White Mica Geochemistry of the Catheart Mountain Porphyry Copper Deposit, Maine
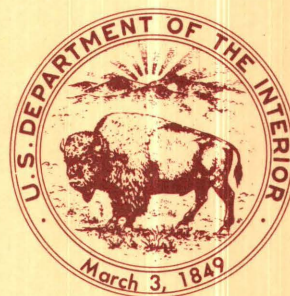
White Mica Geochemistry of the Catheart Mountain Porphyry Copper Deposit, Maine

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CONTENTS

FIGURES

TABLES

White Mica Geochemistry of the Catheart Mountain Porphyry Copper Deposit, Maine

By Robert A. Ayuso

Abstract

White micas from hydrothermally altered and mineralized zones in the Catheart Mountain Cu-Mo porphyry deposit have regular compositional variations that are generally related to the contents of copper, total iron, and sulfur in the whole rock. Micas in unmineralized rocks exhibit no such relationship. White mica compositions reflect primarily the control imposed by the celadonitic substitution $Al^{IV} + Al^{VI} = Si + (Fe, Mg)$.

The variation in white mica composition in the Catheart Mountain porphyry may be explained by superposition and overprinting of mineral assemblages by ore fluids during mineralization and during the waning stages of hydrothermal alteration. Local bulk compositional differences, changing P_{H_2O} and fluid compositions during mineralization, and superposition of mineral assemblages along microzoned veins contributed to variation in white mica composition. However, the general relation between white mica composition and base-metal content in the mineralized rocks at Catheart Mountain suggests that identification of this white mica population might be useful as an indicator of mineralization gradients.

INTRODUCTION

Mineralized rocks from porphyry copper deposits represent a complex interaction of magmatic and hydrothermal processes. Titley (1982) and Beane and Titley (1981) recently summarized the geologic complexity of most porphyry copper deposits and noted the variation of the intensive parameters before, during, and after mineralization. Thus, the observed mineral assemblage depends on composition of the host rock, on position of the rock with respect to the ore fluid and heat sources, and on the intensity and efficiency of late hydrothermal alteration events.

Mineralogic studies may be of great value in understanding the chemical environment during mineralization in porphyry copper systems. For example, white mica occurs in the potassic, phyllic, and mineralized zones of most porphyry copper systems (Creasey, 1959; Meyer and Hemley, 1967; Lowell and Guilbert, 1970; Rose, 1970)

and, thus, it is potentially a good monitor of the changing chemical environment. This paper discusses the composition of white mica from different hydrothermal alteration zones in the Catheart Mountain Cu-Mo deposit in Maine (fig. 1) as a function of the copper content of the whole rock.

Recent investigations on the composition of white micas in porphyry copper deposits include studies by Guilbert and Schafer (1978), Beaufort and Meunier (1983), and Parry and others (1984). Guilbert and Schafer (1978) and Guilbert (1980) suggested that white mica in porphyry mineralized areas might be an aid in exploration. McDowell and Elders (1980) studied white micas from a geothermal field, and Hendry (1981) used white mica composition to study wall-rock alteration in volcanic-hosted copper mineralization. Gunow and others (1980) studied the fluorine content of sericite in the Henderson molybdenite deposit in Colorado. In addition, the possibility that white mica composition changes as a function of proximity to mineralization has been investigated in hydrothermally altered submarine exhalative ores (Plimer and de Carvalho, 1982), in stratiform sulfide deposits (McLeod and Stanton, 1984), and in stratabound Ba-Zn mineralization (Fortey and Beddoe-Stephens, 1982).

ANALYTICAL PROCEDURES

Twenty-two samples from the Catheart Mountain Cu-Mo deposit were obtained from representative drill cores traversing the regional hydrothermally altered and mineralized zones (fig. 1). Polished microprobe thin sections were obtained as close as possible to single veins in drill core splits analyzed for major and trace elements as well as for base metals (Mo, Cu, Sn, W, and so on). An effort was made to obtain the thin-section samples from areas in the drill core that clearly contained chalcopyrite and molybdenite in close proximity to white mica.

Electron microprobe analyses of white mica were done at the U.S. Geological Survey, Reston, Va. Initially, the micas were analyzed with an automated, three-channel electron microprobe employing a combination of
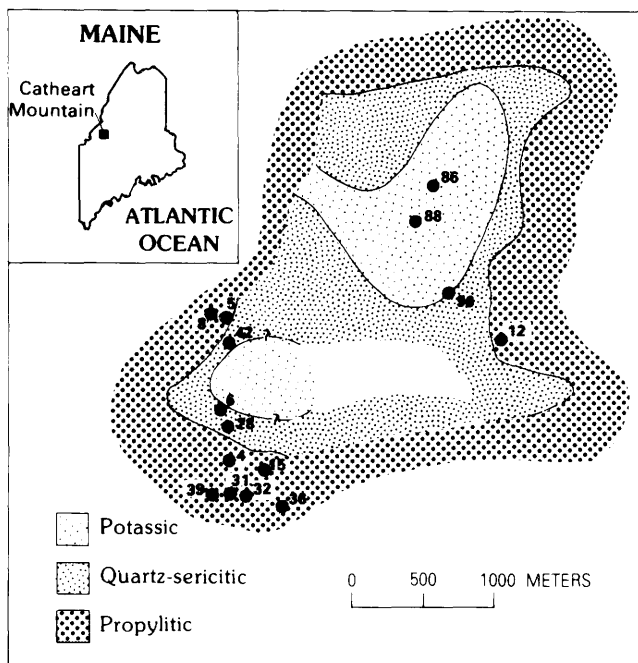
Figure 1. Location map and surface expression of hydrothermal alteration of the Catheart Mountain porphyry Cu-Mo deposit. Also shown are the drill-hole sites.

wave-length and energy-dispersive procedures. Approximately half of the analytical work was done using an automated ARL-SEMQ[1] nine-channel electron microprobe under similar operational conditions as in the first part of the study, including 15-kilovolt operating voltage, 0.1-microamp beam current, and data-acquisition (McGee, 1983) and correction procedures by the Bence and Albee (1968) and Albee and Ray (1970) methods. Standards used in this study included natural and synthetic silicates and oxides. Typically, during standardization and analysis, 20 seconds were counted on the peak and 10 seconds on the background for both the standards and the unknowns. The analytical procedure was monitored by repeated analysis of known sheet silicates, including muscovite and fluorphlogopite.

Microprobe analyses of white mica in carbon-coated thin sections were done on at least 10 grains per sample. At least three spot analyses per grain were performed, the number depending on the size of the white mica. Water determinations were not obtained independently of the microprobe analyses of white mica.

Rock compositions were determined using the rapid rock technique (Shapiro, 1975) for the major elements; minor- and trace-element abundances were determined by

chemical, emission-spectrographic, and instrumental neutron-activation analyses. A complete presentation of the bulk-rock analyses and a discussion of the bulk chemistry are in preparation.

GEOLOGY

The Catheart Mountain Cu-Mo deposit is in a shallowly emplaced, fine- to medium-grained pluton that intruded the southeast flank of the Boundary Mountain anticlinorium (Albee and Boudette, 1972); this pluton belongs to a group of mineralized intrusives within the Appalachian porphyry province (Hollister, 1978). The two most important rock types at Catheart Mountain are quartz monzonite and quartz-feldspar porphyry, both of which contain mineralization. Nearby mineralized plutons in northern Maine include the newly reported Mo mineralization at Priestly Lake (Ayuso and Shank, 1983; Ayuso, 1984) and the Cu-Mo mineralization at Deboullie (Boone, 1962; Hollister, 1978).

The Catheart Mountain quartz monzonite and quartz-feldspar porphyry occur within the Attean Quartz Monzonite of Ordovician age; this occurrence has led to the assumption that the Attean Quartz Monzonite and the rocks at Catheart Mountain are genetically related and may be of the same age. However, petrographic studies have indicated that rocks at Catheart Mountain are significantly different from those from the Attean Quartz Monzonite, and that they constitute a distinct mappable unit.

The Attean Quartz Monzonite is coarsely porphyritic and intrudes volcanic and volcaniclastic rocks that unconformably overlie the Precambrian (Naylor and others, 1973) Chain Lakes Massif. No mineralization associated with intrusion of this pluton has been identified. Metasedimentary rocks of Silurian and Devonian age (Boone and others, 1970) are in the greenschist facies of regional metamorphism and unconformably overlie the Attean Quartz Monzonite. These metasedimentary rocks are also cut by plutons of Devonian age that were emplaced in the area during the closing stages of the Acadian orogeny.

Boone and others (1970) reported ages of 433 m.y. by Rb-Sr dating of white mica and 465 m.y. by K-Ar dating of biotite in the Catheart Mountain area. On the basis of field relations, however, Schmidt (1974) suggested that the Catheart Mountain quartz monzonite was possibly intrusive into the 444-m.y.-old Attean Quartz Monzonite (Lyons and others, 1983), and that perhaps the main stage of plutonism and mineralization had not been properly dated. Schmidt's suggestion is supported by preliminary dating by the Rb-Sr whole-rock method of the least altered portions of the Catheart Mountain deposit, which indicates an age of about 425±6 m.y. (Ayuso, 1986).

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[1] Any use of trade names and trademarks in this publication is for descriptive use only and does not constitute endorsement by the U.S. Geological Survey.

This age probably does not represent the crystallization age but may be a result of the hydrothermal alteration. From the exploration standpoint, determining the true age of rocks associated with mineralization in this part of the New England Appalachians would be useful in order to identify other volcanoplutonic suites that may be mineralized.

Schmidt (1974) recognized two centers of alteration (the main alteration system and a smaller peripheral system) on Catheart Mountain; samples used in this study were obtained from both centers. Petrographic study of rock alteration of the drill cores at Catheart Mountain allowed Schmidt (1974) to classify the regional alteration types and to emphasize their gradational nature. He distinguished five major gradational regional alteration zones in the Catheart Mountain area on the basis of the predominant alteration type found in the upper parts of the drill core (fig. 1). The regional zones ranged, from least altered to most intensely altered, in the sequence propylitic, outer phyllic, phyllic, quartz potassic, and potassic. The overall geometry of the hydrothermal system (fig. 1) resembles that of many other porphyry systems summarized by the Lowell and Guilbert (1970) model.

SUMMARY OF THE PETROGRAPHY

The predominant rock types in the Catheart Mountain deposit are fine- to medium-grained porphyritic quartz monzonite and quartz-feldspar porphyry. The least altered portions of these rocks consist of plagioclase and alkali feldspar, quartz, biotite, accessory minerals (sphene, zircon, apatite?), and secondary minerals (epidote, sericite, chlorite, and hematite). Most rocks in the area, however, exhibit the effects of hydrothermal alteration, so that alteration minerals (white mica, calcite, epidote, chlorite, and pyrite) commonly replace the original mineralogy (table 1).

Quartz and white mica are the predominant alteration minerals, and all other phases, with the possible exception of calcite in some samples, are relatively minor in abundance. Hydrothermal alkali feldspar and biotite appear to be restricted to the most intensely altered portion of the hydrothermal system (potassic zone), whereas chlorite, calcite, and epidote are widely distributed across the hydrothermal zones. Most of the original silicate mineralogy and fabric of the granodiorite has been drastically modified. Traces of albite twinning in feldspar, and of granitic texture, are rarely seen except in portions of the quartz-sericite and propylitic zones.

Quartz phenocrysts are one of the most persistent textural features retained from the original rock. They are generally subhedral to euhedral but may have significant embayments and indentations. Plagioclase forms fewer phenocrysts than quartz and occurs mostly in the matrix, where it is intensely replaced by hydrothermally produced minerals. Alkali feldspar occurs in the most strongly altered portions of the hydrothermal system. Biotite was the predominant primary mafic mineral at Catheart Mountain, but white mica, chlorite, and epidote replace magmatic biotite in all of the hydrothermal zones.

The potassic zone has numerous veins of calcite, white mica, epidote, quartz, alkali feldspar, and sulfides (chalcopyrite, pyrite, and molybdenite). Most veins in the quartz-sericite alteration are mineralogically simple and consist of white mica, quartz, and sulfides.

White mica is widely distributed in the hydrothermal system, varying in abundance and ranging in size from very fine grained selvages on the feldspars to coarse plates, rosettes, clusters, and vein-filling material (table 1). Sericite ranges from trace to moderate amounts in the propylitic and argillic zones of the Catheart Mountain deposit. In many of the intensely fractured samples, the overall abundance of coarse white mica is much higher than that of the fine-grained mica, and intergrowths of white mica and sulfides are common. Coarse white mica in the fine-grained samples formed as a result of piecemeal and patchy replacement of biotite.

Chalcopyrite, pyrite, and molybdenite are the predominant sulfides at Catheart Mountain. The area near the interface between the potassic and the quartz sericite alteration zone contains the highest abundance of ore minerals (Schmidt, 1974), and this feature is also in agreement with the general concepts of porphyry copper mineralization (Lowell and Guilbert, 1970). Stannite was reported to occur erratically in veins within the phyllic zone, and sphalerite in the propylitic zone (Hollister, 1978). There is, however, no clear evidence of zoning of these minerals as a function of the intensity of hydrothermal alteration. The sulfides occur in siliceous veinlets and as disseminated grains. The total amount of sulfides is probably less than 5 percent in the samples studied. Pyrite accounts for the bulk of the sulfides, attaining a ratio of 10:1 with chalcopyrite in samples of the quartz-sericite zone. Molybdenite occurs as fine-grained disseminations, large rosettes, and molybdenite "stain," and as clusters in quartz sulfide veins. Many of the veins carrying white mica and quartz in the potassic zone also contain large plates of molybdenite. A good correlation exists between the type of alteration, the intensity of veining, and the intensity of mineralization, so that the highest amounts of Cu and Mo, as well as the lowest Cu/Mo ratio, are found in potassically altered rocks closely associated with the quartz-feldspar porphyry. In the potassic zone the grade is about 0.2 percent Cu plus minor Mo (Hollister, 1978). Some of the veinlets in the propylitically altered parts of the system, according to Schmidt (1974), consist of an inner zone containing the ore minerals and quartz

Table 1. Summary of hydrothermal alteration, mineralogy, and sulfide occurrence in the Catheart Mountain Cu-Mo deposit, Maine

[Sample identification numbers refer to drill core number and depth, in feet; regional hydrothermal alteration zones based on core descriptions by Schmidt (1974, and personal commun., 1981) and this study. Abbreviations: q, quartz; af, alkali feldspar; s, sericite; ep, epidote; cc, calcite; b, biotite; z, zircon; ch, chlorite; l, large plates of sericite; s, small plates of sericite; M, mineralized; U, unmineralized]

Sample	Alteration	Alteration Minerals	Sericite Occurrence	Sulfide(%)	% Pyrite/ % Chalcopyrite	Molybdenite Occurrence	Remarks
5-680	potassic	q, af, s, ep, cc, b?, z	l>s	<1	10	Concentrated in quartz veins	M
8-288	potassic	q, af, s, ep, cc, b?	s>>l	1	3	Very fine grained	M
36-1142	potassic	q, af, s, cc	l>>s	3	3	Concentrated in quartz veins	M
86-240	potassic	q, af, s, ch	s>>l	1	5	Few concentrations	M
28-159	potassic	q, af, s, cc	l>>s	1	5	Disseminated, sparse	M
28-214	potassic	q, af, s, cc	l>>s	2	8	Disseminated, sparse	M
28-263	potassic	q, af, s, cc	l>s	2	8	Disseminated, sparse	M
4-250	quartz-sericite	q, s	s>l	1	10	None seen	U
4-280	quartz-sericite	q, s, cc	s>l	1	10	None seen	U
4-300	quartz-sericite	q, s, cc	s>l	1	10	Concentrated in fractures	U
4-350	quartz-sericite	q, s	l>>s	3	10	Concentrated in quartz veins	M
5-740	quartz-sericite	q, s, cc, ch	s>l	2	10	Concentrated in quartz veins	U
12-370	quartz-sericite	q, s, ep, ch	s>>l	1	5	None seen	U
15-124	quartz-sericite	q, s, cc, ch	s>>l	1	5	Very fine grained	U
42-289	quartz-sericite	q, s, cc	l>>s	4	3	Disseminated	M
88-452	quartz-sericite	q, s	s>l	no data	no data	No data	M
96-110	quartz-sericite	q, s, ep, cc, ch	s>l	2	5	None seen	M
96-310	quartz-sericite	q, s, ep, cc	s>>l	2	5	None seen	U
6-200	sericitic	q, s, ep	s>l	2	3	None seen	U
32-642	sericitic	q, s, cc	s>>l	5	3	Disseminated, sparse	M
86-186	sericitic	q, s, ep, ch	s>>l	<1	3	Disseminated	M
31-160	propylitic	q, s, cc	l>>s	<1	5	No data	U
39-463	propylitic	q, s	s>>l	1	10	Concentrated in quartz veins	U

sericite (phyllic) alteration, enveloped by a potassium-feldspar-enriched alteration zone (potassic).

Samples used in this study are subdivided into a mineralized or unmineralized group according to degree of alteration, and sulfide abundance determined on the basis of core descriptions and thin-section analyses (table 1). Samples from the mineralized group have higher contents of Cu and Mo than samples from the unmineralized group (table 2). Unmineralized samples are also easily distinguishable by a lack of disseminated sulfides and by their generally lower density of fractures.

SUMMARY OF ROCK BULK COMPOSITION

A brief summary of the major features of the major oxide composition of the rocks at Catheart Mountain is presented in this section (table 2). The Catheart Mountain rocks are characterized by a narrow silica range and by a lack of well-defined variations of the major elements as a function of silica. The major oxides CaO, MgO, TiO_2, and P_2O_5 are broadly and inversely correlated with SiO_2, as are F and H_2O^+. Compared with the average high-calcium calc-alkaline granite of Nockolds (1954), the unmineralized rocks at Catheart Mountain are generally lower in SiO_2, TiO_2, Al_2O_3, FeO, Na_2O, and P_2O_5 (table 2). Also, rocks from the unmineralized group are slightly higher in Fe_2O_3, CaO, and MgO than the average calc-alkaline granite and show a broadly calc-alkaline trend on the AFM diagram.

Comparison of the mineralized and unmineralized rock groups shows that higher contents of K_2O, Fe_2O_3, S, Cu, and Mo are generally characteristic of the mineralized rocks. The unmineralized rocks are generally higher in FeO than the mineralized rocks. Values for F as high as 0.14 weight percent were found at Catheart Mountain, suggesting only a moderate enrichment in fluorine in these rocks. In contrast to F, the content of Cl is low, generally about 0.01 weight percent. Although high values for S (up to 4.0 weight percent) are characteristic of the mineralized rocks at Catheart Mountain, many of the rocks from the unmineralized group also have abnormally high values of S compared with unaltered calc-alkaline rocks. The range in values for CO_2 and H_2O^+ in these rocks is generally great and clearly indicates the effects of hydrothermal alteration; this is further supported by the presence of calcite, hydrous alteration minerals, pyrite, and other sulfides. In general, both groups of rocks also show higher Cu and Mo contents than do rocks from typical calc-alkaline suites (table 2).

For the most part, Cu in rocks of the mineralized group is not directly correlated with other elements. For example, there is no clear trend between Al_2O_3 content and Cu (fig. 2A), although there is probably a trend toward higher Cu in rocks containing the highest Fe_2O_3
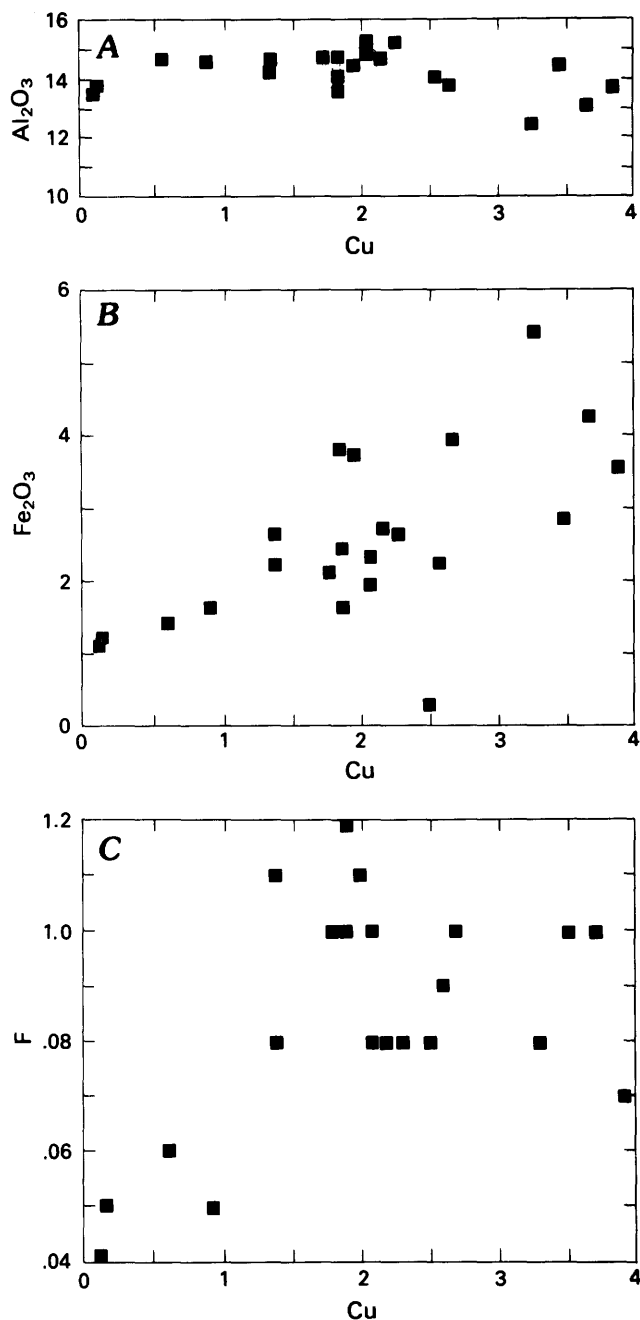
Figure 2. Composition of mineralized bulk rocks at Catheart Mountain: A, Variation in Al_2O_3 and Cu; B, Wide range in Fe_2O_3 and Cu; and C, Variation in F and Cu. All values are in weight percent. Graphs show all available data on mineralized bulk samples from Catheart Mountain and include samples used in this study.

(fig. 2B), because of the presence of chalcopyrite. Many of the rocks containing high Cu also have high F values (fig. 2C).

Mineralized rocks from the Catheart Mountain Cu-Mo deposit show a general, positive correlation between S and Cu (fig. 3A), a tendency for higher Mo in

Table 2. Representative analyses of the mineralized and unmineralized rocks in the Catheart Mountain deposit

Sample	MINERALIZED												UNMINERALIZED					
	88-452	39-463	32-642	28-263	28-159	36-1142	96-110	86-240	42-289	4-350	86-186	96-310	4-250	15-124	31-160	4-300	4-280	Granodiorite[1]
	Major and minor element composition in weight percent																	
SiO_2	64.50	65.40	67.40	67.40	66.90	67.10	69.30	69.40	70.30	70.70	71.10	66.10	67.40	67.70	68.70	69.30	69.70	66.88
Al_2O_3	15.30	15.10	14.80	14.50	13.80	14.10	14.70	14.70	13.10	12.50	14.60	15.90	15.30	14.40	14.80	14.10	14.30	15.66
Fe_2O_3	2.60	2.60	2.10	2.80	3.90	2.20	2.70	1.40	4.20	5.40	1.60	2.90	1.50	2.20	1.50	1.80	1.90	1.33
FeO	.52	.20	.12	.20	.20	.32	.28	.44	.20	.20	.20	1.00	.28	1.10	.92	.28	.32	2.59
MgO	1.30	1.30	1.00	.94	.77	.74	1.10	1.00	.58	.50	.93	1.40	.63	1.30	1.10	.70	.66	1.57
CaO	2.50	3.00	3.00	1.90	1.60	1.70	1.40	1.60	.90	.46	2.10	2.40	3.00	2.10	2.40	2.70	2.80	3.56
Na_2O	1.50	.47	1.70	.87	.14	.60	2.00	2.30	.13	.15	2.70	2.70	2.90	2.30	2.70	2.10	2.50	3.84
K_2O	4.60	5.70	4.30	5.20	6.00	6.90	4.70	5.50	5.60	4.10	4.70	3.50	3.40	4.50	4.50	3.90	3.50	3.07
TiO_2	.38	.33	.31	.32	.29	.31	.37	.18	.32	.27	.31	.38	.24	.39	.31	.25	.24	.57
P_2O_5	.18	.14	.14	.18	.17	.15	.15	.15	.15	.14	.15	.16	.09	.14	.14	.11	.10	.21
MnO	.04	.07	.06	.02	.04	.03	.06	.05	.03	.01	.04	.06	.02	.04	.04	.05	.05	.07
SrO	.04	.01	.01	.01	.01	.02	.03	.03	.01	.01	.05	.04	.02	.03	.04	.01	.02	n.d.
BaO	.07	.07	.06	.07	.10	.12	.10	.09	.11	.06	.09	.07	.08	.08	.10	.09	.07	n.d.
ZrO_2	.02	.01	.02	.02	.02	.01	.02	.02	.01	.02	.01	.02	.02	.02	.01	.01	.01	n.d.
Cr_2O_3	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	n.d.
NiO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	n.d.
CO_2	2.00	2.20	2.30	1.50	1.24	1.40	.48	1.30	.62	.27	.18	.54	2.30	1.10	.91	2.00	2.12	n.d.
S	1.50	1.40	1.40	2.20	3.10	1.70	1.60	.73	3.30	4.00	.56	1.70	.80	1.10	.84	.87	1.10	n.d.
Cl	.00	.00	.00	.00	0.00	.01	.01	.01	.00	.00	.01	.01	.01	.01	.01	.00	.00	n.d.
F	0.08	.14	.10	.10	0.10	.09	.08	.06	.10	.08	.05	.10	.10	.08	.07	.07	.07	n.d.
H_2O^+	2.10	2.00	1.80	1.80	1.70	1.40	1.60	1.30	1.60	1.70	1.20	1.80	1.50	1.80	1.20	1.40	1.40	.65
H_2O^-	.16	.07	.04	.06	.06	0.04	0.08	.06	.13	.04	.04	.07	.08	.15	0.08	.08	.08	n.d.
Subtotal	99.39	100.22	100.66	100.10	100.10	98.94	100.76	101.93	101.39	100.60	100.63	100.85	99.66	100.55	100.37	99.79	100.92	n.d.
Less O	.78	0.76	.74	1.14	1.59	.89	.83	.39	1.69	2.03	.30	0.89	.44	.58	.45	.45	.58	n.d.
Total	98.61	99.46	99.92	98.96	98.51	98.05	99.92	99.92	99.70	98.57	100.32	99.96	99.22	99.96	99.92	99.34	100.34	---
	Elements in parts per million																	
Cu	2300	780	1800	3500	2700	2600	2200	620	3700	3300	940	520	180	420	450	280	250	30
Mo	20	.3	31	210	160	420	65	120	510	84	120	18	7	11	.4	30	18	1

[1] Average composition of granodiorite (Nockolds, 1954; Turekian and Wedepohl, 1961); n.d.: not determined.
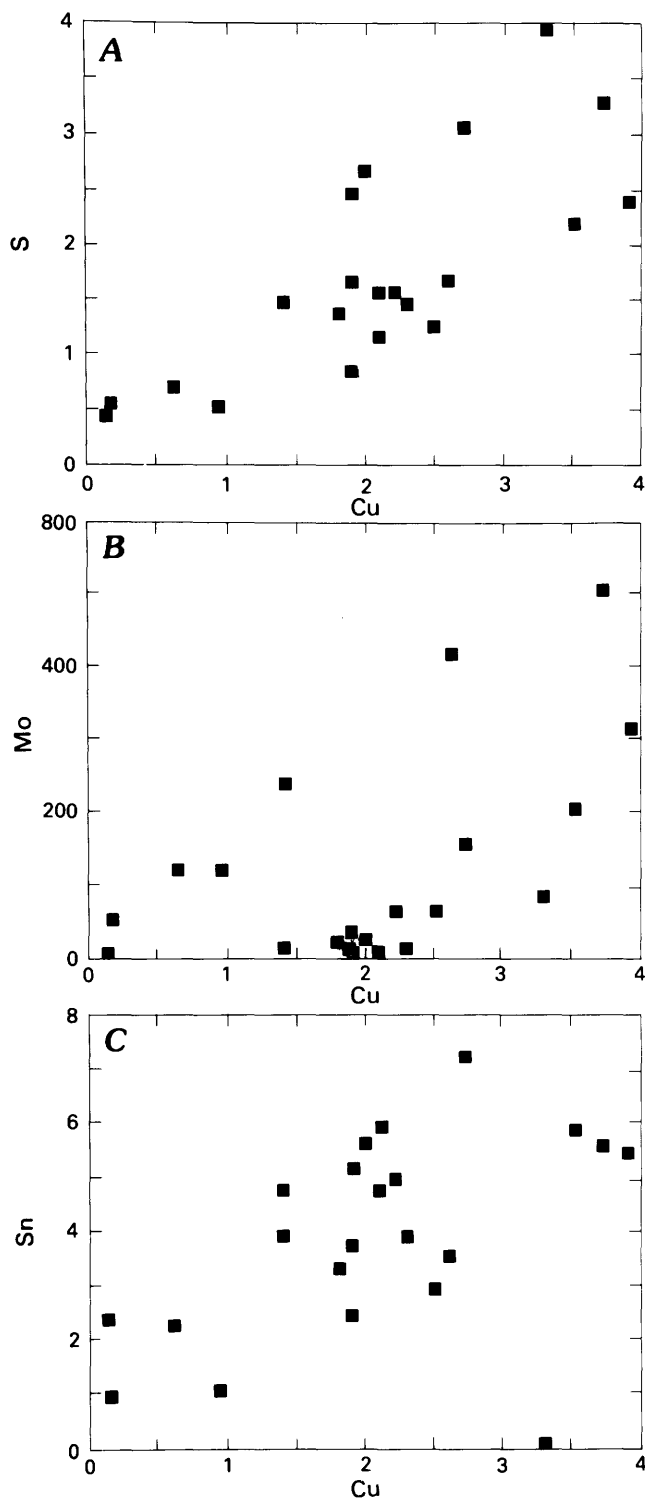
Figure 3. Composition of mineralized bulk rocks at Catheart Mountain: *A*, Wide range in S as a function of Cu; *B*, Variation in Mo and Cu; and *C*, Variation in Sn and Cu. All values are in weight percent. Graphs show all available data on mineralized bulk samples from Catheart Mountain and include samples used in this study.

rocks containing high Cu (fig. 3*B*), and a positive correlation between Sn and Cu (fig. 3*C*).

DEFINITION OF WHITE MICA

The field term "sericite" has previously been used to refer to any white mica and illite, regardless of composition (for example, Meyer and Hemley, 1967). The term "white mica," as used in this paper, includes sericite, illite clay minerals, hydromuscovite, and micas having compositions in the solid solutions between muscovite and paragonite, muscovite and phengite, muscovite and ferrimuscovite, and phengite and ferriphengite. Illites are more silica-rich than muscovite and contain fewer interlayered cations.

Dioctahedral white micas have two-thirds of the octahedral sites filled and have the general formula $XY_2(T_4O_{10})(OH)_2$, where $X=K$, Na, Ca, Rb, Cs, and Ba and is the interlayer cation; $Y=Al$, Mg, Fe^{2+}, Mn, Li, Cr, Ti, and V and comprises the octhaderal cations; and $T=Si$, Al, and Fe^{3+}(?) and fills the tetrahedral sites (Deer and others, 1962). The most important substitutions in naturally occurring muscovite are Fe^{2+} and Mg for Al in the Y-site and Na for K in the X-site (Guidotti and Sassi, 1976). However, other substitutions involving vacancies, other alkali elements, or Ca in the X-site and Ti and Fe^{3+} for Al in the Y-site are also indicated. Solid solution between K and Na gives rise to the well-known muscovite $KAl_2(AlSi_3O_{10})(OH_2)$-paragonite $NaAl_2(AlSi_3O_{10})(OH_2)$ series (Eugster and Yoder, 1955; Eugster and others, 1972).

Muscovite $(KAl_2(AlSi_3)O_{10}(OH)_2)$, ferrimuscovite $(KFe_2^{+3}(AlSi_3)O_{10}(OH)_2)$, and celadonite $(K(Fe^{+3},Al)(Mg,Fe)Si_4O_{10}(OH)_2)$ have complete solid soultion and result from the substitution in the octahedral sites of Mg and Fe^{+2} for Al in the X- and Y-sites (Guidotti and Sassi, 1976). Phengite (Ernst, 1963) refers to Fe- and Mg-rich white micas (Velde, 1965) that obey the substitution $Al^{IV}+Al^{VI}=(Mg,Fe^{+2})^{VI}+Si$, but Guidotti and Sassi (1976) suggest that the term "celadonitic muscovite" be used instead of phengite.

COMPOSITION OF WHITE MICAS AT CATHEART MOUNTAIN

Results of white mica analyses obtained using the electron microprobe are summarized in tables 3 and 4. The lowest sum of the oxides is 90.22 and the highest is 96.88. Many white micas have lower sums than typical muscovites (Deer and others, 1962) and probably represent more hydrated white mica varieties (for example, hydromuscovite and illite). White micas having low total sums tend to have low K in the X-site (all calculations herein were for 11 oxygens), and thus these micas agree with the compositions of hydromuscovite and illite.

White micas from the Catheart Mountain deposit have substantial contents of trioctahedral components and are similar to plutonic muscovites (Anderson and Rowley,

Table 3. Average compositions, standard deviations, and structural formulas of white mica in the potassic alteration zone at Catheart Mountain[1]

Sample	5-680	8-288	36-1142	86-240	28-159	28-214	28-263
			Weight percent				
SiO_2	47.63 ± .17	45.98 ± .62	49.84 ± 1.70	50.50 ± .88	48.36 ± .16	47.18 ± 1.30	48.66 ± 1.99
Al_2O_3	33.58 ± 1.22	32.04 ± 1.05	31.76 ± 1.90	27.17 ± .85	30.50 ± .02	31.51 ± 1.50	33.60 ± 1.30
TiO_2	0.45 ± .49	0.64 ± .15	0.74 ± 0.38	0.04 ± .05	0.59 ± .06	0.51 ± .27	0.74 ± .32
FeO	2.28 ± .87	2.54 ± .28	1.86 ± .46	2.08 ± .28	1.67 ± .45	1.89 ± .61	2.26 ± .17
MnO	0.04 ± .01	0	0.03 ± .01	0.05 ± .01	0	0.04 ± .01	0
MgO	0.97 ± .10	1.71 ± .32	1.51 ± .51	3.14 ± .37	1.95 ± .04	2.68 ± 1.40	1.29 ± .35
CaO	0	0	0.02 ± .02	0	0.03 ± .02	0	0
Na_2O	0.29 ± .05	0.26 ± .04	0.26 ± .05	0.01 ± .01	0.18 ± .05	0.24 ± .11	0.29 ± .14
K_2O	8.46 ± .30	9.87 ± .27	9.75 ± .31	8.03 ± .34	9.00 ± .08	9.31 ± .14	6.63 ± .09
Cl	0	0.06 ± .02	0.01 ± .02	0.02 ± .02	0.03 ± .01	0.02 ± .02	0.01 ± .02
F	0.09 ± .02	0.18 ± .07	0.24 ± .07	0.21 ± .04	0.32 ± .01	0.30 ± .12	0.28 ± .20
Subtotal	93.79	93.28	96.02	91.25	92.63	93.68	93.76
O=Cl,F	.04	.09	.10	.09	.14	.13	.12
Total	93.75	93.19	95.92	91.16	92.49	93.55	93.64
			Number of ions per 11 oxygens				
Si	3.19	3.15	3.26	3.46	3.29	3.21	3.22
Al^{IV}	0.81	0.85	0.74	0.54	0.71	0.79	0.78
Al^{VI}	1.84	1.72	1.74	1.65	1.73	1.70	1.84
Ti	0.02	0.03	0.04	0	0.03	0.03	0.04
Fe	0.13	0.14	0.10	0.12	0.09	0.11	0.13
Mn	0	0	0	0	0	0	0
Mg	0.10	0.17	0.17	0.32	0.20	0.27	0.13
Ca	0	0	0	0	0	0	0
Na	0.04	0.04	0.03	0	0.02	0.03	0.04
K	0.72	0.86	0.82	0.70	0.78	0.81	0.56
Fe/(Fe+Mg)	0.57	0.45	0.37	0.27	0.32	0.29	0.50

[1] Total iron as FeO

1981; Miller and others, 1981) because of their high total Fe+Mg, high Ti, and excess Si. Thus, the micas contain an excess of octahedral cations (Fe, Mg, Mn) compared with the complement of Al in octahedral positions (Al octahedral deficiency: $2-Al^{VI}$). Micas from the unmineralized and mineralized rock groups show substantial compositional overlap (fig. 4) despite significant bulk chemical differences. Plutonic muscovites also show significant variation in composition which Miller and others (1981) could not relate directly to the coexisting phase assemblage. They attributed this variation to the latest stage at which the mica reached equilibrium.

In contrast to the sericites studied by Guilbert (1980) and Guilbert and Schaefer (1978) in porphyry copper deposits from Arizona, the compositions of white micas at Catheart Mountain do not show consistent variations in Mg/(Mg+Fe) across the regional hydrothermal zonation, probably because the white mica composition depends on the composition of the precursor mineral (Ayuso, 1983). In the porphyries from Arizona, Guilbert (1980) demonstrated that aluminum diminished outward from the phyllic to phyllic-argillic zones, but at Catheart Mountain this variation is more random and inconsistent. Similarly, the Si/Al^{IV} ratio does not show a progressive

variation compared with micas from the Arizona porphyry copper deposits. In both the Arizona deposits and the white micas at Catheart Mountain, however, the changes in Fe, Mg, and Ti in the octahedral site are the most informative and suggest the control of coupled substitutions with Al.

White micas containing high Ti in the Catheart Mountain hydrothermal system might have crystallized at higher temperatures than micas containing low Ti. This suggestion agrees with Guidotti's (1978a) demonstration of Ti enrichment in muscovites at high metamorphic grades, and with the general high Ti content of primary, igneous muscovite, as suggested by Anderson and Rowley (1981) and by Miller and others (1981). Other possible but qualitative indicators of temperature in micas from a hydrothermal system include the Fe/(Fe+Mg) ratio and the Na/(Na+K) ratio (paragonite substitution). The range in Na/(Na+K) ratio in the Catheart Mountain white micas is from 0 to 0.67, with the change in K being the dominant factor (table 3). The Na/(Na+K) ratio is inversely correlated with the calculated Si content in the formula (a measure of the celadonite substitution) for white micas from Catheart Mountain (fig. 5).

In the Catheart Mountain deposit, the most aluminous micas are also the most enriched in magnesium. In most of these micas, the octahedral substitution of Mg for Al^{VI} is regular and contrasts with the more dispersed variation of Fe. Variation in intrazonal mica composition is significant, however, and the composition does not change systematically from the weakest regional alteration zone to the strongest regional alteration zone.

Regular Variations in White Mica Composition

The composition of white mica in the Catheart Mountain deposit changes regularly, progressively, and consistently according to the control imposed by crystal chemical substitutions. Among the major substitution schemes for ideal muscovite are (1) the solid-solution series with celadonite (Velde, 1967, 1972) according to $Al^{IV}+Al^{VI}=Si+(Fe,Mg)$, (2) the substitution Si+vacancy $(XII)=Al^{IV}+(K+Na)$, which represents a solid solution between pyrophyllite and muscovite (McDowell and Elders, 1980), and (3) the reaction $2-Al^{VI}=Mg+Ti$, which has been suggested as a possible control for Ti enrichment in white micas (see, for example, Guidotti 1973, 1978a,b; Anderson and Rowley, 1981).

White micas from individual hydrothermal alteration zones in the Catheart Mountain deposit have variable compositions that lack a direct correlation with their position within the regional alteration zonation (figs. 4–8). This diversity of composition conforms to the substitutional schemes but results in a wide compositional range

for micas within individual regional hydrothermal zones, as exemplified by the variation in celadonite content (fig. 5) of white micas in the regional potassic zone. Similarly, white micas from the sericitic alteration zone show a wide range in aluminum content, and they generally overlap the range of white micas in the potassic zone. Thus, despite the overall regional systematic change in aluminum content, white micas from individual regional alteration zones are not systematically grouped. This probably reflects that hydrothermal alteration events produce superimposed mineral assemblages, and that in Catheart Mountain there are veins containing quartz-sericite alteration within the regional zone designated as part of the potassic alteration.

Beaufort and Meunier (1983) found that around phyllic veins (sericitic alteration) of the Sibert prophyry, the compositions of white micas were mainly restricted to the muscovite-illite-phengite solid solution. They suggested that white micas that are poorer in Fe, Mg, and Ti occurred in the alteration zone that attained the highest temperature, and that more celadonitic micas were in areas that might have crystallized at lower temperatures. This concept of celadonitic mica stability was initially suggested by Velde (1965) and agrees with McDowell and Elders (1980), who demonstrated a change in white mica composition from celadonite-rich micas toward more ideal muscovite with increasing temperature. Results for the Catheart Mountain white micas are consistent with these studies, and the speculation is that the more aluminous white micas may indicate higher temperatures than the more celadonitic white micas.

The solid solution between muscovite and pyrophyllite as expressed by Si+vacancy $XII=Al^{IV}+(Na+K)$ also may have contributed to the compositional variation of the white micas of the Catheart Mountain deposit (fig. 7). This substitution, however, is not clearly demonstrated here because of the wide variation of Al^{IV} and interlayer cations. As in the celadonitic substitution, the composition of white micas in each alteration zone varies in the same way the entire hydrothermal system varies.

The variation of Ti in the white mica of the Catheart Mountain deposit might reflect the control imposed by a substitution of the type $2Al^{VI}=Mg+Ti$ (fig. 8). According to Guidotti (1978b), this reaction is probably the most important control of Ti in muscovite, and for the Catheart Mountain white micas, no reasonable alternative exists. Substitutions of the type $Si+Al^{VI}=Ti+Al^{IV}$ and $Ti=2(Mg,Fe)$ do not appear to be significant.

DISCUSSION

Relation of White Micas and Bulk Composition

The compositions of white micas in the mineralized rocks of the Catheart Mountain deposit show a broad,

Table 4. Average compositions, standard deviations, and structural formulas of white mica

Sample	4-250	4-280	4-300	4-350	5-740	12-370	15-124
							Weight
SiO_2 ----	48.87 ± 1.02	49.70 ± .58	48.47 ± .09	46.61 ± 1.14	46.03 ± .18	49.96 ± 1.10	49.00 ± .65
Al_2O_3 ---	31.20 ± .47	31.25 ± .69	30.47 ± 1.11	35.74 ± 2.58	30.96 ± 2.70	31.64 ± .82	30.77 ± .90
TiO_2 ----	0.25 ± .11	0.28 ± .12	0.51 ± .18	0.59 ± 1.20	0.41 ± .22	0.30 ± .21	0.15 ± .95
FeO -----	2.26 ± .16	2.68 ± .49	2.23 ± .51	2.13 ± .22	3.86 ± 1.20	1.31 ± .27	2.41 ± .11
MnO -----	0	0	0.04 ± .01	0	0.04 ± .02	0.04 ± .02	0.01 ± .01
MgO -----	0.48 ± .19	2.29 ± .74	2.49 ± .48	0	1.68 ± .66	1.91 ± .37	1.91 ± .32
CaO -----	0	0	0	0	0	0.01 ± .01	0.04 ± .03
Na_2O ----	0.10 ± .03	0.16 ± .02	0.17 ± .15	0.29 ± .03	0.15 ± .08	0.22 ± .07	0.34 ± .05
K_2O -----	6.61 ± .15	9.80 ± .33	9.31 ± .22	7.09 ± .29	8.29 ± .33	8.91 ± .95	10.04 ± .34
Cl ------	0.01 ± .02	0.01 ± .02	0.02 ± .02	0.01 ± .02	0	0.01 ± .01	0.01 ± .01
F -------	0.76 ± .17	0.33 ± .03	0.27 ± .10	0.25 ± .08	0.11 ± .06	0.17 ± .02	0.11 ± .04
	90.54	96.50	93.98	92.71	91.53	94.48	94.79
$O=Cl, F$	.32	.13	.11	.11	.05	.07	.05
Total	90.22	96.37	93.87	92.60	91.48	94.41	94.74
							Number of ions
Si -------	3.35	3.27	3.27	3.13	3.19	3.31	3.28
Al^{IV} -----	0.65	0.73	0.73	0.87	0.81	0.69	0.72
Al^{VI} -----	1.88	1.69	1.68	1.96	1.72	1.78	1.71
Ti -------	0.01	0.01	0.03	0.03	0.02	0.02	0.01
Fe -------	0.13	0.15	0.13	0.12	0.23	0.07	0.12
Mn -------	0	0	0	0	0	0	0
Mg -------	0.05	0.22	0.25	0	0.17	0.19	0.19
Ca -------	0	0	0	0	0	0	0
Na -------	0.01	0.02	0.02	0.04	0.02	0.03	0.04
K --------	0.58	0.82	0.80	0.61	0.74	0.75	0.86
Fe/(Fe+Mg)	0.72	0.41	0.34	1.0	0.58	0.27	0.39

[1] Total iron as FeO

positive correlation with the copper (fig. 9*A*) and sulfur (fig. 9*B*) content of the whole rock, so that the most celadonitic micas are found in rocks containing lower amounts of base metals. With the exception of SiO_2 of the whole rock, the major oxides are not clearly correlated with white mica composition. The trace elements, including the rare-earth elements, are also uncorrelated.

Rock samples classified as mineralized because of their numerous fractures and high Cu content contain a population of white micas having progressively higher total aluminum contents (fig. 9*A*). This relation may be a useful indicator of compositional gradients in the Catheart Mountain hydrothermal system and suggests that the events responsible for mineralization may also control the composition of the coexisting white micas in the rocks containing high Cu. Unmineralized rocks containing fewer fractures and lower abundance of sulfides show no correlation between Cu in the whole rocks and total Al in the white micas. White mica compositions exhibit no consistent correlation with molybdenum content of the whole rock because of the erratic distribution of molybdenite in the drill core.

Sulfur content of the whole rock is positively correlated with white mica composition (fig. 9*B*). This relation gives strong evidence for reconstitution of white micas during the massive increase in sulfur during alteration of the whole rock. Although the geometric position of quartz-sericite rocks in porphyry copper systems is intermediate to potassic and propylitic rocks (Lowell and Guilbert, 1970; Rose, 1970; Guilbert and Lowell, 1974), there is

in the quartz sericite, sericitic, and propylitic alteration zones at Catheart Mountain[1]

	SERICITE					— SERICITIC —	— PROPYLITIC —	
42-289	88-452	96-110	96-310	6-200	32-642	86-186	31-160	39-463
percent								
47.37 ± .56	47.50 ± 1.00	46.67 ± .06	45.67 ± 1.21	46.70 ± .58	50.40 ± .70	50.21 ± 1.30	46.91 ± .73	51.00 ± .29
33.78 ± .82	32.67 ± .31	32.56 ± 1.30	32.95 ± 1.30	34.10 ± .11	30.16 ± 1.30	29.04 ± 1.10	32.78 ± .86	29.90 ± .40
0.51 ± .09	0.31 ± .05	0.55 ± .09	0.80 ± .58	0.13 ± .02	0.20 ± .10	0.24 ± .10	0.31 ± .23	0.11 ± .04
1.71 ± .51	1.44 ± .02	2.36 ± .93	1.59 ± .48	2.66 ± .16	1.49 ± .44	2.10 ± .23	1.76 ± .70	0.83 ± .09
0.04 ± .01	0	0.01 ± .01	0.04 ± .01	1.02 ± .06	0.05 ± .01	0.03 ± .03	0.04 ± .01	0.09 ± .02
1.16 ± .06	1.40 ± .14	1.64 ± 1.10	1.29 ± .31	1.35 ± .52	3.15 ± .65	2.59 ± .10	1.56 ± .37	3.35 ± .38
0	0	0	0	0	0	0.01 ± .01	0	0.02 ± .02
0.03 ± .03	0.44 ± .04	0.38 ± .12	0.29 ± .04	0.43 ± .06	0.06 ± .01	0.01 ± .07	0.29 ± .06	0.08 ± .02
8.57 ± .03	9.75 ± 1.40	8.60 ± .21	9.23 ± .53	10.39 ± .49	9.55 ± .17	8.96 ± .34	9.76 ± .30	8.74 ± .05
0	0.02 ± .01	0.02 ± .02	0.01 ± .01	0.01 ± .01	0	0.02 ± .01	0.01 ± .01	0.02 ± .01
0.17 ± .02	0.16 ± .04	0.20 ± .09	0.06 ± .02	0.16 ± .08	0.46 ± .02	0.37 ± .06	0.15 ± .04	0.57 ± .06
93.34	93.69	92.99	91.93	96.95	95.52	93.58	93.57	94.71
.07	.07	.08	.03	.07	.19	.16	.06	.24
93.27	93.62	92.91	91.90	96.88	95.33	93.42	93.51	94.47
per 11 oxygens								
3.17	3.20	3.17	3.14	3.12	3.33	3.37	3.17	3.37
0.83	0.81	0.83	0.59	0.88	0.67	0.63	0.83	0.63
1.84	1.80	1.77	1.80	1.80	1.68	1.68	1.79	1.70
0.02	0.02	0.03	0.04	0.01	0.01	0.06	0.02	0.01
0.10	0.08	0.14	0.09	0.15	0.08	0.12	0.10	0.05
0	0	0	0	0	0	0	0	0.01
0.11	0.14	0.17	0.13	0.10	0.31	0.26	0.16	0.33
0	0	0	0	0	0	0	0	0
0.04	0.06	0.05	0.04	0.06	0.01	0.01	0.04	0.01
0.73	0.84	0.74	0.81	0.89	0.81	0.77	0.84	0.74
0.48	0.36	0.45	0.41	0.60	0.21	0.32	0.38	0.13

much evidence suggesting that alteration zones did not form contemporaneously (Meyer and Hemley, 1967; Gustafson, 1978; Titley and Beane, 1981; Titley, 1982) and that quartz-sericite alteration is a relatively late, feldspar-destructive event in which a large amount of pyrite is deposited. Thus, the broad correlation between white mica composition and the sulfur content of the whole rock suggests that the white micas were probably reequilibrated late in the evolution of the Catheart Mountain deposit.

Aluminous White Micas in Mineralized Rocks

White micas are potential monitors of the physio-chemical parameters during crystallization, as reflected by extensive solid solution in the tetrahedral and octahedral sites. In the Catheart Mountain deposit, the fact that white micas change compositions but are not grouped in the regional hydrothermal alteration zones might be explained as follows: (1) consistent and progressive variations in mica composition within the system were undetected by microprobe analysis; (2) compositional variations were removed by subsequent regional metamorphic effects; and (3) mica compositions reflect the changing conditions during mineralization, including the strong overprint and superposition of mineral assemblages during the waning stages of hydrothermal activity, possibly involving massive fluid influx as suggested in other porphyry copper systems.

Additional components in the mica structure such as Li, Rb, Ba, Fe^{+3}, and H_2O were not analyzed in this
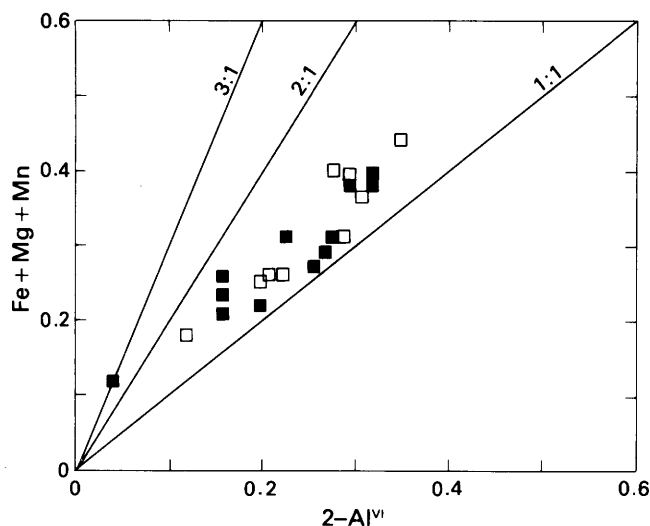
Figure 4. Change in Fe+Mg+Mn as a function of 2-Al^{VI} in the white micas from Catheart Mountain. Samples plot between the 1:1 and 3:1 lines, suggesting an excess of octahedral cations (Fe+Mg+Mn) compared with octahedral aluminum in the formula. Solid squares are white micas from mineralized rocks, and open squares are white micas from unmineralized rocks. Values are number of ions per 11 oxygens.
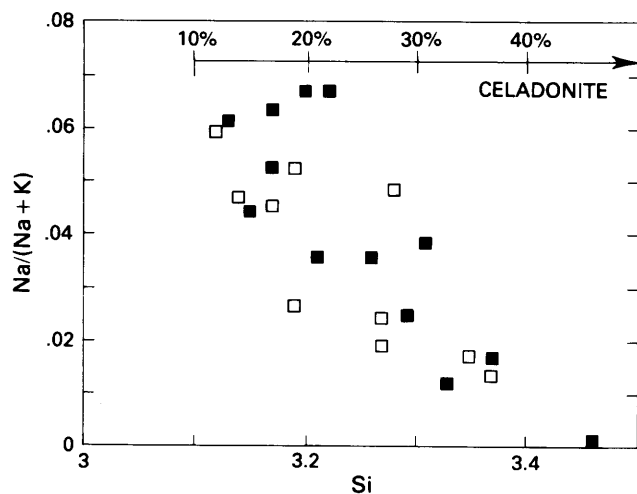

Figure 6. Distribution of Al^{IV}+Al^{VI} and Si+(Mg+Fe) in the white micas from mineralized rocks (solid squares) and unmineralized rocks (open squares) from Catheart Mountain. Trend shown connects ideal muscovite to celadonite. Values are number of ions per 11 oxygens.

Figure 5. Distribution of Na/(Na+K) and Si in the white micas from mineralized rocks (solid squares) and unmineralized rocks (open squares) from Catheart Mountain. Arrow shows increasing percentages of celadonitic component. Values are number of ions per 11 oxygens.

Figure 7. Distribution of Si and Al^{IV}+(Na+K) in the white micas from mineralized rocks (solid squares) and unmineralized rocks (open squares) from Catheart Mountain. Values are number of ions per 11 oxygens.

study, and they might show strong variations correlated with their position in the regional hydrothermal system. For example, barian muscovite is a major constitutent in the Alberfeldy Ba-Zn mineralization (Fortey and Beddoe-Stephens, 1982), and variations in Ba might be useful indicators of the mineralized area in porphyry systems.

White mica compositions in the Catheart Mountain deposit probably do not reflect intense reequilibrium
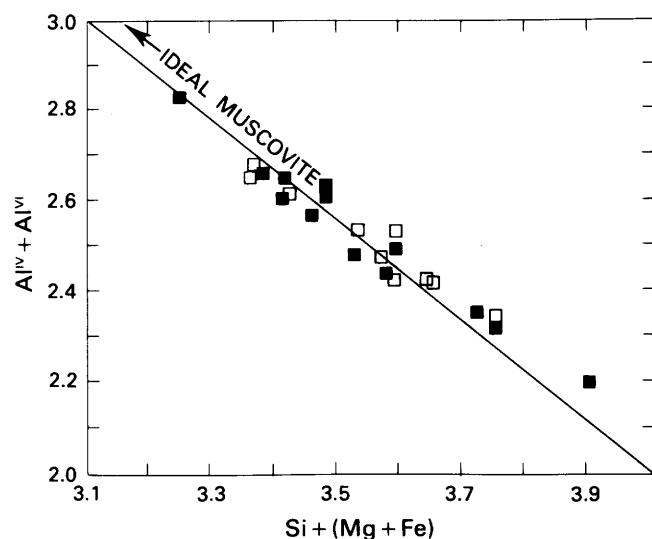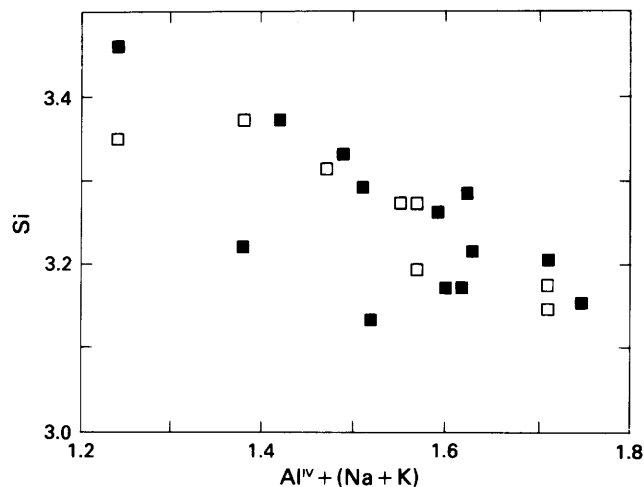
resulting from Acadian metamorphism. Although mica compositions might have been affected by Acadian events, the general correlation between mineralized rocks and their white mica compositions probably would not have been spared during massive, regional metamorphic equilibration. If a strong overprint existed, white mica compositions probably would reflect the subsequent metamorphic event and their compositions should not be correlated with the Cu contents of the rocks.

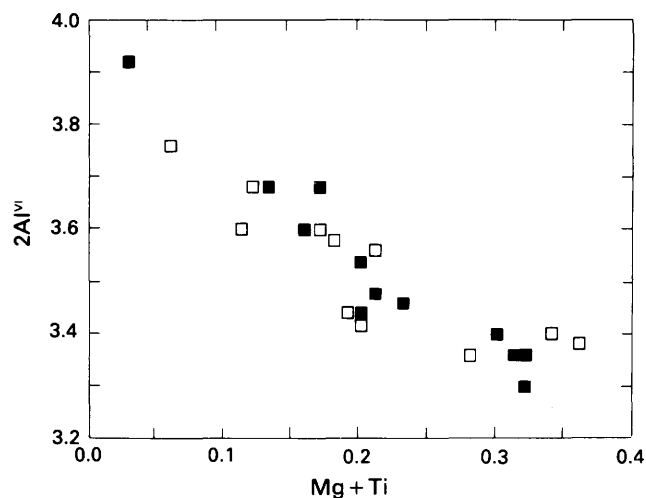Catheart Mountain rocks near the interface between the potassic and quartz-sericite regional alteration zones

Figure 8. Distribution of $2Al^{VI}$ and Mg+Ti in the white micas from mineralized rocks (solid squares) and unmineralized rocks (open squares) from Catheart Mountain. Values are number of ions per 11 oxygens.

contain the highest Cu and Mo contents, but the white micas in these rocks are not systematically distinct in composition from the white micas in rocks from milder regional alteration zones and having lower contents of Cu and Mo. The preferred explanation for this is that mica compositions in the different veins and fractures were locally controlled by changes in P_{H_2O} and by the composition of the evolving fluid phase as a result of thermal collapse of the hydrothermal system. Thus, regional determinations of metal content and intensity of alteration on a zonal basis are not directly equivalent to the chemical changes in the small chemical domains represented by single veins from drill cores used in this study.

White mica composition and bulk-metal content at the Catheart Mountain deposit might best be related because the micas formed from mineralizing hydrothermal fluids of predominantly magmatic origin which carried the base-metal complexes. In contrast, white micas from the unmineralized rock group are generally unrelated to the Cu content of the rock because these micas perhaps formed after the main period of mineralization, and from different fluids than those that produced the influx of metals and white micas associated with the main stage of mineralization. These fluids might have been predominantly of meteoric origin, reflecting the progressive thermal collapse during the waning stages of the hydrothermal system. Such temporal evolution of fluids during the mineralizing process would be in accord with studies by Sheppard and others (1969, 1971). Thus, significant differences in mica composition might be a result of subsequent reequilibration of previously formed white micas, followed by and modified as a result of the formation of newly crystallized white micas during the waning stages of the hydrothermal system.
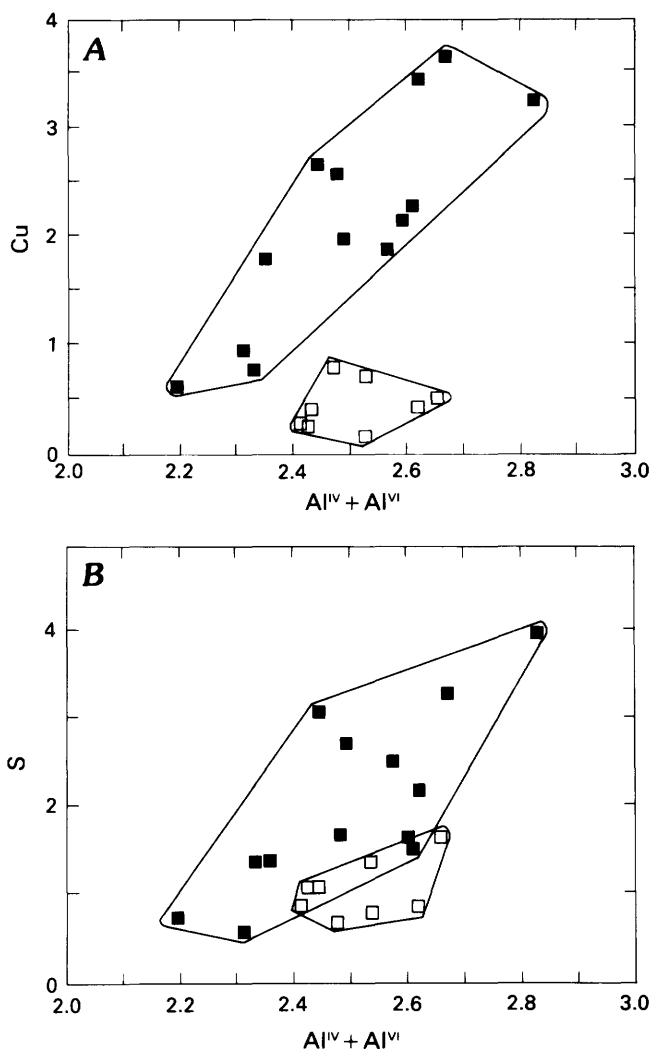

Figure 9. *A*, Change in Cu content (in weight percent) of the bulk rock and the $Al^{IV}+Al^{VI}$ (ions per 11 oxygens) in the white micas coexisting with sulfides. *B*, Distribution of S (in weight percent) in the bulk rock and the $Al^{IV}+Al^{VI}$ (ions per 11 oxygens) in the white micas coexisting with sulfides. Mineralized samples are shown as solid squares, and unmineralized samples as open squares.

The most likely explanation of the variability in mica composition within each of the regional alteration zones is that white micas reflect local bulk-compositional differences retained in the host rock. In fact, overprinting of younger mineral assemblages on older assemblages has been documented in many hydrothermal systems, including the Bingham (Utah) (Peters and others, 1966), the Silver Bell (Arizona) (Graybeal, 1982), and the Sierrita (Arizona) (West and Aiken, 1982). Because of the complex superposition of fracturing and vein mineral assemblages in many porphyry systems, including Catheart Mountain, during the waning stages of alteration, the host rock is composed of microdomains exhibiting a range in bulk composition. Thus, because of the variation in min-

eralogy, subsequent hydrothermal reactions also must show strong local control over the occurrence, stability, and composition of the resulting minerals.

The broad correlation between white mica composition and base metal content of the rocks at Catheart Mountain suggests that white micas can be used as general indicators of mineralization gradients. Although rocks that are not intensely fractured and do not contain abundant disseminated sulfides also contain white micas and have compositions broadly similar to those in the mineralized rocks, the white micas remain uncorrelated with the metal content of the rocks. The comparison of compositional trends in the white micas and the bulk rocks at Catheart Mountain readily distinguishes the positive trend between the population of white micas in mineralized rocks from white micas in rocks containing lower amounts of Cu and Mo. By applying this distinction, highly mineralized zones may be found in systems that exhibit less obvious petrographic features associated with mineralization.

SUMMARY

1. White micas from intensely fractured and hydrothermally altered rocks containing abundant disseminated sulfides show a broad positive correlation between their aluminum content and the Cu content of the whole rock.

2. The compositional gradients in the white micas are not clearly related to their position in the regional hydrothermal zonation.

3. Compositional variability of the white micas is best explained by superposition and overprinting of fluids during mineralization and during the last stages of hydrothermal alteration.

4. The general correlation between white mica composition and base metal content in the mineralized rocks at Catheart Mountain suggests that white mica composition could be a useful indicator of the mineralization gradient.

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