

# CALCULATION OF MASS TRANSFER AND ELEMENT MOBILITY DURING THE HYDROTHERMAL ALTERATION IN THE SUNGUN PORPHYRY COPPER DEPOSIT, IRAN

A. Hezarkhani

Department of Mining, Metallurgy and Petroleum Engineering, Amirkabir University  
Hafez Ave., No. 424, Tehran, Iran, [ardehez@cic.aku.ac.ir](mailto:ardehez@cic.aku.ac.ir)

(Received: January 30, 2001 – Accepted in Revised Form: March 19, 2002)

**Abstract** The Sungun porphyry copper deposit is located in northwestern Iran and is associated with diorite/granodiorite to quartz-monzonite of Miocene age, which intruded Eocene volcano-sedimentary and Cretaceous carbonate rocks. Copper mineralization was accompanied by both potassic and phyllic alteration. Three main mineralization related alteration episodes (potassic, transition, and phyllic alterations) have been studied in terms of mass transfer and element mobility during the hydrothermal evolution of the Sungun deposit. In order to illustrate these changes quantitatively, isocon plots [1] have been applied. Isocon plots illustrate that Al, Ti and Ga were relatively immobile during alteration, and that mass was essentially conserved alteration. At all stages in the evolution of the hydrothermal system, the volume change is close to zero. In the potassic alteration zone, there is an obvious enrichment of K, and depletions of Na, Ca, Mn and Fe. These changes were due to replacement of plagioclase and amphibole by K-feldspar and biotite, respectively. Potassic alteration was associated with large addition of Cu as might be expected from the occurrence of disseminated chalcopyrite and bornite in this zone. In the transition alteration zone, Ca was added, Na, Fe and Mg were relatively unchanged, and K, Ba and Cu were depleted. The loss of K and Ba relatively to Na reflects replacement of K-feldspar by albite. Phyllic alteration was accompanied by the depletion of Na, K, Fe and Ba and enrichment of Si and Cu. The losses of Na, K and Fe reflect the sericitization of alkali feldspar and destruction of ferromagnesian minerals. The addition of Si is consistent with the widespread silicification, which is a major feature of phyllic alteration and the addition of Cu with mobilization from the transition zone which is depleted in this element.

**Key Words** Mass Transfer, Element Mobility, Porphyry Copper, Sungun, Iran

**چکیده** معدن مس پورفیری سونگون در شمال غرب ایران و در یک توده دیوریت/گرانودیوریتی تا کوارتز مونزونیتی با سن ائوسن قرار دارد. این توده، سنگهای آتشفشانی-رسوبی ائوسن و کربناتی کرتاسه را قطع کرده است. کانی زائی مس در این معدن با هردو نوع دگرسانی پتاسیک و فیلیک همراه می باشد. در این مقاله، تحولات سه نوع دگرسانی مرتبط با کانی زائی (پتاسیک، انتقالی و فیلیک) در معدن مس سونگون بر مبنای انتقال جرم و تحرک عنصری بررسی شده است. به منظور نشان دادن کمی این تغییرات، روش ترسیمی ایزوکن (گرانیت، ۱۹۸۶) به کار گرفته شد. نتایج نشان می دهند که آلومینیم، تیتانیم و گالیم در حین دگرسانی، به طور نسبی غیر متحرک بوده و از نظر جرمی اساساً تغییری نداشته و تغییرات حجمی در تمامی تحولات سیستمهای دگرسانی، بسیار نزدیک به صفر بوده اند. در منطقه دگرسانی پتاسیک، یک غنی شدگی مشخص در میزان پتاسیم و یک کاهش در میزان سدیم، کلسیم، منگنز و آهن مشاهده میشود. این تغییرات به ترتیب به علت جانشینی پلاژیوکلاز و آمفیبول توسط فلدسپات پتاسیم دار و بیوتیت بوده است. وقوع دگرسانی پتاسیک همراه با افزایش قابل ملاحظه مس می باشد که با تشکیل کالکوپیریت و بورنیت پراکنده در این منطقه، قابل انتظار است. در منطقه دگرسانی انتقالی، کلسیم افزایش داشته، سدیم، آهن و منیزیم به طور نسبی تغییر نکرده و لی پتاسیم، باریم و مس کاهش یافته است. کاهش پتاسیم و باریم نسبت به سدیم نتیجه جانشینی فلدسپات پتاسیم دار توسط آلبیت می باشد. دگرسانی فیلیک همراه با کاهش سدیم، پتاسیم، آهن و باریم و افزایش سیلیس و مس است. کاهش سدیم، پتاسیم و آهن حاصل سرسیتی شدن فلدسپاتهای آلکالن و تخریب کانی های آهن و منیزیم دار بوده است. افزایش سیلیس با وقوع یک پدیده سیلیسی شدن وسیع، که در دگرسانی فیلیک به طور بارزی رخ داده، و نیز افزایش مس که بر اثر جابجائی مس از منطقه انتقالی صورت گرفته است، همراه می باشد.

## 1. INTRODUCTION

Sungun porphyry copper deposit is hosted by a composite intrusive, comprising early diorite/granodiorite

and later monzonite/quartz-monzonite, which was emplaced at a paleo-depth of ~2000 m, and at temperatures of 670-780 °C [2]. The parental magma was a medium to high-K andesite and

trachyandesite similar in composition to syn-collisional calc-alkaline magmas generated in continental arc settings that have been also studied in other localities [3,4]. Copper mineralization occurs within the diorite/granodiorite, which is the most strongly altered intrusive phase [5].

During the alteration and mineralization three distinct hydrothermal fluids were identified. The first hydrothermal fluid caused potassic alteration and Cu±Mo mineralization, was characterized by high temperatures and moderate to high salinities, and was derived magmatically. The second hydrothermal fluid formed mainly by mixing magmatic fluid with a predominantly meteoric fluid, resulting in lower temperature and salinities. This fluid was responsible for transition alteration at depth and sericitization at higher levels. The third hydrothermal fluid consisted of relatively oxidized meteoric water, which produced a peripheral propylitic alteration zone outside the core of potassically-altered rock. Therefore, the alteration in dioritic/ranodioritic rocks at Sungun can be classified into three different types: I) potassic, II) propylitic and, III) phyllic.

Many studies of porphyry copper deposits have provided descriptions of minerals present in different alteration zones, and chemical characteristics of fluids associated with alteration episodes [6,7,8]. However, there have been only a few attempts to determine the complete evolutionary path of alteration, with corresponding quantification of mass changes in different alteration zones during reaction with hydrothermal fluids [6,9,10].

In this paper, the mass changes of major and minor elements that accompanied alteration in dioritic/granodioritic rocks of the Sungun porphyry copper deposit are evaluated quantitatively. The method of Gresens [11], as modified by Grant [1] is employed to calculate mass changes, and is based on elements that were immobile during alteration. These elements are used to establish the bulk mass/volume changes during the different alteration episodes, and correct the analyses of the altered rocks. The masses of components added to or removed from the rock as a result of its interaction with hydrothermal fluids are determined by comparing the corrected analyses for the altered rocks with those of least altered equivalents.

## 2. METHODOLOGY

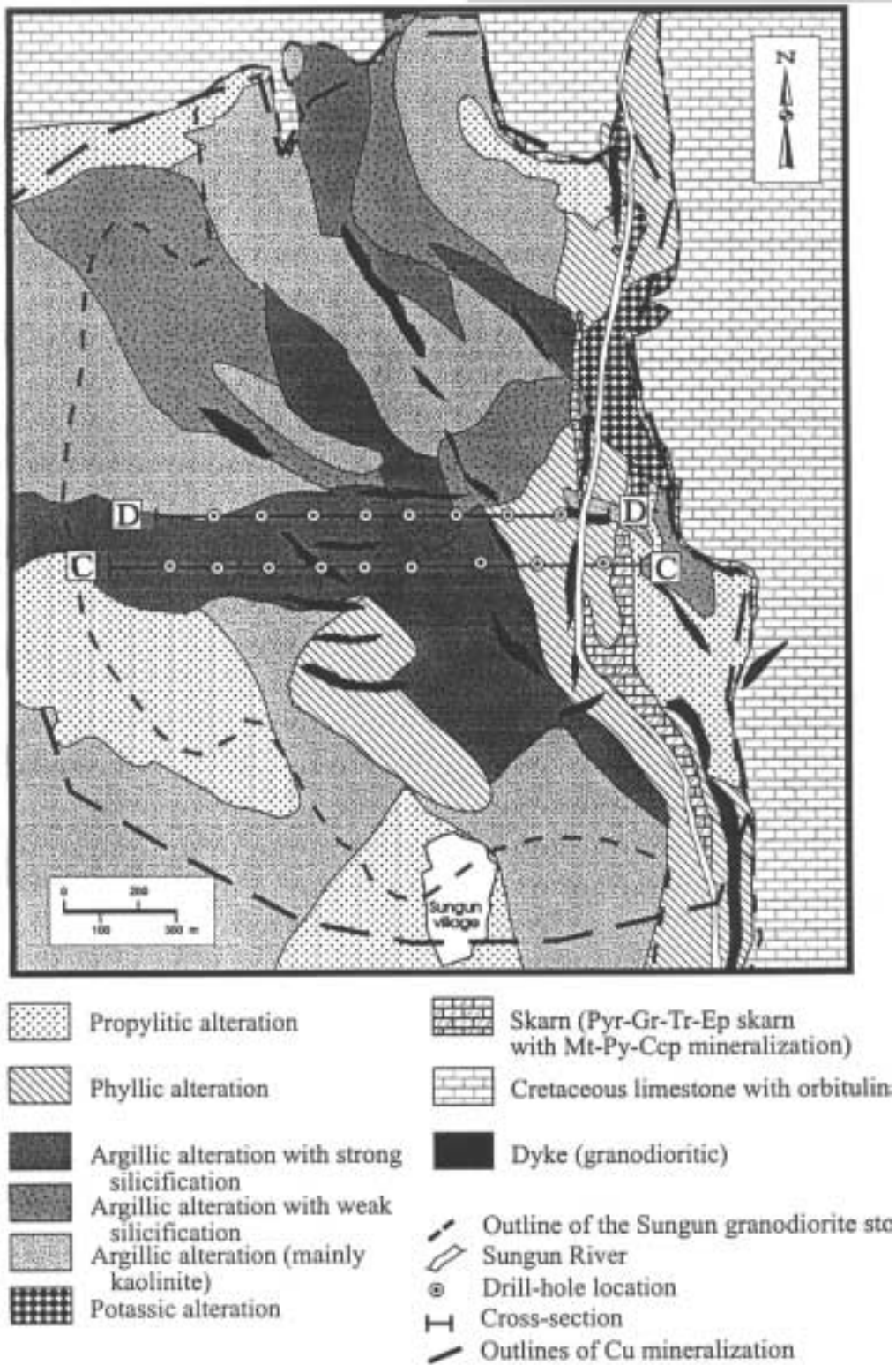
Representative samples were examined from the different alteration zones in the deposit. Detailed petrographic studies of wallrocks, veins and alteration envelopes were performed on more than 100 hand samples and 60 polished thin sections. Mineral identification and qualitative estimation of mineral abundances were conducted using optical microscopy, electron microprobe analyses, and scanning electron microscopy. Lithochemical analyses were performed by X-ray fluorescence spectrometry, with a detection limit of 0.01 wt. % for major elements (as oxides), and 2 ppm for trace elements, (except TiO<sub>2</sub> 10 ppm, and Cu and Mo 1 ppm). The major alteration and ore minerals in fourteen samples were analyzed using a JEOL-8900L electron microprobe, with 15 kV acceleration voltage, 8 nA beam current, 2 μm beam diameter, and 25 second peak counting times. The mineral standards used were orthoclase (Al, K, Si), albite (Na), diopside (Ca, Mg), andradite and magnetite (Fe), spessartine (Mn, Si, Al), fluorite (F), and synthetic MnTi (Mn, Ti).

## 3. ALTERATION

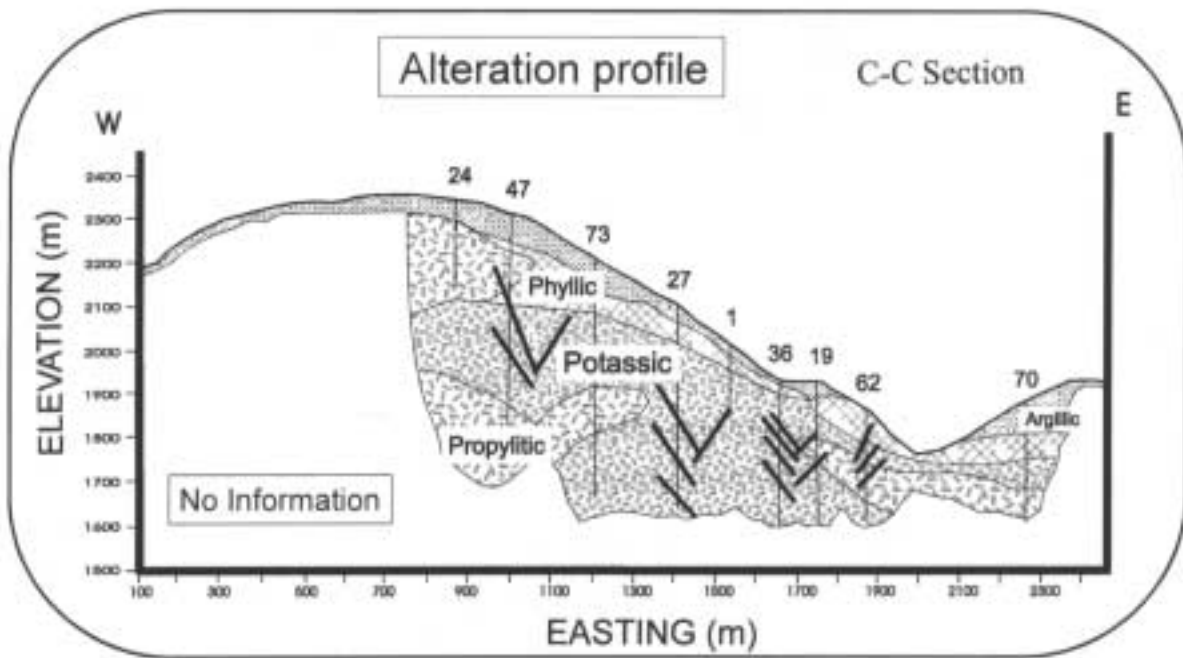
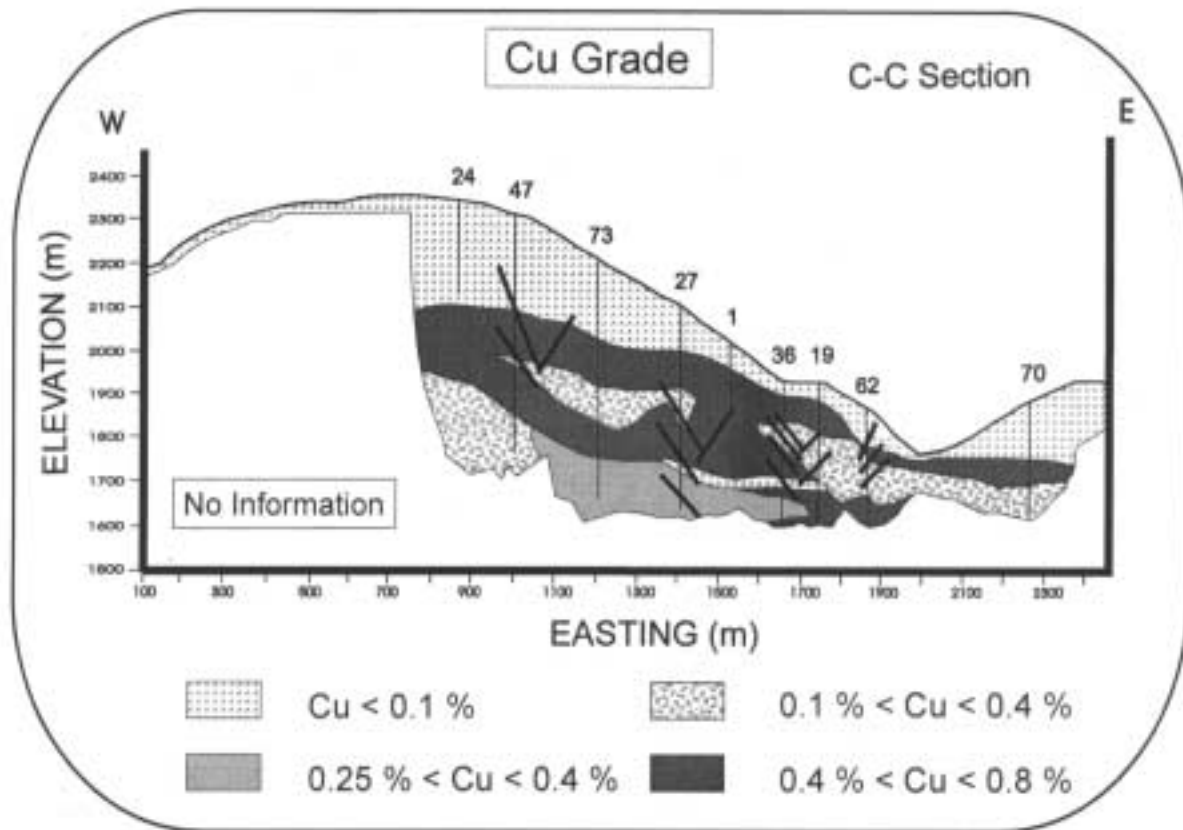
Hydrothermal alteration and mineralization at Sungun are centered on the diorite/granodiorite intrusion and were broadly synchronous with its emplacement (Figure 1). Early hydrothermal alteration was dominantly potassic and propylitic, and was followed by later transition and phyllic alteration [5,12].

## 4. POTASSIC ALTERATION

The earliest alteration in diorite/granodiorite, which was produced by fluxes of magmatic fluids away from the pluton center [12], is represented by potassic mineral assemblages developed pervasively and as halos around veins in the deep and central parts of the Sungun stock (Figures 2 and 3). Potassic alteration is characterized by K-feldspar, irregularly shaped crystals of Mg-rich biotite (Table 1), and anhydrite. On average, potassically altered rocks



**Figure 1.** Detailed alteration map of the Sungun deposit. It emphasizes the effect of supergene argillic alteration at the current erosional surface.



**Figure 2.** Profiles showing the distribution of Cu grades and alteration zones along cross-section C-C. Numbers on surface identify drill holes.

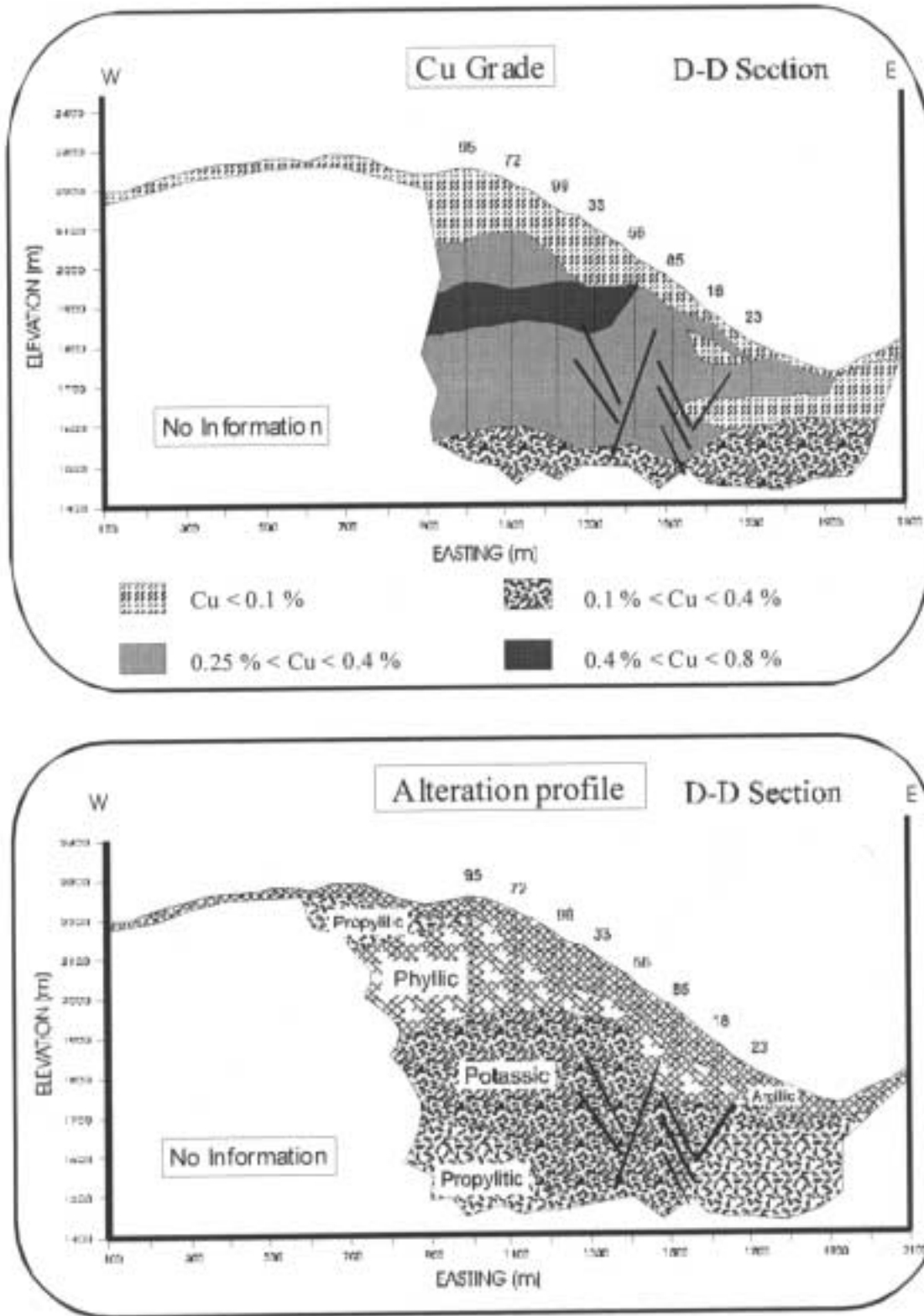


Figure 3. Profiles showing the distribution of Cu grades and alteration zones along cross-section D-D. Numbers on surface indicate drill holes.

**TABLE 1. Representative Electron Microprobe Analyses of Magmatic and Hydrothermal Biotite In the Sungun Porphyry Copper Deposit.**

Sample no. Dril-core no. Type <sup>1</sup>	Magmatic Biotite (dark-brown Color)						Hydrothermal Biotite (greenish-brown Colour)					
	25-514	34-163	33-437	33-437	33-437	33-437	34-477	25-431	34-477	34-477	34-477	34-477
	25	34	33	33	33	33	34	25	34	34	34	34
	Frs	Trn	K	K	K	K	K	K	Phc	Phc	Phc	Phc
SiO <sub>2</sub> (wt %)	38.58	37.27	38.54	37.70	38.34	37.79	43.72	39.03	41.29	39.25	39.03	38.74
TiO <sub>2</sub>	3.82	4.27	3.26	4.00	3.98	4.03	2.65	2.11	2.02	2.17	2.11	3.72
Al <sub>2</sub> O <sub>3</sub>	14.55	13.53	15.45	14.10	14.17	14.85	17.17	15.54	15.05	15.50	15.54	15.81
FeO <sup>2</sup>	15.69	16.38	13.23	15.30	15.42	14.17	3.87	4.18	2.53	4.17	4.18	7.54
MnO	0.17	0.18	0.06	0.05	0.06	0.04	0.01	0.01	0.00	0.04	0.01	0.00
MgO	14.34	14.40	15.00	14.94	15.07	14.78	17.41	21.58	23.18	21.50	21.58	18.38
CaO	0.03	0.01	0.00	0.00	0.00	0.00	0.05	0.04	0.00	0.00	0.04	0.02
Na <sub>2</sub> O	0.30	0.30	0.10	0.10	0.13	0.11	0.15	0.17	0.14	0.18	0.17	0.24
K <sub>2</sub> O	9.35	9.41	10.25	10.16	10.05	10.21	9.94	10.25	10.51	10.43	10.25	10.52
F	0.38	0.33	1.03	0.75	0.73	0.82	1.92	2.10	2.60	1.96	2.10	1.58
Cl	0.20	0.17	0.19	0.22	0.23	0.23	0.08	0.08	0.04	0.09	0.08	0.15
Total	97.41	96.24	97.11	97.31	98.18	97.02	96.97	95.09	97.35	95.29	95.09	96.71
No. of atoms based on 11 O												
Si	2.81	2.77	2.77	2.75	2.77	2.75	2.94	2.72	2.77	2.73	2.72	2.72
Ti	0.21	0.24	0.18	0.22	0.22	0.22	0.13	0.11	0.10	0.11	0.11	0.20
Al	1.26	1.20	1.32	1.22	1.22	1.28	1.37	1.29	1.20	1.28	1.29	1.32
Fe	0.96	1.02	0.80	0.93	0.93	0.86	0.22	0.24	0.14	0.24	0.24	0.44
Mn	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	1.56	1.60	1.61	1.63	1.62	1.60	1.74	2.24	2.32	2.23	2.24	1.94
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.04	0.04	0.01	0.01	0.02	0.02	0.04	0.02	0.02	0.04	0.02	0.03
K	0.90	0.89	0.94	0.95	0.93	0.95	0.95	0.91	0.90	0.93	0.91	0.94
F	0.09	0.08	0.23	0.17	0.17	0.19	0.41	0.46	0.55	0.43	0.46	0.39
Cl	0.02	0.02	0.02	0.03	0.03	0.03	0.01	0.01	0.00	0.01	0.01	0.02
F/(F+Cl)	0.82	0.80	0.92	0.85	0.85	0.86	0.98	0.98	1.00	0.98	0.98	0.95
Fe/(Fe+Mg)	0.38	0.39	0.33	0.36	0.36	0.35	0.11	0.10	0.06	0.10	0.10	0.18

<sup>1</sup> Frs = fresh rock, Trn = transition zone, K = potassic zone, Phc = phyllic

<sup>2</sup> FeO = total Fe

contain 28% plagioclase, 35% orthoclase, 20% quartz, 15% mafic minerals (mainly biotite, and sericite and chlorite after biotite), 2% chalcopyrite, pyrite, titanite, and zircon, and traces of scheelite, uraninite, bismuthinite and rutile. Biotite occurs primarily as a replacement of hornblende, and as anhedral grains disseminated through the groundmass, and is inferred to be mainly of hydrothermal origin. It is greenish-brown, shows ragged, anhedral shapes, occurs generally interstitial to feldspar and quartz. Relict crystals of secondary biotite are observed almost everywhere in the stock, suggesting that potassic alteration was initially very extensive but has been subsequently overprinted by later alteration. Biotite that replaced amphibole commonly contains inclusions of chalcopyrite and/or pyrite. Primary biotite is present only as rare phenocrysts.

Potassium feldspar can be either magmatic, occurring mainly as perthitic phenocrysts, or is hydrothermal, having formed during potassic alteration. K-feldspar domains in perthite have a compositional range of  $Or_{97}Ab_2An_1$  to  $Or_{99}Ab_1$ , and albite domain compositions ranging from  $Ab_{76}Or_1An_{23}$  to  $Ab_{81}Or_3An_{16}$ . The compositions of the perthitic feldspars require subsolidus exsolution at  $\sim 500$  °C [9]. Magmatic K-feldspar has a composition ranging from  $Or_{88}Ab_{10}An_2$  to  $Or_{99}Ab_1$ , and variable but relatively high barium contents (BaO up to 1.74 wt %). Hydrothermal K-feldspar is distinguished from its magmatic equivalent by the absence of perthitic intergrowths. Hydrothermal K-feldspar is also much more albitic having a composition of  $Or_{72}Ab_{27}An_1$  to  $Or_{78}Ab_{10}An_{12}$ .

Rutile occurs as small grains and needles associated with titanite and biotite. Textural relationships suggest that titanium was not mobilized during alteration and mineralization, as rutile is closely associated with parent minerals (hornblende, biotite or titanite).

## 5. PROPYLITIC ALTERATION

Propylitic alteration is characterized by chloritization of primary and secondary biotite, amphibole and groundmass material in rocks peripheral to the central potassic zone [5,13]. Epidote replaces plagioclase, but this replacement, is less pervasive and intense than chloritization. Microprobe analyses indicate that the chlorite composition corresponds

mostly to that of clinocllore [14,15]. The variation in chlorite composition is minor, and is mainly reflected in Fe/(Fe + Mg) values (Table 2). Minor minerals associated with propylitic alteration are albite, calcite, sericite, anhydrite (gypsum), and pyrite. Mass transfer calculations were not done for this type of alteration due to a lack of reliable analyses.

## 6. TRANSITION ALTERATION

The outermost part of the potassic alteration zone, which contains lesser biotite and K-feldspar, and a greater proportion of sericite, has been termed the transition zone. Mineralogically, this alteration is represented by chloritization and sericitization of both primary and secondary biotite, and sericitization in the groundmass. This alteration is also characterized by albite replacement of more An-rich plagioclase, and albite rims on orthoclase. A distinguishing characteristic of this type of alteration is the white color of the affected rocks. This change of color from the original gray to white reflects a strong depletion of ferromagnesian minerals like hornblende and biotite, which is obvious in isocon diagrams (discussed later).

## 7. PHYLIC ALTERATION

Phyllic alteration is characterized by replacement of almost all primary silicates by muscovite (sericite) and quartz, and overprints the earlier-formed potassic assemblage [5]. Sericite is generally the most abundant alteration mineral in the Sungun deposit, and occurs mainly in the phyllic and potassic alteration zones. Thirty microprobe analyses were performed on sericite (Table 3). Sericite commonly forms as irregular, oriented grains containing relicts of biotite and amphibole, and inclusions of zircon. Some of these crystals are phengite (Table 3). The concentration of fluorine in sericite ranges from 0.22 to 0.05 atom per molecule formula (apmf), whereas chlorine contents are lower, (0.01. apfu). Silicification was synchronous with phyllic alteration and variably affected much of the stock and most dykes.

**TABLE 2. Representative Electron Microprobe Analyses of Chlorite In the Sungun Porphyry Copper Deposit.**

Sample No. Drill-core No. Type <sup>1</sup>	34-164	34-161	34-163	34-163	34-162	33-163	34-163	34-163	34-163	25-514	25-514	25-514	25-514	25-514	34-477	34-477
	34	34	34	34	34	33	34	34	34	25	25	25	25	25	34	34
	Pro	Pro	Pro	Pro	Phc	Phc	Phc	Phc	Phc	K	K	K	K	K	Pro	Pro
SiO <sub>2</sub> (wt %)	30.09	29.94	30.39	30.45	29.89	29.18	31.11	29.91	30.06	30.75	27.90	27.64	29.63	28.70	29.91	29.89
TiO <sub>2</sub>	0.05	0.02	0.03	0.02	0.02	0.03	0.02	0.03	0.00	0.06	0.05	0.07	0.04	0.01	0.03	0.02
Al <sub>2</sub> O <sub>3</sub>	18.28	18.18	18.11	18.09	18.06	17.59	18.61	18.64	18.32	21.40	20.39	20.18	21.39	20.88	18.64	18.06
FeO <sup>2</sup>	14.32	13.70	14.47	13.57	14.74	14.07	13.10	15.18	13.85	16.44	17.02	16.72	11.22	12.06	15.18	14.74
MnO	0.20	0.24	0.15	0.17	0.21	0.24	0.17	0.16	0.21	0.05	0.08	0.08	0.11	0.15	0.16	0.21
MgO	24.50	24.40	24.16	24.15	24.18	24.04	22.87	23.76	24.60	18.42	21.48	21.04	23.85	25.24	23.76	24.18
CaO	0.05	0.05	0.07	0.07	0.04	0.06	0.09	0.08	0.06	0.08	0.07	0.06	0.03	0.04	0.08	0.04
Na <sub>2</sub> O	0.03	0.09	0.04	0.06	0.07	0.05	0.10	0.09	0.03	0.01	0.01	0.03	0.02	0.04	0.09	0.07
K <sub>2</sub> O	0.09	0.07	0.15	0.35	0.19	0.10	0.26	0.07	0.09	1.32	0.04	0.03	0.66	0.14	0.07	0.19
F	0.28	0.27	0.35	0.37	0.31	0.27	0.35	0.30	0.19	0.16	0.36	0.20	0.39	0.17	0.30	0.31
Cl	0.02	0.06	0.02	0.05	0.01	0.03	0.04	0.06	0.02	0.01	0.00	0.01	0.01	0.01	0.06	0.01
Total	87.91	87.01	87.94	87.34	87.71	85.65	86.72	88.28	87.42	88.69	87.40	86.06	87.35	87.42	88.28	87.71
No. of atoms based on 11 O																
Si	2.96	2.97	2.99	3.00	2.96	2.95	3.07	2.94	2.97	3.10	2.80	2.82	2.88	2.81	2.94	2.96
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Al	2.13	2.14	2.11	2.12	2.12	2.11	2.18	2.18	2.15	2.50	2.43	2.44	2.47	2.43	2.18	2.12
Fe	1.18	1.14	1.19	1.12	1.22	1.19	1.08	1.25	1.14	1.35	1.43	1.43	0.91	0.99	1.25	1.22
Mn	0.02	0.02	0.01	0.01	0.02	0.02	0.01	0.01	0.02	0.00	0.01	0.01	0.01	0.01	0.01	0.02
Mg	3.59	3.61	3.54	3.55	3.57	3.63	3.36	3.48	3.62	2.70	3.20	3.20	3.46	3.68	3.48	3.55
Ca	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.00
Na	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.00	0.00	0.01	0.00	0.01	0.02	0.01
K	0.01	0.01	0.02	0.04	0.02	0.01	0.03	0.01	0.01	0.17	0.01	0.00	0.08	0.02	0.01	0.02
F	0.09	0.08	0.11	0.12	0.10	0.09	0.11	0.09	0.06	0.05	0.11	0.06	0.12	0.05	0.09	0.10
Cl	0.00	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Total	10.00	10.00	9.99	9.99	10.02	10.03	9.88	10.00	9.99	9.88	10.00	9.99	9.93	10.00	10.00	10.00
F/(F+C l)	1.00	0.89	1.00	0.92	1.00	0.90	0.92	0.90	1.00						0.90	
Fe/(Fe +Mg)	0.25	0.24	0.25	0.24	0.25	0.25	0.24	0.26	0.24	0.33	0.31	0.31	0.21	0.21	0.26	0.26

<sup>1</sup>K = potassic zone, Phc = phyllic alteration zone, Pro = propylitic zone

<sup>2</sup> FeO = total



**TABLE 3. Representative Electron Microprobe Analyses of Muscovite in the Sungun Porphyry Copper Deposit.**

Sample No. Dril-core No. Type <sup>1</sup>	Phengite		Muscovite							
	33-236	33-237	33-237	25-325	34-477	34-477	34-477	34-477	34-477	25-198
	Phc	Phc	Phc	K	Phc	Phc	Phc	Phc	Phc	Phc
SiO <sub>2</sub> (wt %)	42.70	43.29	47.24	50.96	47.34	46.95	46.19	51.31	50.54	44.58
TiO <sub>2</sub>	0.98	0.74	0.69	0.10	0.22	0.33	0.15	0.11	0.12	0.21
Al <sub>2</sub> O <sub>3</sub>	21.35	23.59	29.51	28.45	28.30	31.36	33.75	28.13	27.34	27.17
FeO <sup>2</sup>	8.80	7.80	3.43	0.92	2.76	1.72	0.81	1.14	1.22	5.61
MnO	0.02	0.03	0.00	0.01	0.03	0.01	0.00	0.00	0.01	0.03
MgO	11.65	10.45	3.52	2.74	3.92	2.87	1.02	3.55	3.77	7.84
CaO	0.00	0.03	0.02	0.18	0.02	0.01	0.01	0.13	0.11	0.05
Na <sub>2</sub> O	0.12	0.07	0.16	0.09	0.31	0.38	0.37	0.16	0.13	0.07
K <sub>2</sub> O	10.18	10.10	9.55	8.84	11.40	11.17	11.03	9.52	9.52	7.75
F	0.98	1.01	0.22	0.73	0.40	0.40	0.22	0.83	0.90	0.35
Cl	0.08	0.05	0.03	0.13	0.05	0.08	0.05	0.12	0.10	0.01
Total	96.85	97.16	94.36	93.15	94.74	95.28	93.59	94.99	93.76	93.64
No. of atoms based on 11 O										
Si	2.95	2.95	3.19	3.38	3.21	3.14	3.12	3.36	3.36	3.06
Ti	0.05	0.04	0.04	0.00	0.01	0.02	0.01	0.01	0.01	0.01
Al	1.75	1.91	2.37	2.25	2.28	2.49	2.72	2.19	2.16	2.22
Fe	0.51	0.44	0.19	0.05	0.16	0.10	0.05	0.06	0.07	0.32
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	1.20	1.06	0.35	0.27	0.40	0.29	0.10	0.35	0.37	0.80
Ca	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.00
Na	0.02	0.01	0.02	0.01	0.04	0.05	0.05	0.02	0.02	0.01
K	0.90	0.88	0.82	0.75	0.99	0.95	0.95	0.80	0.81	0.70
F	0.21	0.22	0.05	0.15	0.09	0.09	0.05	0.17	0.19	0.08
Cl	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.00
F/(F+Cl)	0.95	0.96	1.00	0.94	0.90	0.90	0.83	0.94	0.95	1.00
Fe/(Fe+Mg)	0.30	0.29	0.35	0.16	0.29	0.26	0.33	0.15	0.16	0.29

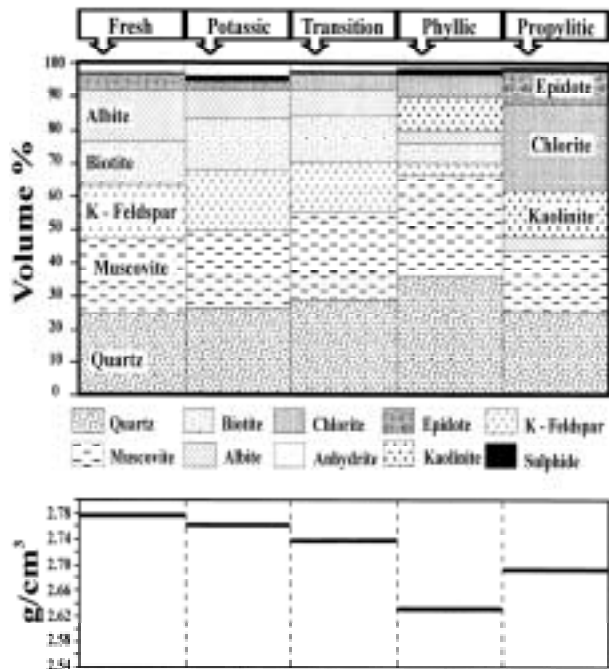
<sup>1</sup> Phc = phyllic alteration zone, K =  
potassic alteration zone,

<sup>2</sup> FeO = total Fe

## 8. ARGILLIC ALTERATION

Feldspar is locally altered to clay minerals to a depth of 400 m, and within 80 m of the present-day surface, all rocks have been altered to an assemblage of clays, hematite and quartz. XRD analyses indicate that kaolinite is the dominant phyllosilicate, and that it is generally accompanied by illite. This shallow alteration

is interpreted to represent a supergene blanket over the deposit, and the deeper clay alteration of feldspar may have had the same origin. However, the possibility can not be excluded that parts of the latter may locally represent an advanced argillic stage of hypogene alteration. Mass transfer calculations were not done for this type of alteration due to its uncertain origin and the lack of reliable analyses.



**Figure 4.** Variations in normative mineralogy in alteration zones in the Sungun porphyry copper deposit. Kaolinite occurs in the phyllic alteration zone, and to a lesser extent in the propylitic zone. This may reflect supergene alteration, which is widespread in the deposit. In the propylitic alteration zone, albite, oligoclase and orthoclase react to form muscovite and quartz. Muscovite is present in all alteration zones. Sulphide abundance is significant in the potassic, transition and phyllic alteration zones. The density profile was obtained by summing the multiples of weight proportion and the density of the different minerals in each alteration zone. The calculated average densities of all altered rocks are lower than that of the least-altered rock, and are particularly low in the strongly altered phyllic zone.

## 9. NORMATIVE MINERALOGY

The normative composition of representative samples from each alteration zone has been calculated using whole rock chemistry and compositions of the constituent minerals. An inexact matrix was used to calculate mineral abundance by the linear least squares regression method [16,17].

$$A \cdot X = B \quad (1)$$

In this equation, the matrix A represents the stoichiometric coefficients of the elements in each

mineral, B is the matrix of the molar abundance of the elements obtained from the whole rock analysis, and X is a vector containing the molar abundance of each mineral, i.e., the unknown parameter. The solution for X represents a least squared fit of mineral abundance to whole rock composition. Weight percent abundance of minerals and rock density were calculated by using mineral molecular weights and densities (Figure 4; Table 4). Potassic alteration is characterised by 23 % K-feldspar, 22 % quartz, 19 % muscovite, 16 % biotite, 13 % albite, 2 % anhydrite, <0.1 % chlorite, 1.9 % epidote, 1.5 % pyrite, 0.8 % chalcocopyrite, and 0.2 % magnetite. The transition zone is characterized by 19 % K-feldspar, 23 % quartz, 19 % muscovite, 15 % biotite, 10 % albite, 4 % anhydrite, 4 % chlorite, <0.1 % epidote, 2 % pyrite, <0.9 % chalcocopyrite, 1 % kaolinite, and <0.1 % magnetite. Phyllic alteration contains 5 % K- feldspar, 30 % quartz, 23 % muscovite, 11 % biotite, 8 % albite, 2% anhydrite, 4 % chlorite, 1 % epidote, 3 % pyrite, 1 % chalcocopyrite, 13 % kaolinite (Figure 4; Table 4).

## 10. MASS CHANGES DURING ALTERATION

**Mass Balance Calculations** Several methods have been used to calculate mass losses or gains in ore deposits: the volume factor method of [11]; the isocon method of [1]; and the immobile element method of [18]. In this study, mass gains and losses during alteration were calculated using the method of [1]. In order to avoid errors due to variations inherent in the density of the least altered rock, a sample from the deepest part of the diorite/granodiorite intrusion was selected and tested by comparing it with the other “fresh” rocks from the deposit. This sample, a diorite/granodiorite # 30-138, is very similar compositionally to the other “fresh” rock and was used to represent the least altered rock (see below). Petrographic examination indicates that even in this sample there was limited alteration of feldspars, hornblende and biotite to muscovite, quartz and oxides. However, this will not greatly affect interpretations of the alteration reactions, which are based on comparisons between different alteration zones.

The isocon approach of [1] is mathematically

**TABLE 4. Calculated Normative Mineral Abundances.**

Sample #	Alteration	Density	Quartz	K-feldspar	Biotite	Muscovite	Albite	Chlorite	Epidote	Pyrite	Chalcopyrite	Kaolinite	Anhydrite	Magnetite	Total
0-168	Potassic	2.74	21.82	26.53	19.33	12.00	13.98	0.00	3.10	2.10	1.14	0.00	0.00	0.00	100.0
21-32	Potassic	2.77	23.12	23.85	15.21	20.10	10.96	0.00	2.41	1.81	0.12	0.00	2.12	0.30	100.0
6-277	Potassic	2.74	21.33	24.20	13.17	22.45	12.34	0.30	1.81	0.54	0.65	0.00	3.11	0.10	100.0
4-345	Potassic	2.75	21.75	14.98	18.09	21.00	16.81	0.00	2.10	1.98	0.19	0.00	3.10	0.00	100.0
4-371	Potassic	2.81	22.08	26.30	12.76	20.97	11.96	0.00	0.00	1.10	1.70	0.00	2.73	0.40	100.0
<i>Average of Potassic Alteration</i>		2.76	22.02	23.17	15.71	19.30	13.21	0.06	1.88	1.51	0.76	0.00	2.21	0.16	100.0
0-200	Transition	2.73	24.32	17.11	17.21	21.81	10.78	2.32	0.07	2.90	1.18	0.20	2.10	0.00	100.0
5-522	Transition	2.72	22.76	23.65	14.32	11.45	8.83	7.65	0.27	1.85	1.70	2.10	5.32	0.10	100.0
5-122	Transition	2.76	22.31	15.30	13.00	24.74	11.70	4.32	0.00	1.60	0.90	1.90	4.23	0.00	100.0
<i>Average of Transition Alteration</i>		2.74	23.13	18.69	14.84	19.33	10.44	4.76	0.11	2.12	1.26	1.40	3.88	0.03	100.0
7-150.6	Phyllic	2.67	34.71	4.32	13.10	20.56	6.78	5.30	0.00	1.89	1.90	10.21	1.23	0.00	100.0
5-275	Phyllic	2.54	28.67	1.60	4.65	23.11	12.20	4.56	0.00	2.10	0.90	20.71	1.50	0.00	100.0
3-281	Phyllic	2.69	29.23	8.10	10.72	20.10	10.21	1.67	0.00	1.90	1.01	14.08	2.98	0.00	100.0
6-237	Phyllic	2.71	28.54	8.21	15.20	27.41	4.37	0.00	0.00	4.11	0.64	7.52	4.00	0.00	100.0
5-371	Phyllic	2.61	27.95	3.76	10.11	24.30	3.83	6.10	4.21	3.39	0.19	14.65	1.51	0.00	100.0
<i>Average of Phyllic Alteration</i>		2.64	29.82	5.20	10.76	23.10	7.48	3.53	0.84	2.68	0.93	13.43	2.24	0.00	100.0

similar to that of [11], but differs in the graphical representation of the data. In Gresens' method, the components that are likely to have been immobile during alteration can be used to identify any volume change, which may have taken place. If it is assumed that volume change is a factor common to the behavior of all components, it is possible to calculate gains or losses of the other components. Mass gains and losses are calculated using the following relationship:

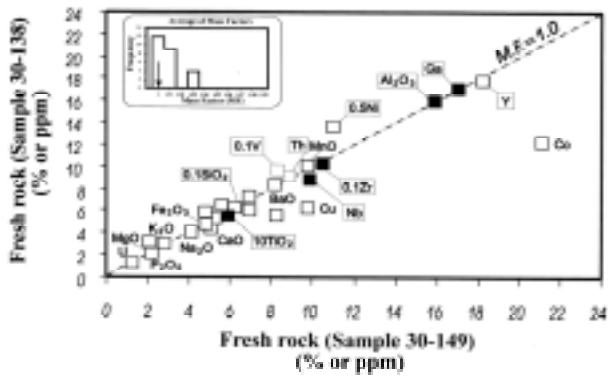
$$X_n = [F_v (S^b / S^a) C_n^b - C_n^a] * 100 \quad (2)$$

where  $X_n$  is the mass gain or loss for component n,

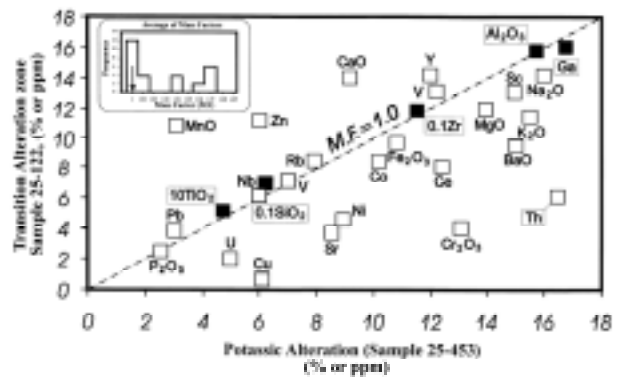
$F_v$  is the volume factor,  $S^b$  is the specific gravity of the altered sample,  $S^a$  is the specific gravity of the unaltered (original) sample,  $C_n^b$  is the concentration of component n in the altered sample, and  $C_n^a$  is the concentration of component n in the unaltered (original) sample. In the isocon method of [1], Equation 2 is reformulated as:

$$DX_n = 100 (M^b / M^a) X_n^b - X_n^a \quad (3)$$

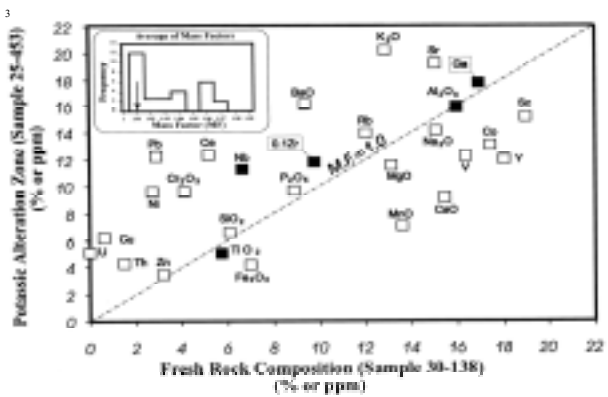
where  $M^b / M^a$  is the mass ratio between the altered sample and the unaltered sample. This ratio is calculated by plotting the concentration of components in the altered rock (e.g., X axis)



**Figure 5.** Isocon diagram comparing two “least altered” rocks. Almost all major oxides fall on or near a line with a slope or mass factor (M.F.) of one.

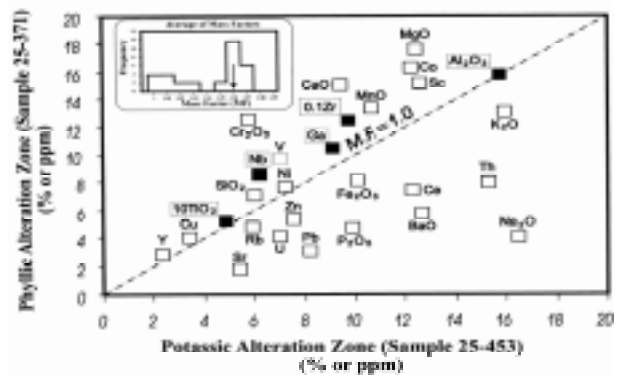


**Figure 7.** Isocon diagram comparing the composition of a representative sample of a altered rock from the transition zone with that of a representative potassically altered rock. See text and caption of Figure 6 for details.



**Figure 6.** An isocon diagram comparing a representative sample of the potassic alteration zone (25-453), with a representative sample of least altered rock (30-168). The dashed line (isocon) is drawn for the largest number of potentially immobile elements (solid squares). The best constraints on mass changes during potassic alteration are given by  $TiO_2$ ,  $Al_2O_3$  and Ga. Only those elements on the isocon, and those present in appreciable concentrations have been labelled. The inset histogram shows the distribution of mass factors calculated for each element.

versus those in the unaltered sample (e.g., Y axis). The components that are immobile will fall on a line of slope  $M^b/M^a$ , referred to as the isocon. Components that lie above the isocon have been added while those, which are below the line, have been lost during the alteration. The slope of the isocon (mass factor) can be determined graphically, and is used to calculate the mass gains and losses of the remaining components by applying Equation 3.



**Figure 8.** Isocon diagram comparing the composition of a representative sample of a representative phyllically altered rock with that of a potassically altered rock. See text and caption of Figure 6 for details.

**Mass Factors** Estimation of the mass factor (i.e., identification of the isocon) maybe complicated by the fact that, in addition to mass changes during alteration, the diorite/granodiorite rock suite may also have undergone compositional change due to fractional crystallization. Fortunately, as shown in the Hezarkhani and Williams-Jones [5], by the behaviour of compatible immobile trace elements, e.g., Y, fractional crystallization in the diorite/granodiorite intrusion was comparatively limited, <10%. Consequently, it is reasonable to assume that mass changes due to magmatic processes were unimportant.

**TABLE 5. Variations in Major and Trace Element Mass Changes in the Fresh Rocks.**

type	Granodiorite		Fresh Rock				Molecular Proportions				Range	Average
	no.	1	2	3	4	1	2	3	4			
sample	30-138		30-149	34-282	58-71	30-138	30-149	34-282	58-71			
<b>g/100 g</b>												
SiO <sub>2</sub>	60.54		60.53	61.68	56.04	69.73	69.57	70.34	65.03		5.30	68.31
TiO <sub>2</sub>	0.58		0.57	0.57	0.73	0.50	0.49	0.49	0.64		0.14	0.54
Al <sub>2</sub> O <sub>3</sub>	15.96		15.88	16.02	16.41	10.83	10.76	10.77	11.22		0.47	10.92
Fe <sub>2</sub> O <sub>3</sub>	4.91		4.94	4.94	6.34	2.13	2.14	2.12	2.77		0.65	2.34
MnO	0.10		0.1	0.09	0.12	0.10	0.10	0.09	0.12		0.03	0.10
MgO	2.61		2.56	2.52	3.73	4.48	4.39	4.28	6.45		2.17	5.04
CaO	4.66		4.98	4.64	6.39	5.75	6.13	5.67	7.94		2.28	6.58
Na <sub>2</sub> O	3.96		4.04	3.85	3.55	4.42	4.50	4.26	3.99		0.51	4.25
K <sub>2</sub> O	2.63		2.48	2.58	2.32	1.93	1.82	1.88	1.72		0.16	1.80
P <sub>2</sub> O <sub>5</sub>	0.24		0.24	0.24	0.23	0.12	0.12	0.12	0.11		0.00	0.12
<b>g/1000 kg</b>												
BaO	833.0		835	944.0	684.0	833.0	787.0	944.0	684.0		260.0	-28.0
Ce	53.0		80	58.0	61.0	53.0	59.0	58.0	61.0		3.0	6.3
Co	12.0		21	19.0	24.0	12.0	15.0	19.0	24.0		9.0	7.3
Cr <sub>2</sub> O <sub>3</sub>	56.0		49	64.0	57.0	56.0	47.0	64.0	57.0		17.0	0.0
Cu	64.0		98	224.0	81.0	64.0	201.0	224.0	81.0		143.0	104.7
Ni	27.0		22	25.0	42.0	27.0	29.0	25.0	42.0		17.0	5.0
Pb	7.0		18	7.0	9.0	19.0	6.0	7.0	9.0		3.0	0.3
Sc	19.0		85	16.0	26.0	95.0	19.0	16.0	26.0		10.0	1.3
V	95.0		53	99.0	141.0	50.0	98.0	99.0	141.0		43.0	17.7
Zn	50.0		17	52.0	58.0	17.0	55.0	52.0	58.0		6.0	5.0
Ga	17.0		10	17.0	18.0	9.0	17.0	17.0	18.0		1.0	0.3
Nb	9.0		16	10.0	5.0	14.0	13.0	10.0	5.0		8.0	0.3
Rb	64.0		58	56.0	50.0	64.0	56.0	56.0	50.0		6.0	-10.0
Sr	664.0		699	715.0	1334.0	664.0	210.0	715.0	1334.0		1124.0	89.0
Th	9.0		9	10.0	10.0	9.0	7.0	10.0	10.0		3.0	0.0
U	0.0		0	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0
Y	18.0		18	17.0	20.0	18.0	19.0	17.0	20.0		3.0	0.7
Zr	99.0		104	105.0	96.0	99.0	115.0	105.0	96.0		19.0	6.3

Mass transfers are calculated, adjusting for total mass change, using the method explained in the text.

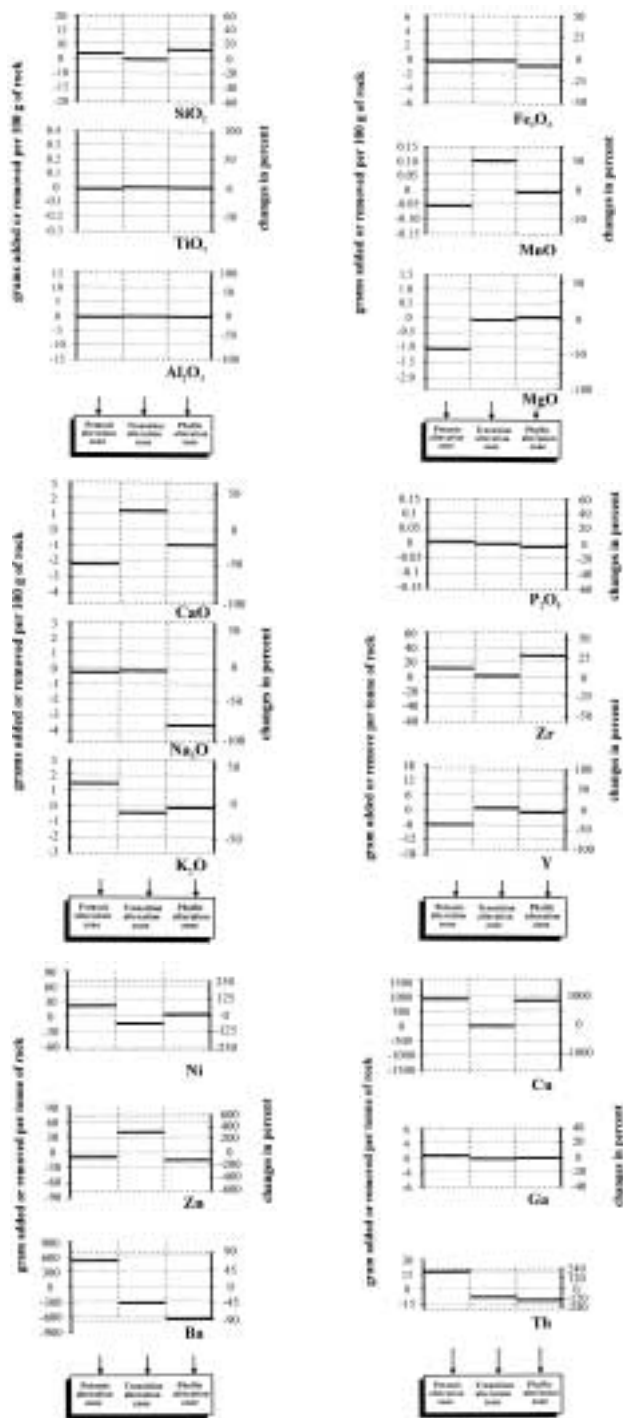
Total Fe as Fe<sub>2</sub>O<sub>3</sub>.

**M.D**<sup>(1)</sup> = measures of dispersion

**δ**<sup>(2)</sup> = standard deviation

The least altered diorite/granodiorite samples are typically found in the deepest part of the deposit.

Four of these rocks were selected and compared in terms of element concentrations. Pair-wise comparisons



**Figure 9.** Mass change profiles for major element oxides and trace elements during alteration based on a sample of least altered rock as a reference for potassic alteration, and potassically altered rock as a reference for transition zone and phyllically altered rock (mass gain and loss corrected using the isocon method). Units are weight percent for major oxides and ppm for trace elements. Percentage changes are relative to concentrations in the least altered or potassically altered reference samples.

of these samples yield isocons having mass factors of approximately one; most elements plot close to or on these isocons, which illustrates a very similar composition of chosen precursor samples (Figure 5, Table 5). Based on the latter results sample 30-138 was selected to represent the precursor (least altered) rock for comparison with alteration zone rocks.

## 11. MASS CHANGES

**Potassic Alteration** Comparison of sample 25-453 (representative of the potassic zone) with least altered sample 30-138 shows that the immobile elements, Ti, Al and Ga plot close to or on a line of constant mass with a slope of 1.0 (Figure 6). However, the elements Zr and Nb, which are generally considered to be geochemically immobile, plot off the line, possibly due to a nugget effect.

As expected from the mineral assemblage in the potassic alteration zone, K and Ba are enriched in sample 25-453 and copper, as expected, is strongly enriched. By contrast Na is depleted, as are Fe, Ca and Mn. Mass changes associated with potassic alteration are presented graphically in Figure 9 and numerically in Table 6. Most calculated volume factors (V.F) lie between 0.99 and 1.04, (Table 7, Figure 6) indicating that there was essentially no volume change.

**Transition Alteration** The transition alteration zone is transitional between the potassic alteration zone and the phyllic alteration zone, but is clearly superimposed on the potassic alteration zone. In order to determine mass changes associated with this alteration, the reference for comparison was therefore a potassically altered rock (25-453). Comparison of a representative sample of rock that has undergone transition alteration (25-122) with potassically altered rock (25-453) shows that  $TiO_2$ ,  $Al_2O_3$ , Zr and Ga plot close to or on a line of constant mass with a slope of approximate 1.0 (Table 6, Figure 7). Most calculated volume factors also lie between 0.99 and 1.02, indicating that there was essentially no volume change. The mass changes of major and trace elements are plotted in Figure 9 (also see Table 6).

Relative to potassically altered rocks Cu, Na,



**TABLE 7. Element Immobility, Mass Factor (MF) and Volume Factor (VF) Calculations Based on the Isocon Method (Grant, 1986). Sample 30-138 Has Been Chosen as Precursor.**

Sample #	Alteration	Relatively Immobile Elements	M.F.	V.F	Average M.F.	Average V.F.
30-168	Potassic	Ti, Al, Ga, Si, Zn, P	1.01	1.06	1.01	1.01
21-32		Ti, Zn, Al, Ga, Si, Mn, Ca	1.00	0.99		
26-277		Cr, P, Ti, Al, Ga	1.00	1.08		
44-345		Y, Sc, Ti, Al, Ga, Si	1.00	1.02		
44-371		Mn, Th, Ti, Al, Ga, Si, Co	1.03	0.99		
44-409		Fe, Ti, Al, Ga	1.02	0.99		
44-429		Y, Ti, Zn, Al, Ga, Si	1.02	1.00		
29-195		Nb, Ti, Al, Ga, Si, Co, Ca	1.00	1.01		
25-517		Y, Zr, Th, Ti, Al, Ga	1.00	1.01		
25-122	Transition	Ti, Al, Ga, V, Rb, Nb, Zr, P	1.02	0.99	1.01	0.99
25-522		Ti, Rb, Ga, P	1.02	0.99		
30-200		Y, Ti, Zn, Al, Ga, Si, P	1.00	1.01		
7-150.6	Phyllic	Ti, Th, Zr, Si, Al, Ga	1.00	0.99	1.02	1.01
25-275		Mn, Mg, Al, Ga, P	1.00	1.01		
33-281		Ti, Th, Si, Al, Ga, Ca	1.04	1.01		
26-237		V, Fe, P, Th, Zr, Si, Al, Ga	1.04	1.08		
25-371		Al, Ni, Ti, Y	1.02	0.99		
25-239		Ti, Y, Th, Zr, Si, Al, Ga, Pb	1.01	0.99		

Mg, Ba, and Fe were depleted and Ca and Mn were added in the transition zone. Absolute mass gains and losses are evaluated quantitatively in Figure 9 and Tables 7.

**Phyllic Alteration** The phyllic alteration zone is characterized by the presence of large proportions of sericite and pyrite and near absence of biotite and K-feldspar. Phyllic alteration has strongly overprinted earlier potassic alteration. Comparison of potassically altered sample 25-453 and representative sample of 25-371 for phyllic alteration shows that the immobile elements Al and Ti plot close to or on a line (Figure 8) of constant mass with a slope of 1.0. However, Zr and Nb, which are typically immobile, plot off the line, due possibly as discussed earlier, to a nugget effect. Most calculated volume factors lie between 0.99 and 1.04, indicating that there was only minor volume change. The most important mass changes in the phyllic alteration zone relative to potassically altered rock are strong depletion of Na and Ba, moderate depletion of K, Fe and Rb, and addition of Ca, Mg, Mn, and SiO<sub>2</sub> and Cu.

## 12. DISCUSSION

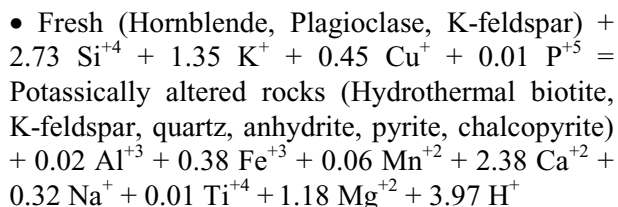
Based on studies of fluid evolution in the Sungun deposit [5,12], potassic alteration (biotite and K-feldspar) and associated Cu ± Mo mineralization were caused by a high temperature, high salinity fluid of dominantly magmatic origin. Subsequent transition and phyllic alteration in the deeper and shallower parts of the stock, respectively, were produced by the incursion of dilute meteoric fluids and mixing of these fluids with residual orthomagmatic fluids. This addition of external fluids increased Na/K ratios in the progressively heated fluids, and caused the remobilization of previously precipitated copper sulphides through acidification and oxidation, and redeposition in highly fractured zones [12]. At all stages in the evolution of the Sungun hydrothermal system, alteration appears to have taken place with no appreciable change in volume as shown by the fact that the volume factors (V.F.) calculated earlier are close to unity.

In the potassic alteration zone, the principal



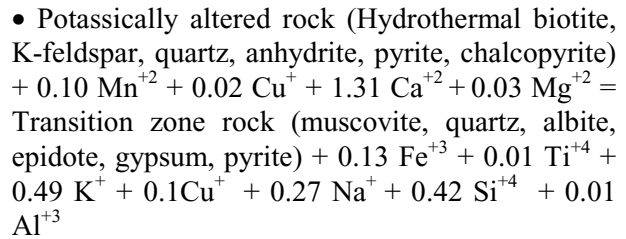
chemical changes were an enrichment of K and Ba, and depletions of Na, Ca, Mg, Mn and Fe. Mineralogically, these changes were accommodated by crystallization of K-feldspar and biotite at the expense of plagioclase and amphibole [12]. The replacement of plagioclase and amphibole by K-feldspar and biotite respectively, served to add K and remove Ca and Na. Depletion of Fe was due to the alteration of Fe-rich magmatic amphibole and biotite, by biotite and phengitic muscovite with appreciably lower Fe/Fe+Mg ratios. The changes K and Na are consistent with fluid inclusion data [5], which suggest comparably high K/Na ratio and low concentrations of cations of other major elements. Barite was not found in the Sungun deposit, and the only minerals that could accommodate Ba are K-feldspar and mica, which formed in potassically-altered rocks. Copper was added to potassically-altered rocks in significant amount as might be expected from the dissemination of chalcopyrite and bornite in this zone.

Based on the chemical analyses, bulk densities calculated from the inexact matrix, microprobe analyses of the minerals which characterize the potassic alteration zone, and the mass changes discussed above (Tables 5 and 6), the overall reaction for the conversion of 1,000 cm<sup>3</sup> of fresh diorite/granodiorite to 1,000 cm<sup>3</sup> of average potassically altered rock (calculated from the average mass changes in Table 6) is:



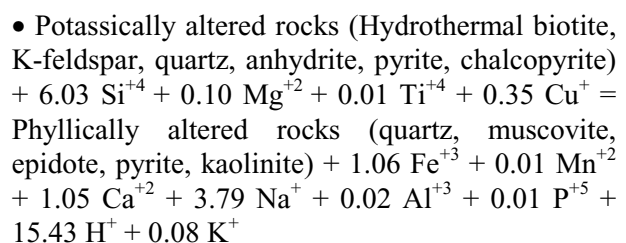
In the transition alteration zone, Ca was added, Na, Fe and Mg were relatively unchanged, and K, Ba and Cu were depleted. The losses of K and Ba relative to Na are consistent with the replacement of K-feldspar by albite. However the substantial addition of Ca is surprising and may reflect the presence of anhydrite (or gypsum), which is more typical of potassic alteration (Table 6). The mass changes discussed above reflect the following reactions (calculated from the average mass changes in Table 6)

between hydrothermal fluid and potassically altered rock.



Phyllic alteration like transition alteration is superimposed on the potassic zone and is characterized by sericitization of feldspars [19]. Compared to the potassic alteration zone, the phyllic alteration zone is depleted in Na, K, Fe and Ba and enriched in Si and Cu (Figure 8). The losses of Na, K and Fe reflect the sericitization of alkali feldspar and ferromagnesian minerals (e.g., hydrothermal biotite which had been formed during the potassic alteration) respectively. The addition of Si is consistent with the widespread silicification, which is a major feature of phyllic alteration. The addition of Cu and depletion in the transition alteration zone is consistent with mobilization of this element and its concentration in the upper parts of the pluton during phyllic alteration. The mass changes associated with phyllic alteration are shown in Figure 9 and in Table 7.

The overall reaction based on the major oxides for the conversion of 1,000 cm<sup>3</sup> of potassically-altered rock to 1,000 cm<sup>3</sup> of the phyllically-altered rock, calculated from the average mass changes in Table 6, is:



### 13. CONCLUSIONS

1) Isocon plots illustrate that Al, Ti and Ga were relatively immobile during alteration, and that mass was essentially conserved alteration.

2) At all stages in the evolution of the hydrothermal system (potassic, transition and phyllic), alteration appears to have taken place with no appreciable change in volume as shown by the fact that the volume factors (V.F.) calculated earlier are close to unity.

3) In the potassic alteration zone, the changes in major elements were an enrichment of K and depletions of Na, Ca, Mn and Fe. These changes were due to replacement of plagioclase and amphibole by K-feldspar and biotite, respectively. Potassic alteration was associated with large addition of Cu as might be expected from the occurrence of disseminated chalcopyrite and bornite in this zone.

4) In the transition alteration zone, Ca was added, Na, Fe and Mg were relatively unchanged, and K, Ba and Cu were depleted. The loss of K and Ba relatively to Na reflects replacement of K-feldspar by albite (which is evident microscopic observations). Addition of Ca is surprising and may reflect the presence of, anhydrite (or gypsum) which is more typical of potassic alteration.

5) Phyllic alteration was accompanied by the depletion of Na, K, Fe and Ba and enrichment of Si and Cu. The losses of Na, K and Fe reflect the sericitization of alkali feldspar and destruction of ferromagnesian minerals. The addition of Si is consistent with the widespread silicification, which is a major feature of phyllic alteration and the addition of Cu with mobilization from the transition zone which is depleted in this element.

#### 14. REFERENCE

- Grant, J. A., "The Isocon Diagram-a Simple Solution to Gresens' equation for Metasomatic", *Economic Geology*, Vol. 81, (1986), 1976-1982.
- Hezarkhani, A., "Physicochemical Controls on Alteration and Copper Mineralization in the Sungun Porphyry Copper Deposit, Iran", Ph.D. Thesis, McGill University, Canada, (1997).
- Oyarzun, R., Marquez, A., Lillo, J., Lopez, I., and Rivera, S., Giant Versus Small Porphyry Copper Deposits of Cenozoic Age in Northern Chile: Adakitic Versus Normal Calc-Alkaline Magmatism", *Mineralium Deposita*, Vol. 36, (2001), 794-798.
- Galley, A., Otto, V. B. and Franklin, J., "The Relationship Between Intrusion-Hosted Cu-Mo Mineralization and the VMS Deposits of the Archean Sturgeon Lake Mining Camp, Northwestern Ontario", *Economic Geology*, Vol. 95, (2000), 1543-1550.
- Hezarkhani, A., and Williams-Jones, A. E., "Controls of Alteration and Mineralization in the Sungun Porphyry Copper Deposit, Iran: Evidence from Fluid Inclusions and Stable Isotopes", *Economic Geology*, Vol. 93, (1998), 651-670.
- Lowenstern, J. B., "Carbon Dioxide in Magmas and Implications for Hydrothermal System, *Mineralium Deposita*, Vol. 36, (2001), 490-502.
- Carten, R. B., "Sodium-Calcium Metasomatism: Chemical, Temporal, and Spatial Relationships at the Yerington, Nevada, Porphyry Copper Deposit", *Economic Geology*, Vol. 81, (1986), 1495-1519.
- Brimhall, G. H., "Deep Hypogene Oxidation of Porphyry Copper Potassium-Silicate Protore at Butte, Montana: A Theoretical Evaluation of the Copper Remobilization Hypothesis", *Economic Geology*, Vol. 75, (1980), 384-409.
- Brimhall, G. H. and Ghiorso, M. S., "Origin and Ore-Forming Consequences of the Advanced Argillic Alteration Process in Hypogene Environments by Magmatic Gas Contamination of Meteoric Fluids", *Economic Geology*, Vol. 78, (1983), 73-90.
- Brimhall, G. H., "Lithologic Determination of Mass Transfer Mechanisms of Multiple-Stage Porphyry Copper Mineralization at Butte, Montana: Vein Formation by Hypogene Leaching and Enrichment of Potassium-Silicate Protore, *Economic Geology*, Vol. 74, (1979), 556-589.
- Gresens, R. L., "Composition-Volume Relationships of Metasomatism", *Chemical Geology*, Vol. 2, (1967), 47-55.
- Hezarkhani, A., Williams-Jones, A. E., and Gammons, C., "Copper Solubility and Deposition Conditions in the Potassic and Phyllic Alteration Zones, at the Sungun Porphyry Copper Deposit, Iran", *Geol. Assoc. Canada-Mineralogical Assoc. Canada (GAC-MAC) Annual Meeting*, Ottawa, Vol. 50, (1997), A-67.
- Hezarkhani, A., and Williams-Jones, A. E., "Physico-Chemical Controls of Alteration and Mineralization at the Sungun Porphyry Copper Deposit, Iran", *Geol. Assoc. Canada-Mineralogical Assoc. Canada (GAC-MAC) Annual Meeting*, Winnipeg, Vol. 21, (1996), A-44.
- Rule, A. C., Bailey, S. W., "Refinement of the Crystal Structure of a Monoclinic Ferroan Clinocllore", *Clays and Clay Minerals*, Vol. 35, 129-138.
- Bailey, S. W., "Re-Evaluation of Ordering and Local Charge Balance of Ia Chlorite", *Canadian Mineralogist*, Vol. 24, (1986), 649-654.
- Böhlke, J. K., "Comparison of Metasomatic Reactions Between a Common CO<sub>2</sub>-Rich Vein Fluid and Diverse Wall Rocks: Intensive Variables, Mass Transfers, and Au Mineralization at Alleghany, California", *Economic Geology*, Vol. 84, (1989), 291-327.
- Spear, F. S., Rumble, D., Ferry, J. M., "Linear Algebraic Manipulation of n-Dimensional Composition Space", *Reviews in Mineralogy*, Vol. 10, (1982), 105-152.
- MacLean, W. H., Kranidiotis, P., "Immobile Elements as Monitors of Mass Transfer in Hydrothermal Alteration: Phelps Dodge Massive Sulfide Deposit, Matagami, Quebec", *Economic Geology*, Vol. 82, (1987), 951-962.
- Hezarkhani, A., Williams-Jones, A. E., and Gammons, C. H., "Factors Controlling Copper Solubility and Chalcopyrite Deposition in the Sungun Porphyry Copper Deposit, Iran", *Mineralium Deposita*, Vol. 34, (1999), 770-783.