

SOME SULFIDE-SILICATE ASSEMBLAGES FROM THE SAR CHESHMEH PORPHYRY COPPER DEPOSIT, KERMAN, IRAN

J. Shahabpour

*Department of Geology, College of Sciences, Shahid Bahonar University, P.O. Box 133, Kerman, Islamic
Republic of Iran*

Abstract

Studies of three selected sulfide-silicate assemblages from ore samples from the Sar Cheshmeh porphyry copper deposit led to some ore genetic conclusions. The presence of chalcopyrite blebs in the groundmass orthoclase and quartz from the stock suggests liquid immiscibility in a cooling late-magmatic melt. This is in favor of the orthomagmatic model proposed for porphyry copper deposits. The presence of bornite grains suggests a partly derivation of copper from biotite. This further supports the results obtained from the electron microprobe studies of the textural varieties of biotite. The presence of pyrite in the sericitized parts of biotite grains suggests a hydrothermal origin for the sericitized biotite enclosed pyrite grains.

Introduction

The Sar Cheshmeh porphyry copper deposit is located in southeastern Iran (Fig. 1). Similar to the porphyry copper deposits of the American southwest [40], the Sar Cheshmeh deposit, along with other porphyry copper deposits of the Kerman region are aligned parallel to an inferred continental margin [12]. The geology, alteration and mineralization of the deposit have been described by Bazin and Hübner [4], Waterman and Hamilton [41], Etminan [10, 11], Haynes and Ghorashi Zadeh [19], Hakim [18], Shahabpour [36], Shahabpour and Kramers [39], and Shahabpour [37, 38]. In the context of the porphyry copper classification of Zvezdov et al. [46], the Sar Cheshmeh porphyry copper deposit is comparable with gold containing porphyry copper-molybdenum deposits.

Three selected sulfide-silicate assemblages from ore

samples from the Sar Cheshmeh deposit are examined here. These assemblages are: (a) chalcopyrite blebs and micro-lobes in groundmass orthoclase and quartz; (b) bornite in chloritized biotite; and (c) pyrite in sericitized biotite. The study of these assemblages is important as it gives an insight into the origin of the ore constituents.

Sulfide-silicate relations have been studied by many authors. Putman [32] considered the possibility of the extraction of chalcophile metals from silicate phases from the end of magmatic crystallization to deuteritic and hydrothermal alteration stages. Kullerud and Yoder [23, 24] indicated some of the possible reactions between ferromagnesian silicates and sulfur rich vapor. Beane [5] considered the chloritic alteration of biotite as a mechanism for the deposition of chalcopyrite from a hydrothermal solution in porphyry copper environments.

Geology

The porphyry copper mineralization at Sar Cheshmeh is associated with a granodioritic stock intruded into a folded and faulted early Tertiary volcano-sedimentary

Keywords: Sulfide-silicate assemblages; Porphyry copper deposits; Sar Cheshmeh; Iran

E-mail: shahab@arg3.uk.ac.ir

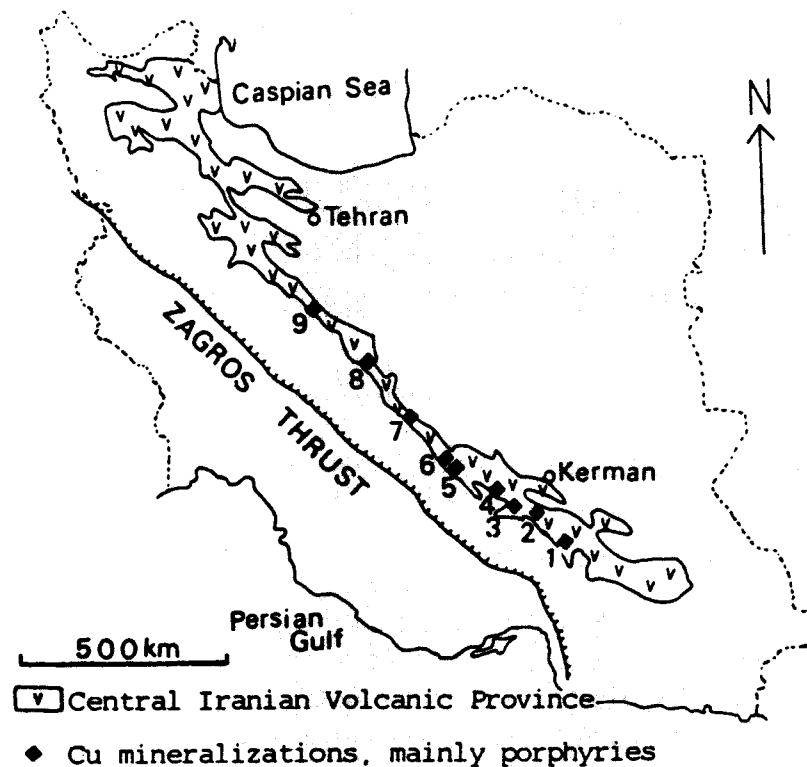


Figure 1. Sketch map showing the position of central Iranian volcanic province and some of the most important porphyry-type mineralizations relative to the main Zagros thrust (modified after Förster, [12]). 1. Bahre Aseman; 2. Takht; 3. Kuhe Panj; 4. Sar Cheshmeh; 5. Meiduk; 6. Gowde Kolvary; 7. Darrehsereshg; 8. South of Ardestan; 9. Sharifabad

series. "The volcanic rocks in the Sar Cheshmeh area are principally fine-grained andesite porphyries; a detailed subdivision of these rocks is in complete" [18,42].

The intrusive activity in the Sar Cheshmeh stock itself has been multi stage. The main intrusion, the Sar Cheshmeh porphyry, is cut by a sub-volcanic body, the so called late fine porphyry and by several felsic dikes. The mineralogy of these dikes and their time relationship to mineralization allow them to be grouped into intra-mineralization (early hornblende porphyry), late mineralization (late hornblende porphyry) and post-mineralization (feldspar porphyry and biotite porphyry) dikes [42, 10, 11, 36].

In andesitic wall rocks, three different zones are observed which are concentric to the potassic and phyllic-altered Sar Cheshmeh porphyry (the stock). The internal zone closest to the stock is characterized by strong biotitic and weak phyllic alteration with a thickness from 50 to 400 m (at 2400 m elevation). This zone passes progressively into the next zone whose external limit corresponds approximately to the cut off grade of 0.4% Cu. This intermediate zone is characterized by weak biotitic and strong phyllic alteration. Its thickness at 2400 m elevation

varies from 50 to 150 m. The external (propylitic) zone is very thick (> 1 km at 2400 m elevation) and at the periphery grades into unaltered country rocks [10, 11].

The primary sulfides at the Sar Cheshmeh deposit are pyrite, chalcopyrite, and molybdenite. The highest copper grades are associated with potassic (biotite) alteration and occur as a semi-continuous ring outward of the Sar Cheshmeh granodiorite stock/wallrock interface, while the highest molybdenum grades occur along the intrusive interface [42].

Alteration Assemblages

The alteration assemblages described from other porphyry copper deposits [7, 8, 33, 25, 34, 5], with some variations exist at Sar Cheshmeh [42, 10, 11, 36, 37, 39]. These assemblages may be summarized as follows: (a) secondary K-feldspar-secondary biotite-quartz-chalcopyrite-pyrite (molybdenite) within the stock (Sar Cheshmeh porphyry) and early dikes, and secondary biotite (K-feldspar)-quartz-chalcopyrite-pyrite (molybdenite) within the andesitic wall rocks; (b) quartz (K-feldspar)-molybdenite (chalcopyrite+pyrite) within the stock, early

dikes and the country rocks; (c) quartz-sericite-chlorite-pyrite (chalcopyrite and molybdenite) which overprints the previous assemblages and the pre-phyllitic rock units; (d) quartz-calcite-epidote-chlorite-albite (pyrite) within the country rocks, and selectively within the stock and early dikes. Patchy propylitic assemblages are also reported to occur within the porphyritic units of the Skouries deposit, NE of Chalkidi, Greece [13]. Propylitic alteration is also reported to overprint the potassic as well as the phyllic alteration zones at the Bini porphyry copper-gold-molybdenum deposit, Papua, New Guinea [9]. Gustafson and Quiroga [17] identified early biotite veinlets below the porphyry copper orebody at El Salvador, and Dugmore et al. [9] identified biotite veinlets at the Bini porphyry copper-gold-molybdenum deposit, Papua, New Guinea. Shahabpour [36] also recognized a similar vein type at the Sar Cheshmeh deposit where the alteration assemblages occur as pervasive as well as veinlet controlled and produce the known alteration-mineralization pattern and zoning reported from the Sar Cheshmeh deposit. Table 1 summarizes the vein controlled assemblages and Figure 2 depicts their paragenetic sequences.

The relationship between the three sulfide-silicate assemblages discussed here and their host ores may be

summarized as follows:

Sulfide silicate assemblages:	Corresponding host rocks:
Chalcopyrite blebs in orthoclase and quartz	Least altered and potassic-altered stock
Bornite in chloritized biotite	Weak potassic altered stock
Pyrite in sericitized biotite	Phyllic-altered stock and dikes

Segregation of Chalcopyrite from the Late-Magmatic Melt

Sulfide minerals with textural relations indicating their magmatic origin are present in most igneous rocks [28]. Banks [3] also reports the occurrence of magmatic sulfides in the Laramide intrusive rocks (quartz diorite, granodiorite, granite). The paucity of data from the porphyry copper deposits is probably due in part to the superposition of porphyry copper mineralization and the alteration on magmatic texture of the plutons [3].

Some groundmass orthoclase and quartz grains from the Sar Cheshmeh porphyry (the stock) contain microlobes and blebs of chalcopyrite (Fig. 3). The textural relationship

Table 1. Vein type at Sar-Cheshmeh

Stage of Development	Group	Type	Alteration Margin	Ore Minerals	Gangue Minerals	Vein-types reported by Etminan(1977)
Late-magmatic	V _{Im} (SCP)	Orth	----	±Cpy	Orth, Qtz	----
Early-Mineralization	V _{Ik} (SCP)	Orth, Qtz, Cpy	Orth	Cpy, Py ±Mo	Orth, Qtz	Type Ap
	V _{Ib} (And)	Bt, Qtz, Cpy	Bt.	Cpy, Py	Bt., Qtz	Type Aa
	V _{Ic} (SCP, And)	Chl, Ep, Py	Chl, Ep	Py, Cpy	Chl, Ep, Qtz	Type C
		Cal, Ep Qtz, Sulfides	---- ----	Py Py ±Cpy	Cal, Chl, Qtz, Ep Qtz	Type C Type D
Transitional Mineralization	V _{Ii} (SCP, And, EHP)	Qtz, Mo	----	Mo, Cpy, Py	Qtz	
Late-mineralization	V _{III} (SCP, And, EHP, LHP)	Qtz, Ser, Chl, Py	Qtz, Ser	Py, Cpy, Mo	Qtz, Ser, Chl, Mu	Type Bp and
		Qtz, Ser, Py	Qtz, Ser	Py, Cpy	Qtz, Ser	
		Qtz, Ser	Qtz, Ser	Py	Qtz, Ser	Type Ba
		Qtz, Ser, Cal Argillic	Qtz, Ser Qtz, Ser, Clay	Py Py	Qtz, Ser, Clay	Type E
Post-Mineralization	V _{VI} (SCP, And, EHP)	Cal, Qtz	----	Py	Qtz, Cal	

Bt = Biotite, Cal = Calcite, Cpy = Chalcopyrite, Ep = Epidote, Mu = Muscovite, Mo = Molybdenite, Qtz = Quartz, Chl = Chlorite SCP = Sar-Cheshmeh Porphyry, EHP = Early Hornblende Porphyry, LHP = late-Hornblende Porphyry, And = Andesite

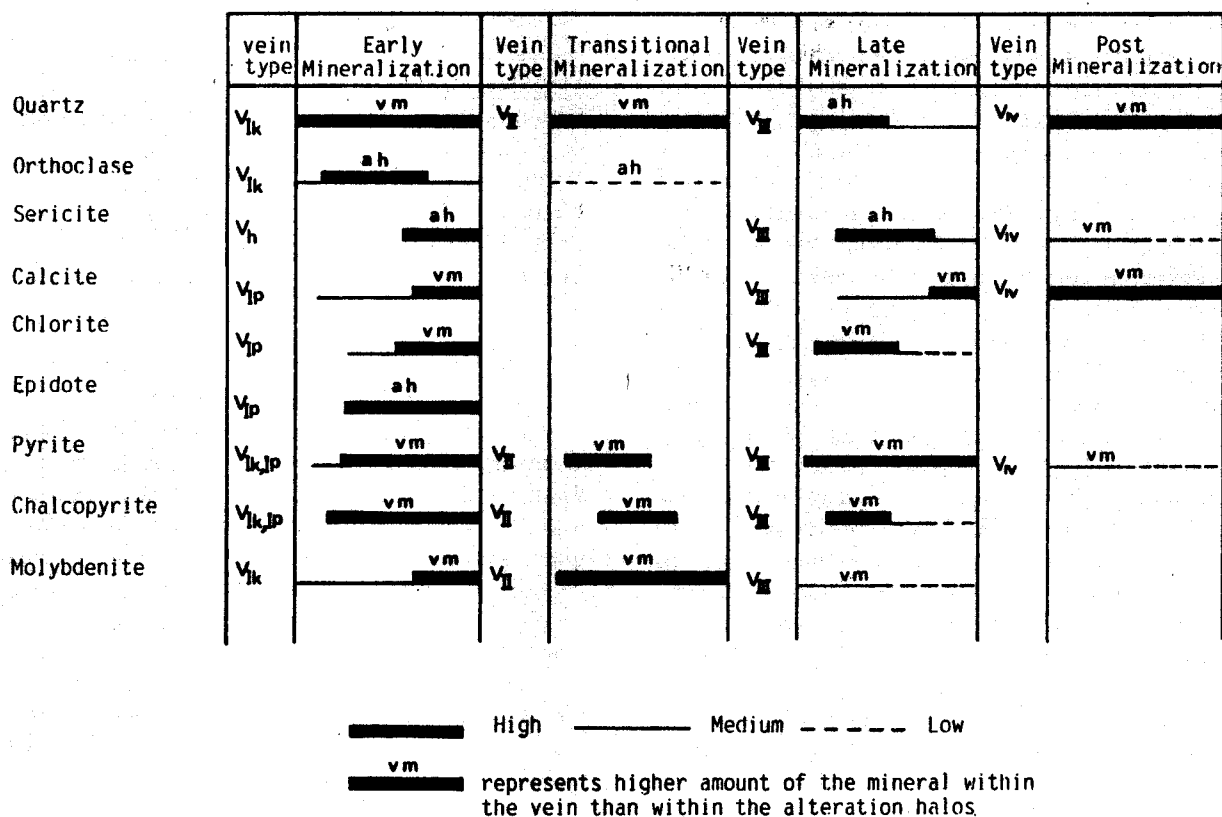


Figure 2. Paragenetic sequence of Sar Cheshmeh hypogene vein minerals. ah = alteration halo; vm = vein material; vh = veins with K-feldspar and quartz-sericite alteration halos, K-feldspar next to the vein and sericite away from the vein (From Shahabpour [36]).

between orthoclase, chalcopyrite and quartz in this mode of association (Fig. 3) is clearly different from the potassic assemblage where chalcopyrite has a contact growth with orthoclase and quartz (Fig. 4). Table 2 summarizes some criteria differentiating the exuded magmatic sulfides from the hydrothermal sulfides at the Sar Cheshmeh deposit. Furthermore, semi-quantitative electron microprobe determination of Co and Ni contents of chalcopyrite types indicates a systematic decrease in Co and Ni contents from the chalcopyrite blebs towards the chalcopyrite from the potassic (Vik) and phyllic veinlets (Viii).

These chalcopyrite blebs are exuded from a late magmatic melt as a result of liquid immiscibility, consequent upon cooling. This type of sulfide-silicate association is further support for the well established orthomagmatic model proposed for porphyry copper deposits [22, 43, 44, 13, 2, 40, 21, 31].

Sulfidization of Biotite

Sulfur species are naturally efficient extractors of chalcophile metals from silicate phases. Holland [22] has discussed the efficiency of chloride-bearing fluids in

Table 2. Some criteria differentiating the exuded magmatic sulfides from the hydrothermal sulfides at the Sar Cheshmeh deposit

Criteria	Magmatic sulfides	Hydrothermal sulfides
Structure	Blebs and micro-lobes	Continuous veinlets and disseminations
Texture	occur as blebs and micro-lobes within the magmatic mineral grains	In contact growth with alteration minerals; open space filling
Host minerals	Mainly in orthoclase and quartz	Virtually all mineral grains
Size	Usually microscopic (1 to 800 microns)	Microscopic to macroscopic

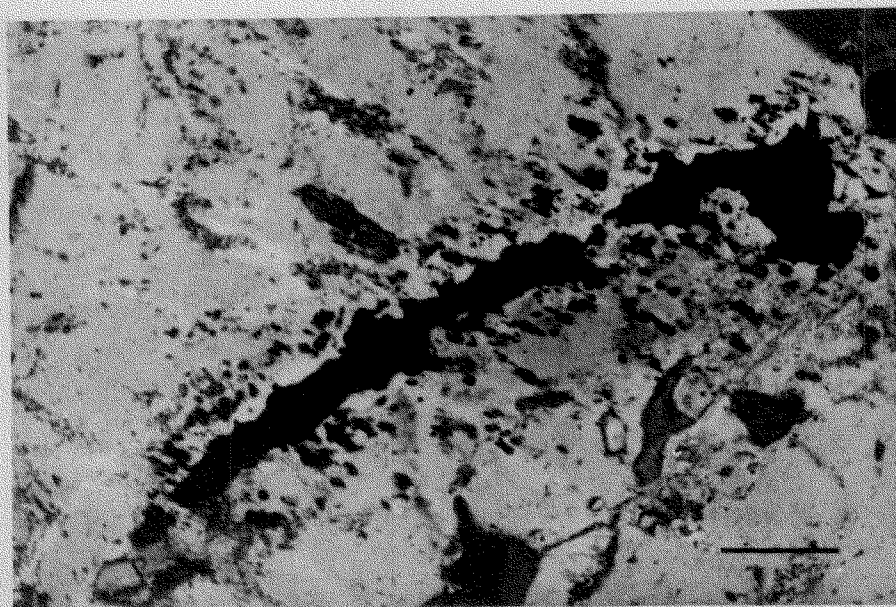


Figure 3. Micro-lobes of chalcopyrite in orthoclase. Scale bar represents 0.10 mm; crossed polars

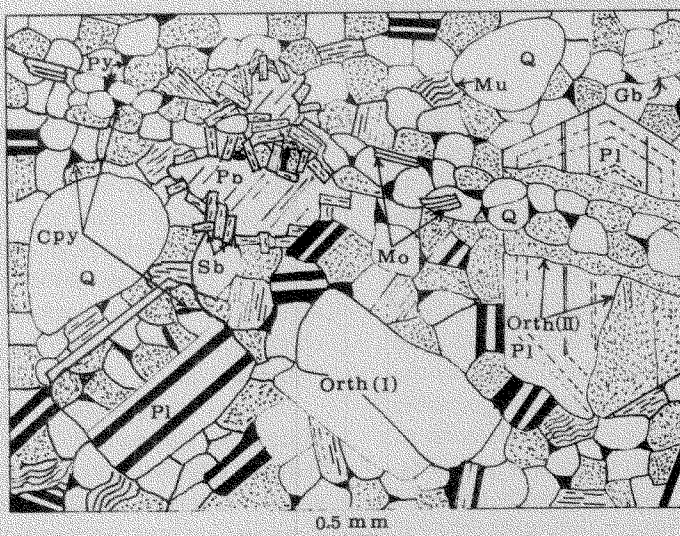


Figure 4. Sketch of a portion of Sar Cheshmeh porphyry (the stock) in crossed polarized light. Note the contact growth of chalcopyrite with orthoclase and quartz. The potassic veinlet (VIK) has produced K-feldspar alteration halo within the plagioclase (pl) phenocryst and secondary biotite within the biotite phenocryst. pb = primary biotite; sb = secondary biotite; Gb = groundmass biotite; orth (I) = primary orthoclase; orth (II) = secondary orthoclase; Mu = muscovite; Cpy = chalcopyrite; Py = pyrite; Mo = molybdenite, Q = quartz

extracting several metals from silicate melts; presumably such fluids could also extract certain metals from solid silicate phases from the end of magmatic crystallization to deuteric and hydrothermal alteration stages [32].

Experimental work has indicated some of the possible reactions between ferromagnesian silicates and sulfur rich vapor. The results of these experiments indicate that typical reaction products are iron oxides, iron sulfides and silicates

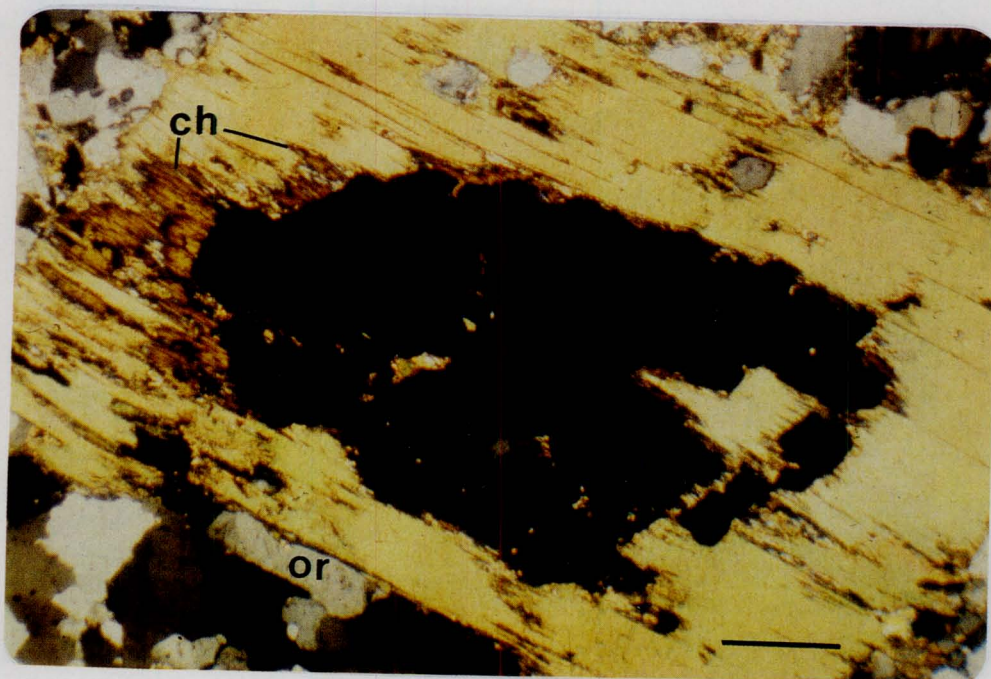
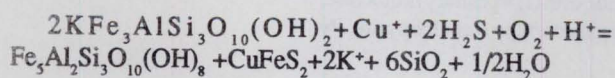


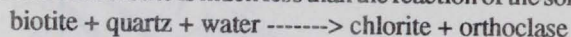
Figure 5. Microphotograph showing a biotite phenocryst with a patch of bornite, in the Sar Cheshmeh porphyry (the stock). Scale bar represents 0.40 mm; crossed polars

depleted in iron and rich in magnesium [23, 24]. The phase relationships that might be found in a number of sulfide-silicate assemblages have been predicted by calculating phase diagrams based on available thermodynamic data [14]. Sulfur combines to form sulfide with some of ferrous metals that previously occurred in the silicates. The remaining ferrous metals react with oxygen made available through the breakdown of silicates to form oxides. The increase in sulfur beyond a certain limit leads to the formation of SO_2 (gas) and then oxides are no longer stable [23]. In the Sar Cheshmeh deposit, the sulfidation of biotite is examined in two alteration types, namely chloritic and quartz-sericitic alterations. Bornite is rarely observed in the Sar Cheshmeh deposit. However, during the chloritic alteration of some biotite phenocrysts within the stock, bornite is developed (Fig. 5). Beane [5] also considers the chloritic alteration of biotite as a mechanism for the deposition of chalcopyrite from hydrothermal solutions in porphyry copper environments:

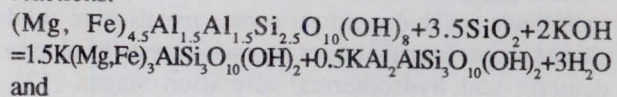


In a study of biotite-chlorite transformation occurring on the hydrothermal alteration of biotite granites, Chayes [6] called attention to the fate of potassium released, recording observations which indicated that at least some

of this potassium was fixed in K-feldspar which remained in the immediate vicinity of the parent biotite. A rather similar occurrence of K-feldspar as a by-product of the chloritization of biotite is described by Paraskevopoulos [30] from the Tessin pegmatites. In this case, microcline was identified. In the chloritized biotites reported here, the amount of K-feldspar grains (Fig. 5) associated with chloritized biotite is much less than the reaction of the sort:



Chayes [6] supposed that potash was actually removed during the transformation and that even when the K-feldspar granules were largest and most numerous, they rarely accounted for anything like the stoichiometric equivalent of potash released by the conversion of biotite to chlorite. The remaining potash may have been added as feldspar to the potash feldspar already existing in the rock. In Sar Cheshmeh porphyry (the stock), the groundmass orthoclase is abundant making it difficult to distinguish between the two types of orthoclase. In a more complex system, quartz-biotite-K-feldspar-muscovite-chlorite-potassium-water, the system containing excess SiO_2 and being open to the perfectly mobile components of potassium and water, McNamara [27] postulated the following reactions:



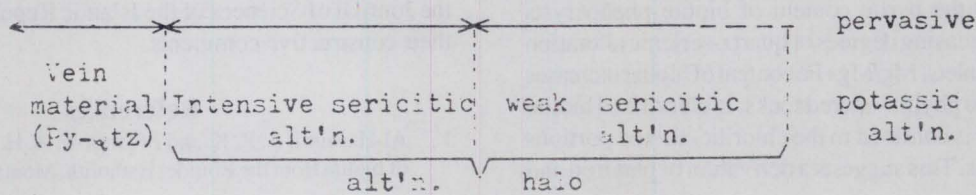
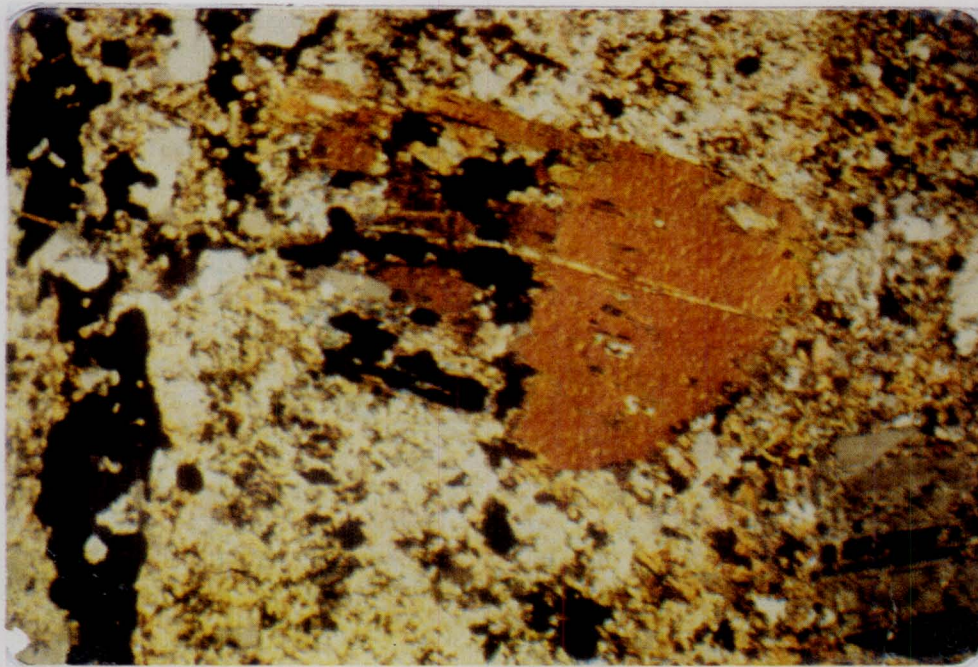
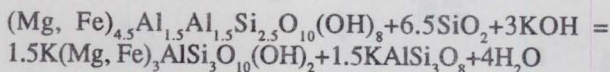


Figure 6. Sulfidization of a biotite phenocryst within the alteration halo of a quartz-sericite (Viii) veinlet. That part of biotite which is within the intensive quartz-sericitic alteration range of the veinlet has been intensely sulfidized. Scale bar represents 0.25 mm; crossed polars (From shahabpour [36]).



Sulfidization of biotite also occurs during the quartz-sericitic alteration of the rock units in the Sar Cheshmeh deposit. As an example, Figure 6 illustrates sulfidization of a biotite grain which is engulfed by the alteration halo of a quartz-sericite veinlet (Viii-vein). The intensity of sulfidization increases towards the veinlet. Sulfides within biotite grains have been considered magmatic [3]. However, the altered biotite enclosed sulfide grains from the Sar Cheshmeh stock are clearly hydrothermal (Fig. 6).

From the study of minerals formed by the alteration of biotite in rocks from Ray and Esperanza porphyry copper deposits, Banks [3] concluded that some of the sulfur in porphyry copper deposits could have been supplied by preore igneous biotite if a sufficient quantity of biotite was altered during the development of the deposits and the sulfur was transported inward from the outer margins of

the deposits. However, according to Gerlach et al. [15], Rutherford and Divine [35] and Pasteris [29], the source of sulfur in porphyry copper deposits remains highly controversial. In altered biotite grains from the Sar Cheshmeh stock, sulfides are restricted to the altered portions of biotites or their immediate vicinity. This rejects the possibility of biotite as being an important source for sulfur in Sar Cheshmeh.

The increase in Mg/Mg+Fe content of the textural varieties of biotite (Fig. 7) from potassic to phyllic altered rocks is attributed to the extraction of iron from biotite during alteration. Therefore, biotite is one of the sources of iron present in sulfides.

Mackin [26] and Hibbard [20] believe that biotite is a source of copper which is removed during a period of "deuteric stewing". The problem of copper in magmatic and hydrothermal biotite is the subject of contradictory claims [1, 16]. However, in Sar Cheshmeh porphyry, magmatic biotite has a higher copper content (121-269

ppm) compared with secondary biotite (<100 to 132 Ppm) [36]. Many shreds of secondary biotite are apparently devoid of copper sulfides. However, the electron microprobe studies of some biotite shreds indicate the presence of ultrafine grained copper sulfides. Therefore, during the alteration of biotite, part of copper is extracted and deposited as bornite or chalcopyrite within the altered biotite and the rest enters the solution.

Conclusion

1) Groundmass orthoclase grains from the Sar Cheshmeh porphyry (the stock) occasionally contain blebs of chalcopyrite. The texture of this association is different from the potassic assemblage where chalcopyrite has contact growth with orthoclase and quartz. These chalcopyrite blebs are exuded from a late-magmatic potassic melt as a result of liquid immiscibility, consequent upon cooling. This association further supports the well established orthomagmatic model proposed for porphyry copper deposits.

2) Microscopic studies of biotite phenocrysts engulfed by the alteration halos of quartz-sericite veinlets indicate an increase in the pyrite content of biotite phenocrysts affected by increasing degrees of quartz-sericitic alteration towards the veinlets; Mg/Mg+Fe content of biotite increases from potassic to phyllic-altered rocks; in chloritized biotite grains, bornite is confined to the chloritic-altered portions of biotite grains. This suggests a derivation of part iron and

copper from magmatic biotite and its partial redeposition as sulfides in altered biotite. However, as Stefanini and William-Jones [40] suggested, the composition of the intrusion, its depth of emplacement and presence of multiple intrusive events are decisive for formation of a copper rich mineralizing fluid.

3) The problem of copper in biotite is a subject of contradictory claims. However, the presence of bornite or chalcopyrite in chloritized biotite and the higher copper content of primary biotite compared with the secondary biotite suggest that part of the copper content of biotite enclosed copper sulfides is derived from primary biotite.

4) Many secondary biotite grains are apparently devoid of copper sulfides. However, electron microprobe studies of some biotite shreds indicate the presence of ultrafine grained copper sulfides. Nevertheless, at least part of copper is removed from the magmatic biotite and redeposited in the form of sulfides in veinlets and as disseminated grains within the groundmass.

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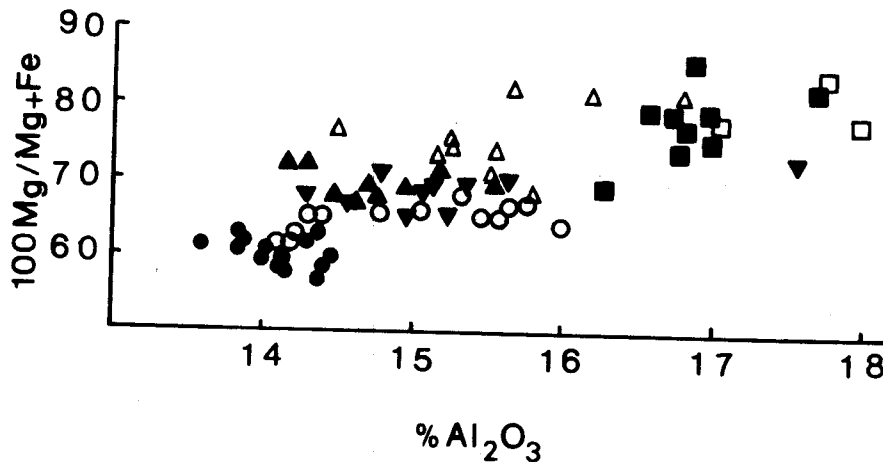


Figure 7. Variation of Mg/ Mg+Fe with weight percent Al_2O_3 in textural varieties of biotite in the Sar Cheshmeh porphyry (the stock) (From shahabpour [36]).

Explanation: (●) Texturally primary biotite from the potassically altered Sar Cheshmeh porphyry; (○) secondary biotite from the potassically altered Sar Cheshmeh porphyry; (▲) texturally primary biotite from potassically and phyllically altered Sar Cheshmeh porphyry; (△) secondary biotite from potassically and phyllically altered Sar Cheshmeh porphyry; (■) texturally primary biotite from phyllically altered Sar Cheshmeh; (□) secondary biotite from phyllically altered Sar Cheshmeh porphyry; (▼) groundmass biotite

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