6). These sandstones, are placed as interbedes within purple siltstones (Fig. 4). Other than these minerals, pyrite, along with iron oxides and hydroxides are some other minerals in the study area that are being discussed briefly in this section.

2-1-Chalcopyrite ($CuFeS_2$)

Chalcopyrite is the most important copper sulphide mineral in the study area which shows relatively low abundance in the surficial zones and is one of the scarce minerals (Fig. 11). This mineral has been often transformed into oxidized and carbonate phases as a result of oxidation (Fig. 12). According to Guilbert and Park[24] chalcopyrite turns to malachite ($Cu_2(OH)_2CO_3$) on the effect of decomposition of diluting fluids with low copper concentrations and during the reaction with CO_2, as follows:

$2CuFeS_2$ (Chalcopyrite) + $8.5O_2$ + $2H_2O$ → Fe_2O_3 +

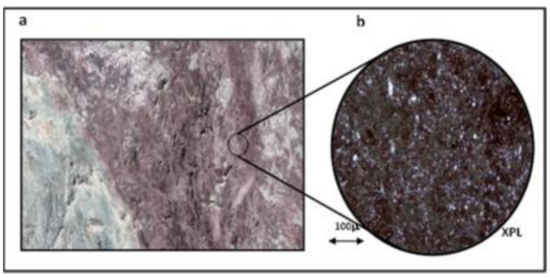


Figure 10. Field outcrop (a) and thin sections (b) images of purple siltstones (Monj area), these siltstones are introduced as outcrops of redbeds in Bavanat.

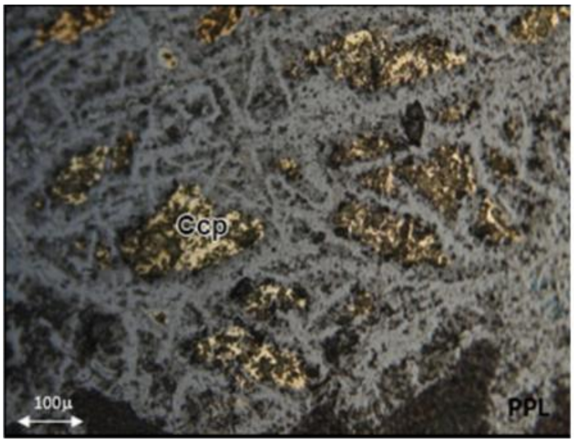


Figure 11. The anhedral crystals of chalcopyrite (Ccp) in sandstone of Monj area; gangue minerals are generally quartz and feldspar.

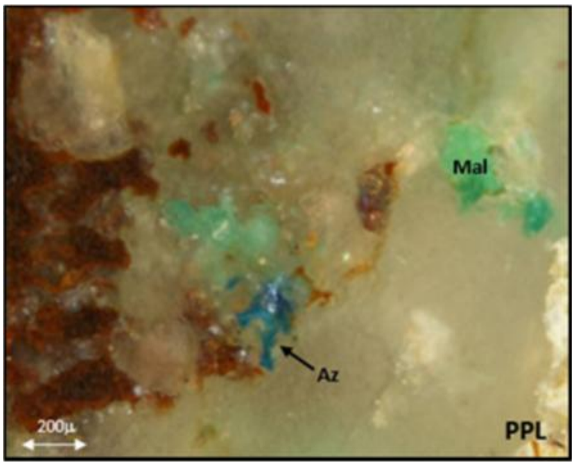


Figure 12. Decomposition of chalcopyrite (Ccp) to malachite (Mal), azurite (Az) and iron oxide (brown) in Monj sandstone

$2Cu^{2+} + 4SO_4^{-2} + 4H^+$

$Cu^{2+} + H_2O \rightarrow CuO + 2H^+$

$2CuO + CO_2 + H2O \rightarrow Cu_2(OH)_2CO_3$ (Malachite)

Also as it is observed in some microscopic samples of Bavanat sandstone, chalcopyrite has transformed to azurite (Fig. 12). According to Guilbert and Park [24], chalcopyrite alteration can only lead to azurite formation where the hydrothermal fluids are very rich with regard to Cu^{2+} solution, and if the concentration of Cu^{2+} ion is reduced, then malachite is formed instead of azurite. Exactly for this reason, the abundance of malachite is higher than azurite in the studied sections.

2-2-Pyrite (FeS_2)

Figure 13 shows a sample of pyrite in the area. In this area the abundance of pyrite crystals is relatively low and sometimes they have decomposed to iron oxides

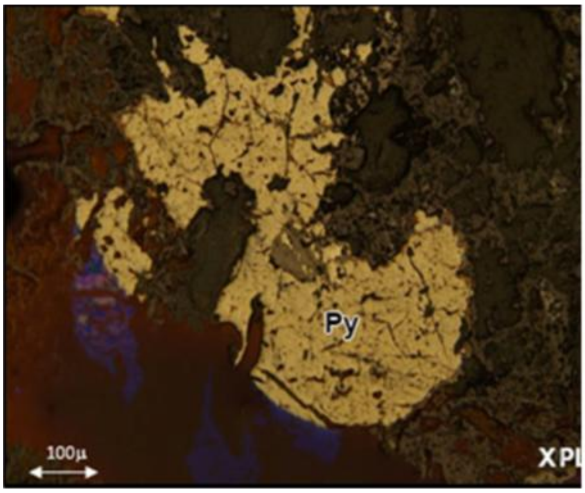


Figure 13. Pyrite crystals (Py) in sandstones of Bavanat, Jolany area

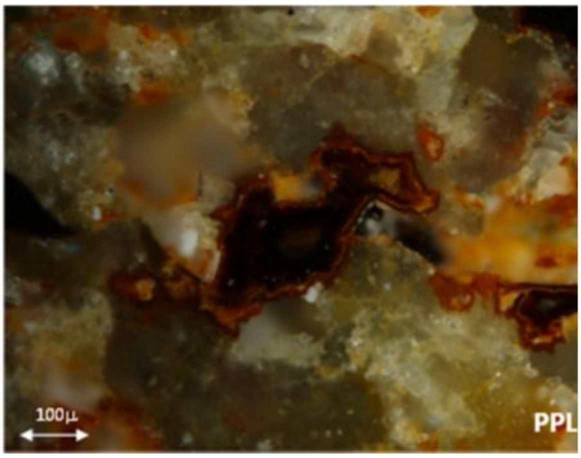


Figure 14. Pyrite crystals (dark) are turned into hematite (brown), sandstone of Bavanat, Jolany area

and hydroxides (Fig. 14) According to Guilbert and Park[24] decomposition reaction of pyrite to hematite in the surficial conditions is as follows:

$2FeS_2 + 7.5O_2 + 4H_2O \rightarrow Fe_2O_3 + 4H_2SO_4$

2.3 Malachite $CuCO_3(OH)_2$

Malachite is the most important secondary copper mineral which has exposure in the green sandstone of Bavanat area (Figure 15). This mineral is secondary and is formed from decomposition of chalcopyrite. It generally has filled the vacant spaces of fractures along with iron oxides and hydroxides.

2-4-Azurite $Cu_3(CO_3)_2(OH)_2$

Azurite as a secondary mineral, is one of copper bearing minerals which can be found in the green sandstone of Bavanat (Fig. 16). Azurite appears in

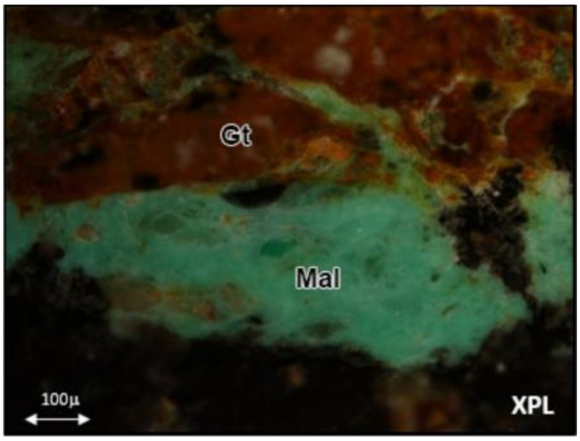


Figure 15. Accompanying of malachite (Mal) an d goethite (Gt) in Jolany sandstones,these minerals are produced by the decomposition of chalcopyrite.

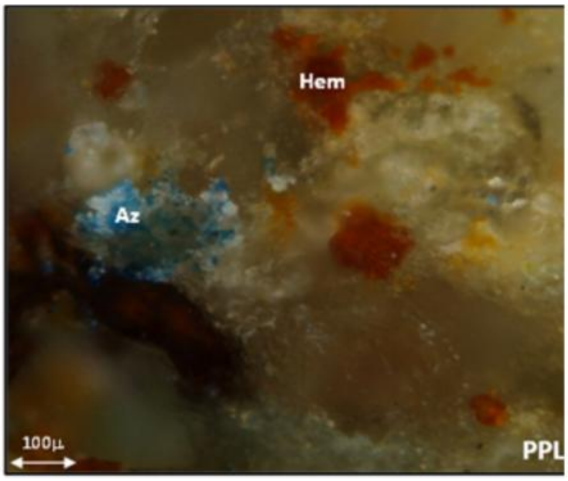


Figure 16. Azurite mineral (Az) along with hematite (Hem), sandstones of Jolany area

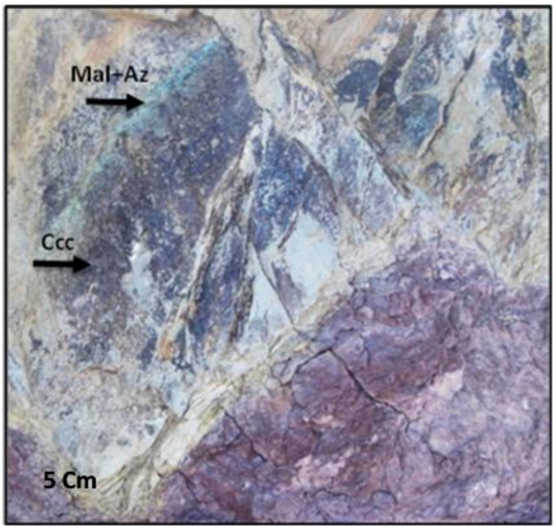


Figure 17. Chalcocite mineral (Ccc) along with malachite (Mal) and azurite (Az) in green sandstone of Bavanat, Purple siltstone rock unit is also visible in this image.

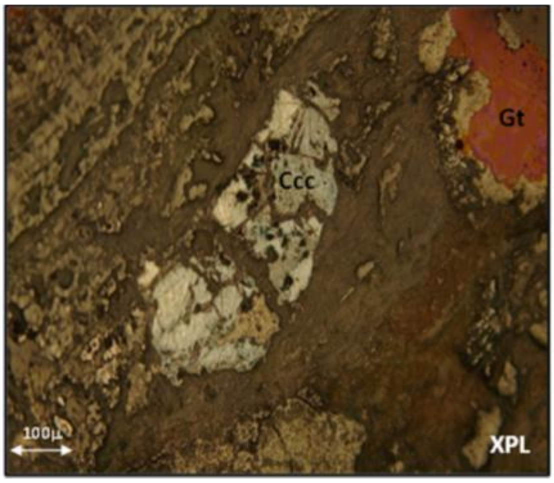


Figure 18. Chalcocite mineral, Ccc (gray) along with goethite, Gt (brown), in green sandstone of Monj area

surficial regions and has vein texture and cavity filling nature same as malachite.

2-5-Chalcocite (Cu_2S)

This mineral is also a secondary copper mineral which can be seen along with malachite in studied sandstones of Bavanat area (Fig. 6). In the field scale in Bavanat area, chalcocite in a hand specimen can be seen as broad and thin crystals, in dark colors that generally has grown as secondary layers on bedding surfaces (Fig. 17).

The study of polished sections obtained from green sandstone of Monj area, indicated that chalcocite is found in the mold of pyrite thus could be formed by pyrite alteration (Fig. 18). Regarding the forming chalcocite from pyrite, Evans [25] believes that fluids contain copper sulfate can convert it to chalcocite according to the following reaction during a contact with pyrite and produce iron sulphate:

$5FeS_2 + 14CuSO_4 + 12H_2O = 7Cu_2S + 5FeSO_4 + 12H_2SO_4$

Since chalcocite mineral has high abundance in green sandstone of Bavanat area, it is important to examine abundance of silver in the sandstone outcrop areas as well. It has been proved that chalcocite can be a suitable host for concentration of silver element [26].

2-6-Covellite (CuS)

In green sandstone of Bavanat area, covellite mineral is observed in the form of pseudomorph. Given that the covellite mineral exists on the margin of primary sulfide

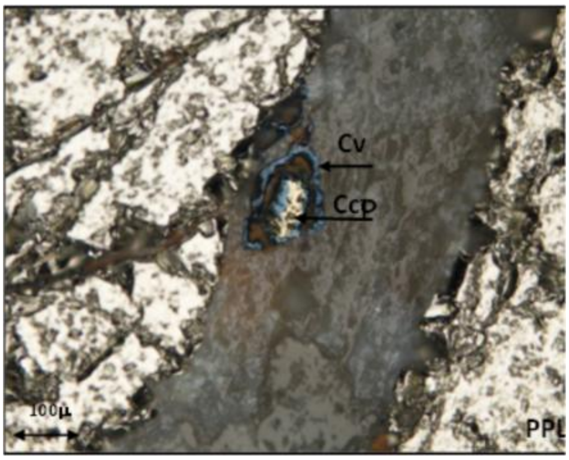


Figure 19. The decomposition of chalcopyrite (Ccp) to covellite (Cv) in green sandstones of Bavanat, as the image shows and because of two following reasons covellite mineral has a secondary origin: 1.The conversion of chalcopyrite from margin to covellite 2. covellite being located along the fractures where hydrothermal fluids have passed.

minerals such as pyrite and chalcopyrite, it can be assumed that covellite has a secondary origin in the sandstones of Bavanat area, (Fig. 19). Evans [25] believes that covellite sulphide mineral is formed as secondary mineral as a result of decomposition of primary sulfides such as chalcopyrite (The following reaction):

$CuFeS_2$ (Chalcopyrite) +$CuSO_4$ = 2CuS (Covellite) + $FeSO_4$

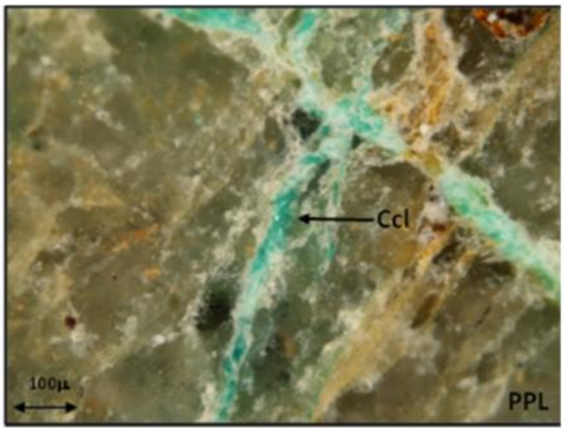


Figure 20. Formation of chrysocolla (Ccl) as a secondary mineral along joints, green sandstone of Bavanat.

2-7- Chrysocolla ($Cu_2H_2Si_2O_5(OH)_4$)

Chrysocolla mineral is a hydrous copper silicate minerals generally of a secondary origin and is formed either by hydrothermal activity or weathering [28]. In green sandstones of Bavanat area, Chrysocolla is generally found along with malachite and azurite and as a cavity filling mineral. This confirms a secondary origin for Chrysocolla mineral (Fig. 20).

3-Results of Geochemical studies

To study the geochemistry, 14 samples using XRF method, 9 samples using ICP-MS and 4 samples using ICP-OES were analyzed chemically (Tables 3 and 4). At first, the chemical names of host rocks for the copper mineralization were identified using the results of

Table 3. Results of XRF chemical analysis of copper sandstone of Bavanat area

Sample	SiO2	Al2O3	Fe2O3	CaO	MgO	Na2O	K2O	P2O5	TiO2	MnO	SO3	Cu	L.O.I
	%	%	%	%	%	%	%	%	%	%	%	ppm	%
SN1*	40	8.1	39.1	4.3	1.3	0.4	1	0.1	0.4	0.2	0.1	800	4.25
SN2*	57.3	18.8	10.1	1.5	2.3	0.9	2.4	0.2	0.8	0.1	0.1	800	4.99
SN3*	63.5	16.2	5.8	2.4	2.2	1	1.9	0.1	0.7	0.2	0.1	4000	5
SN4*	60.7	20.8	7.3	0.2	2	1.1	3.1	0.1	0.8	<0.1	<0.1	800	3.29
SN5*	62.3	12.4	4.9	5.1	1.6	1.3	1	0.2	0.7	0.3	<0.1	22400	6.93
SN6*	73.2	10.4	3	3.7	10	1.4	0.9	0.2	0.6	0.2	<0.1	3200	4.53
SN7*	55.6	18.6	7.7	2.8	3.4	0.6	3.2	0.1	0.7	0.1	<0.1	800	6.63
SN8*	64.4	16	4.7	0.8	2.4	1.8	1.8	0.2	0.8	0.1	<0.1	17600	3.75
SN9*	70.8	13.2	3.9	0.4	2	1.8	1.5	0.2	0.7	<0.1	0.2	11200	2.85
SN10*	63.5	15.3	9.5	0.9	2.5	0.7	2.2	0.1	0.8	0.1	<0.1	800	4.03
SN11*	81.8	5.2	1.7	4.1	0.5	1.3	0.4	0.1	0.1	0.2	0.1	800	4.21
SN12*	63.5	9.7	6	6.2	1.2	1.4	0.1	0.1	0.5	0.2	3.3	800	6.51
SN13*	77.8	7.8	1.9	3.5	0.4	1.1	0.9	0.1	0.2	0.1	0.4	6400	4.32
SN14*	78.5	5.6	2	4.7	0.5	1.2	0.6	0.1	0.2	0.2	0.1	6400	4.84
T1S5	69.74	4.11	3.75	10.9	0.5	0.38	0.62	0.042	0.25	0.43	0	91	8.97
T1S6	56.58	20.73	8.15	1.35	2.72	0.66	4.31	0.126	0.78	0.01	0	18	4.16
T1S12	73.85	7.73	2.27	5.21	0.98	2.2	0.4	0.047	0.21	0.21	0	12826	5.19
T1S13	72.8	8.82	6.48	1.4	2.51	0.75	0.58	0.071	0.25	0.15	0	17797	3.91
MS18	75.86	9.47	4.73	1.29	2.04	1.13	0.73	0.069	0.29	0.12	0	5477	3.43

* [13]

Table 4. Chemical analysis of ICP-MS and ICP-OES of copper hosted sandstone, Taherabad, Bavanat

Sample	JS1*	JS3*	GS5*	SS6*	SS8*	JS16*	GS2*	SS2*	SS3*	T2S6	T2S7	S1	S6
Ag	0.6	5.4	1.8	10	1.3	66	0.29	8	8	0.15	0.16	0.11	0.19
As	13.2	293	10.8	190	168	28.8	3	100	100	2	31.8	5.9	6.5
Cd	0.5	3.17	0.53	0.58	0.25	0.05	10	10	14	0.23	0.24	0.25	0.23
Ce	42.3	38.4	37.4	53.6	47.7	45.9	15	18	14	6	38	14	5
Co	30.7	6.9	9.1	118	12.6	17.8	4	3	2	2	16	188	540
Cu	14680	8116	2256	29320	2597	74120	972	3824	3697	911	1650	14566	6974
Dy	1.66	1.64	2.85	3.26	2.85	2.27	5.27	4.14	4.66	N.A	N.A	N.A	N.A
Er	0.94	0.99	1.75	1.87	1.52	1.16	3.47	2.66	2.74	N.A	N.A	N.A	N.A
Eu	0.5	0.52	0.83	1.16	0.87	0.76	1.66	1.54	1.57	N.A	N.A	N.A	N.A
Gd	2.76	2.62	4.09	5.22	4.49	3.38	6.23	5.33	6.24	N.A	N.A	N.A	N.A
Hf	1.06	1.04	1.01	1.48	1.08	1.21	3.94	3.77	4.9	N.A	N.A	N.A	N.A
La	21.4	19.2	19.9	26.8	22.9	21.8	7	8	6	2	19	5	6
Lu	0.18	0.17	0.3	0.34	0.25	0.21	0.96	0.73	0.75	N.A	N.A	N.A	N.A
Mn	905	1520	4350	1010	1620	486	1557	1160	2093	664	168	2070	331
Nd	18.8	17.4	21.4	28.8	25.6	23.2	30.3	29.3	39	N.A	N.A	N.A	N.A
Ni	26	19	23	31	31	27	15	16	11	43	28	409	35
P	223	277	322	1020	534	304	201	284	233	70	501	691	261
Pb	5	8.2	21.4	54	15.5	18	23	57	36	5	21	5	15
Pr	5.16	4.65	5.38	7.18	6.23	5.98	5.59	5.74	7.9	N.A	N.A	N.A	N.A
Re	0.01	0.01	0.01	0.01	0.01	0.08	-	-	-	N.A	N.A	N.A	N.A
S	50	57	237	116	161	2100	469	69	715	332	239	138	195341
Sb	0.3	12.4	0.3	6.7	38.2	0.9	5	39	119	0.97	0.99	1.11	1.08
Se	0.1	0.09	0.11	0.26	0.18	0.16	0.5	0.5	0.5	N.A	N.A	N.A	N.A
Sm	3.44	3.33	4.64	6.31	5.54	4.51	5.92	5.09	6.67	N.A	N.A	N.A	N.A
Sn	1	0.9	0.9	2.4	1.7	0.8	14	13	12	2.8	3.2	3.5	4.1
Ta	0.5	0.43	0.39	0.54	0.43	0.42	0.1	0.1	0.54	N.A	N.A	N.A	N.A
Tb	0.36	0.35	0.65	0.78	0.66	0.49	0.92	0.73	0.85	N.A	N.A	N.A	N.A
Te	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	N.A	N.A	N.A	N.A
Ti	2020	1660	1360	2140	1810	1590	295	396	275	142	1819	8659	1833
Tl	0.2	0.2	0.2	0.3	0.2	0.2	0.67	0.3	3.02	N.A	N.A	N.A	N.A
Tm	0.15	0.13	0.24	0.27	0.21	0.19	0.53	0.42	0.45	N.A	N.A	N.A	N.A
U	1.72	6.1	2.58	14.3	2.24	12.1	1.3	1	2.3	1.3	4.1	2.7	3
V	39	52	48	104	71	68	20	24	17	5	52	301	81
Y	7.62	8.52	16.1	15.8	14	10.3	7	5	9	7	8	34	7
Yb	0.96	0.84	1.51	1.72	1.38	1.21	4.2	3.1	3.4	0.7	1.1	4.3	1.6
Zn	49.1	45.2	36.3	84.5	58.7	57	42	82	83	2	53	189	102

* Samples of Baluchi[29], Note 1: samples of Baluchi[29] by ICP-MS and other samples analyzed by ICP-OES. Note 2: All values are in ppm. Note 3: N.A = Not Analysis

chemical analysis; then the geological settings were examined and finally the abundance and correlation graphs were plotted and interpreted. The results of this threesteps will be provided separately.

3-1- The chemical classification of rocks

Chemical nomenclature of copper mineralization hosted sandstones of Bavanat area was performed using the chart of Pettijohn et al., [30] (Fig. 21). As can be seen studied rocks are generally in the range of sub arkose and some in the range of arkose. This is consistent with the results of microscopic studies. The chemical naming of rocks indicates that some samples also are in the range of litharenite and sub litharenite.

3-2-Geological Setting

The sandstones in the area were studied in terms of geological and tectonic environment using Roser and Korsch [31], (Fig. 22). The geological environment of copper mineralization of hosted sandstone in Bavanat area generally is in the range of active continental margin (ACM). Cox et al., [5] believe that redbed copper deposits occur in various geological settings.

3-3-Histograms and correlation charts

Histogram in Figure 23 shows the average abundance of valuable elements in analyzed samples. As can be seen the average copper concentration in analyzed sandstone samples of Bavanat area was equal to 15509 ppm which is considered valuable in terms of economic conditions. Meanwhile the average concentration of copper in the Nacimiento mine as a sedimentary deposit with the same origins as of our studied area was equal to 6700ppm [8], so copper concentration in the studied

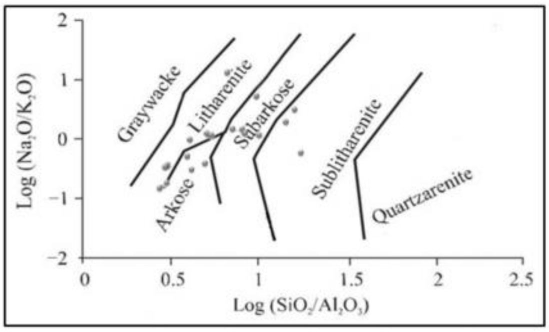


Figure 21. The position of copper mineralization hosted sandstones of Bavanat in the chart of Pettijohn et al., [30]

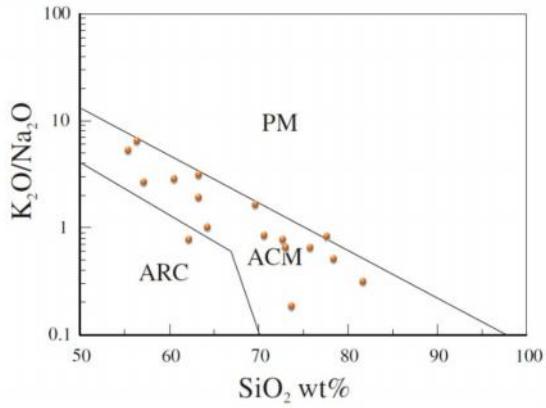


Figure 22. Position of copper bearing sandstones of Bavanat area in the tectonic environment of active continental margin (ACM), base charts from Roser and Korsch, [31]

samples is evaluated in a suitable conditions. Also the average concentration of silver element in analyzed samples was equal to 11.3 gram per ton and in one of samples silver concentration reached to even 66 gram per ton (JS16). Silver concentration in the Nacimiento mine as a similar deposit was equal to 158ppm [7]. Although the average abundance of silver in the analyzed samples is non-economic, it is necessary to pay more attention to similar conditions like sample JS16. The average abundance of other elements shown in figure 23 do not meet the economic conditions. But arsenic as a trace element of gold, with an average concentration of 101.3 ppm significant and in one of the samples (JS3) its abundance even reached 293 ppm. Therefore, samples similar to JS3 are important to identify gold concentrations for supplementary studies.

Also drawing and interpretation of correlation graphs is assumed important because by drawing of correlation diagrams, the relation between two variables measured in individual datasets will be revealed [32]. Moreover, by identifying the dependency of the elements one can discover greatly the environmental conditions and effective processes involved in forming the deposit[33]. Considering the above reasons, correlation charts for different variables were plotted and interpreted. As Figure 24 shows, Cu/S correlation is positive. This represents the greater concentration of copper element in the sulfide minerals. Another interpretation is that although copper mineral in this area is found as both sulfide minerals (chalcopyrite, chalcocite and covellite) and non-sulfide minerals (malachite, azurite and chrysocolla), sulfide copper minerals have the highest abundance. This means as the concentration of sulfur increases, it is followed by an increase in the percentage of copper. Also the Cu / Ag correlation shows a positive relation between copper and silver (Fig. 25). It is confirmed that chalcocite as a sulphide copper mineral, has significant abundance in copper mineralization host sandstones of Bavanat. As previous studies have shown chalcocite acts as a host for silver element in sedimentary copper deposits [26, 27]. In another step, correlation charts of silver with sulfur were illustrated (Fig. 26). Correlation charts for Ag / S show the positive relation of two elements silver and sulfur. By investigation of the relation of Cu/As (Fig. 27) one can

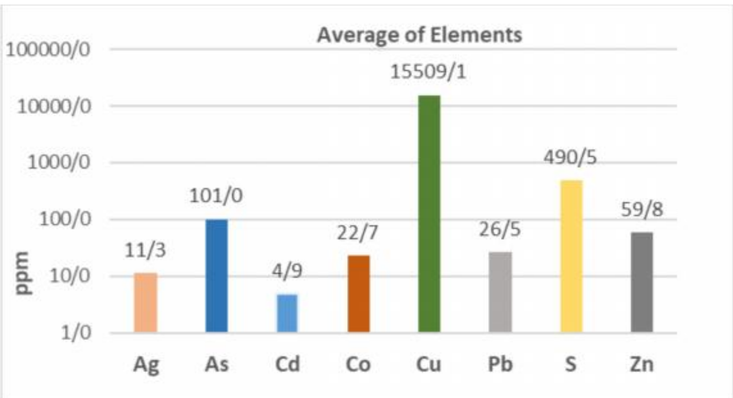
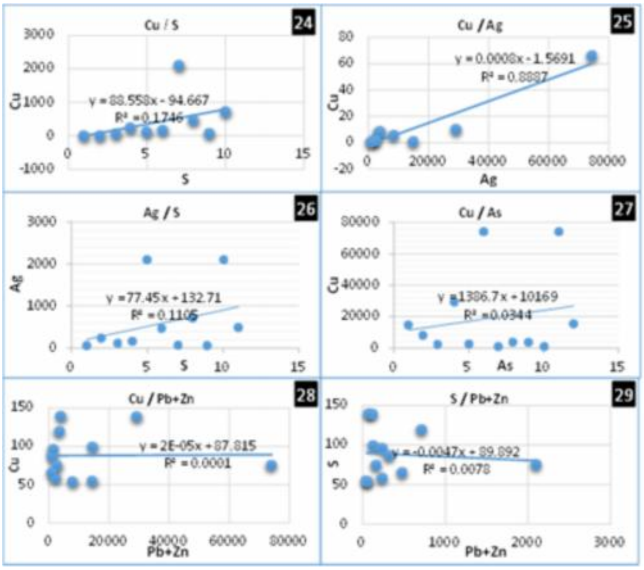
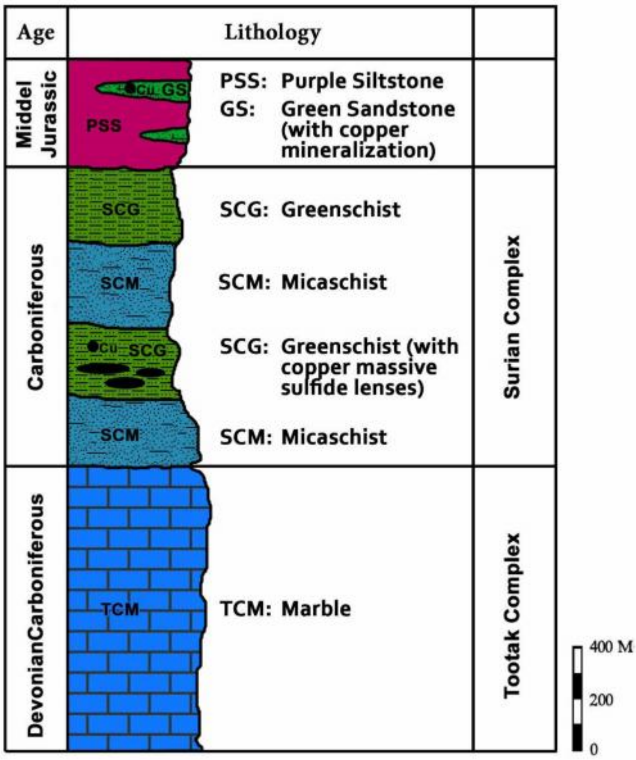


Figure 23. Average abundance histogram of valuable elements in analyzed sandstone samples, Bavanat area



Figures 24–29. Correlation charts of several important elements



Figures 30. Stratigraphic colomn of the Tootak complex, Surian complex and middle Jurassic sandstone and siltstone , Monj area,Bavanat,based on [34,35] with the latest changes

conclude that these two elements are positively correlated. The importance of this relation is that arsenic generally acts as a tracer of gold element and it is important to consider this in supplementary studies. Figure 28 shows the dependency of Cu/Pb + Zn. Accordingly, a certain correlation between these elements cannot be seen as the sulfur Relation with lead and zinc also cannot be recognized (Fig. 29).

Discussion

- Copper mineralization in sedimentary rocks of Bavanat area located in Southern Sanandaj- Sirjan has exposures in several locations such as Monj and Jolany and is very similar to the conditions of sedimentary deposits of redbed type.

- Copper mineralization has occurred in green sandstones that are likely to have Middle Jurassic age.

- Current studies (section 2.5) showed geological environment of these sandstones is generally in the active continental margin but occasionally seen in Pacific continental margin as well.

- This geological environment is in compliance with the conditions of the Jurassic period in Sanandaj – Sirjan area, because according to Aghanabati [17] the gap between the Late Triassic to Early Jurassic, in the zone of Sanandaj - Sirjan, had platform conditions. Such a situation coincides with a sedimentary basin located on the Pacific continental margin while Sanandaj - Sirjan basin is known as an active sedimentary basin in the Middle Jurassic to Late Cretaceous [17]. Based on this logic, one can imagine that copper mineralization host sandstones of Bavanat have begun to form from early Jurassic but should generally have the middle Jurassic age. The age of these sandstones does not seem to reach upper Jurassic because based on field studies and geological maps (Figs. 2 to 4) this sandstones are covered by limestone unit JKL with the age of late Jurassic - early Cretaceous. This age of mineralization can be correlated with third horizon of sediment-hosted copper mineralization in Iran for example Shotori mountain,Ravar and Kalmard area [10].

- Copper mineralization has appeared in this area in the different forms of sulfide and non-sulfide copper minerals (Part 4) but the presence of chalcocite is especially important in terms of accompaniment of silver with this mineral. Since it has already been proved that chalcocite mineral in the copper deposits acts as the host for the precious silver metal [26, 27] therefore it is necessary, to study silver in particular in supplementary research in addition to copper.

- Bavanat sedimentary copper deposit was compared with Nacimiento a well-known deposit in America as a benchmark deposit of redbed type (Table 5). As can be seen several similarities exist in occurrence of both deposits in terms of time of forming, the host rock, concomitant rocks, mineralization and geological environment. Since the sedimentary copper deposits are the second important group of copper deposits, supplementary studies on sedimentary copper deposits of Bavanat is very important and more research and investigation need to be carried out.

Conclusion

Bavanat sedimentary copper deposits can be introduced as a new type of copper mineralization in this part of southern Sanandaj-Sirjan. These sedimentary deposits are different from Jian copper mine in various aspects. In terms of field geology and the relation of rock units in the field, the Cu host rock sandstone, covers surian metabasit at below and has been covered by JKL limestone on the top. Whereas based on [34, 35] surian metabasit which are the host rock of Jian copper mine, overlay marble of Tootak complex at below and has been covered by Jurassic sandstone on the top (Fig. 30). Also, our current studies indicate that malachite and chalcocite are main copper minerals in Bavanat sedimentary copper deposits, whereas based on Mousivand [36] chalcopyrite is main copper mineral in Jian mine. Due to the extension of Jurassic sedimentary units in Bavanat area, supplementary studies in particular subsurface investigations can be effective in identifying the larger dimensions of sedimentary copper mineralization in Bavanat.

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Table 5. A comparative study of Bavanat sedimentary copper deposit with Nacimiento copper deposit.

Deposit / Features	Age formed	The host rock	Along rock	Primary minerals	Secondary minerals	Geological setting
Bavanat Copper deposit	Mesozoic / Jurassic	Subarkose and Arkose	Redbed (Purple Siltstone)	Chalcopyrite, Pyrite	Malachite, Chrysocolla, Azurite	Shallow environment, Active continental margin
Nacimiento Copper Deposit*	Mesozoic / Triassic	Subarkose and Arkose	Redbed	Chalcopyrite, Pyrite Bornite	Malachite, Chrysocolla, Azurite	Shallow sedimentary environment

*Woodward et al.,[7]

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