

MINERALOGY AND PARAGENESIS OF THE COTOPAXI, COLORADO, Cu-Zn SKARN DEPOSIT

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ABSTRACT

A group of similar Precambrian base-metal deposits crops out in south-central Colorado. At Cotopaxi mineralization is confined to a small part of a large xenolith of high grade metamorphic rocks that is included in medium- to fine-grained granite. The deposit is deformed by both Precambrian (?) and Laramide faulting. Mineralization is mainly confined to amphibolite, but biotite gneiss and nodular sillimanite schist also are mineralized. Both biotite gneiss and nodular sillimanite schist are regional rock types; the mineralized amphibolite is not a regional rock type and may have formed during the first stage of the mineralization process. The overall process of formation, although complex, can be separated into the following distinct stages: amphibolite formation, almost exclusively confined to the formation of silicate minerals; pegmatoid stage, mainly the formation of silicate minerals, but some oxides, aluminates, tungstates; ore deposition, successive formation of sulfides of iron, zinc, copper, and lead; retrograde mineralization, conversion of anhydrous to hydrous silicates and the alteration of pyrrhotite to pyrite-magnetite-marcasite; and surficial weathering. During each stage mineralogic changes took place with a striking conservation of material, *i.e.*, reorganization of material already present was a very important process during the formation of the deposit.

INTRODUCTION

Nearly all metallic mineralization in Colorado is associated with igneous rocks and structures of Laramide or late-Tertiary age. However, a group of geologically and mineralogically well-defined but little-studied ore deposits in south-central Colorado is Precambrian in age. These deposits (Fig. 1) occur in high-grade regionally metamorphosed rocks in close proximity to Precambrian granite. The ore is predominantly sphalerite, chalcopyrite, galena and pyrite; it contains only traces of silver and gold. The deposits are readily identified by the intimate association of base-metal sulfide minerals with a complex coarse-grained distinctive silicate gangue, and by the conformation of the ore body to the enclosing metamorphic structures.

Included among these deposits are the following:

- Chaffee County
 - Cleora district prospects (Fig. 1, No. 2)
 - Sedalia mine (Fig. 1, No. 1)
 - Turrett district (Fig. 1, No. 7)
 - Copper King mine
 - Independence mine
- Custer County
 - Marion mine (Fig. 1, No. 6)
- Fremont County
 - Cotopaxi mine (Fig. 1, No. 3)

Isabel mine (Fig. 1, No. 5)
 Copper Boy mine (Fig. 1, No. 8)
 Park County
 Betty (Lone Chimney) mine (Fig. 1, No. 4)

Of the properties listed above only the Sedalia mine has had substantial production. Lindgren (1908) described it as one of the few important copper mines in Colorado.

A reconnaissance of all the deposits indicated that the Cotopaxi mine is representative of this group, and a detailed investigation of this deposit constitutes the basis of this paper. A study of the Cotopaxi deposit is of

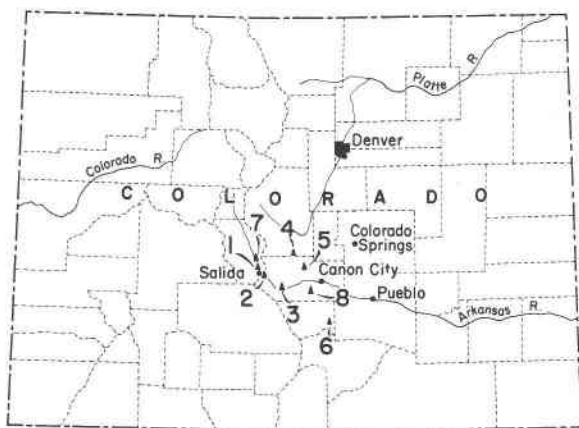


FIG. 1. Index map of Colorado showing the location of eight Precambrian mineral deposits.

value because it adds to the fragmentary knowledge of Precambrian mineralization in Colorado. More importantly, due to the excellent exposures, small size and compact relations of the ore body, and the accessibility of much of the underground workings, such a study offers a rare opportunity for a detailed mineralogic and geologic investigation of deep-seated, high temperature mineralization.

ACKNOWLEDGEMENTS

Mr. P. G. Owens, the present mine owner, allowed free inspection of the property and furnished all available maps and records concerning the previous operation of the mine. Without the competent aid of my colleague, Mr. Donald H. Poole, the plane table map of the mine and its environs could not have been made. Drs. V. J. Hurst and L. D. Ramspott read the manuscript and made a number of helpful suggestions. The

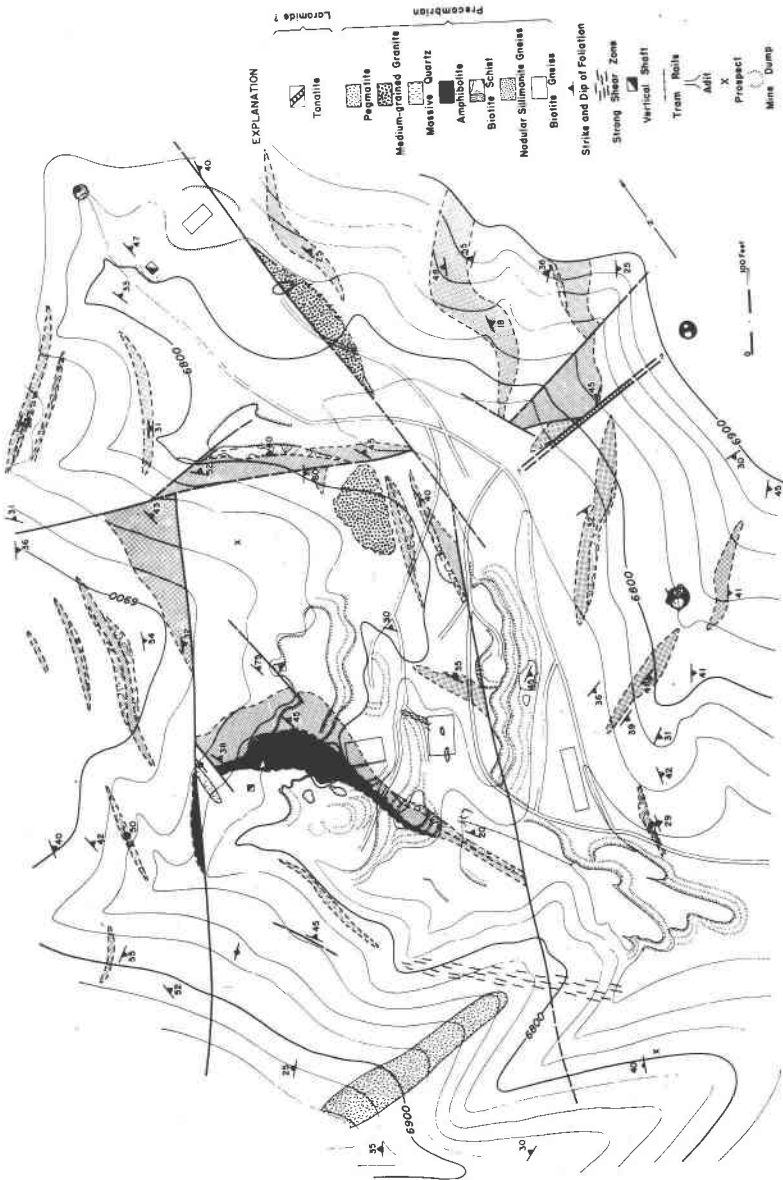


FIG. 2. Geologic map of Cotopaxi Mine area, Fremont County, Colorado.

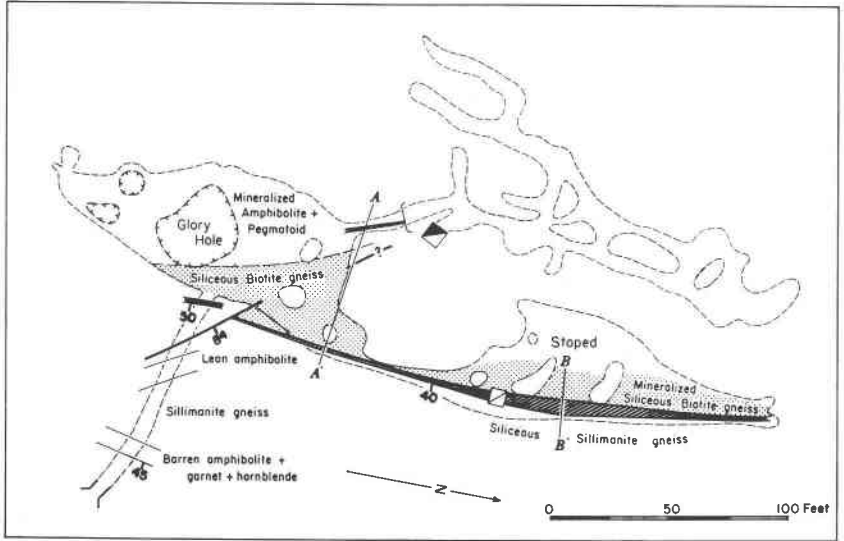


FIG. 3. Plan of upper adit (elev. \approx 6780) Cotopaxi Mine, Colorado.

writer first visited the deposit with Dr. E. Wm. Heinrich in the summer of 1958 and has since examined dozens of Precambrian complex pegmatites; lime silicate, tungsten-bearing "skarns"; and deposits of the Cotopaxi type in south-central Colorado. The National Science Foundation generously supported all phases of the investigation.

REGIONAL GEOLOGY

The Precambrian rocks of central Colorado consist principally of a thick series of high-grade schists and gneisses (Idaho Springs formation) intruded by a succession of granite (Pikes Peak?) and closely related

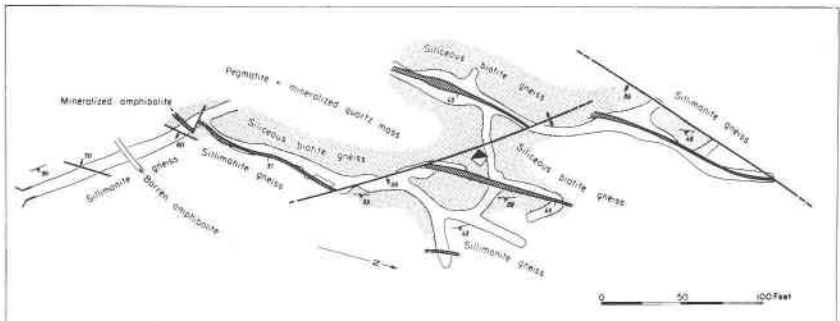


FIG. 4. Plan of lower adit (elev. \approx 6750) Cotopaxi Mine, Colorado.

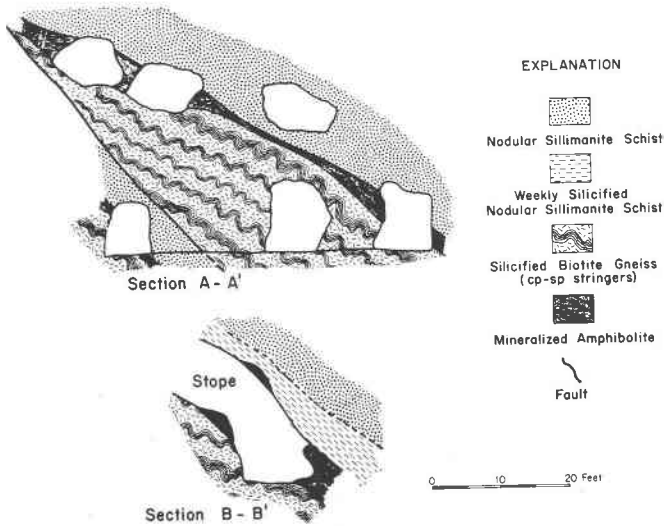


FIG. 5. Sections along upper adit, Cotopaxi Mine, Colorado.

rocks. The metamorphic units near Cotopaxi occur as large, generally concordant, migmatized and pegmatized xenoliths enclosed in granite (Salotti, 1960). Generally the granite shows good foliation parallel to the foliation of the metamorphic xenoliths, with aligned biotite responsible for the structure. The general north trending parallelism of the foliation in the metamorphic rocks and the structure in the granite suggest that the area was a part of the north-striking Front Range anticlinorium postulated by Lovering and Goddard (1950).

The granite is a monotonous, coarse-grained, locally porphyritic, red-



FIG. 6. Generalized paragenetic diagram for amphibolitic pegmatoid.

dish-pink, microcline-quartz-biotite typical Pikes Peak granite; however, several local distinctive variant facies can be grouped as either strongly gneissoid, biotite-poor, allanite-bearing, or aplitic.

The metamorphic rocks show complex folding in which foliation and mineralogic banding apparently parallel the original bedding in most exposures. Included among the small-scale structures are those features peculiar to deeply eroded crystalline complexes, *i.e.*, pygmatic folds, boudins, gradational contacts, augen, schlieren, localization of coarse-

Primary Minerals

Scheelite (peg. stage)
Molybdenite (minor)
Magnetite (euhedral)
Pyrite
Pyrrhotite
Sphalerite
Chalcopyrite
Galena

Secondary Minerals

Amphibolite to Biotite-garnet
Epidote Minerals
Albite
Pyrrhotite to Pyrite + Magnetite + Marcasite
Magnetite (anhedral)
Serpentine
Chlorite
Sericitic

Surficial Alteration

Anglesite
Azurite
Chrysocolla
Covellite
Cuprite
Hematite + Hydrous Iron Oxides
Malachite
Strontionite

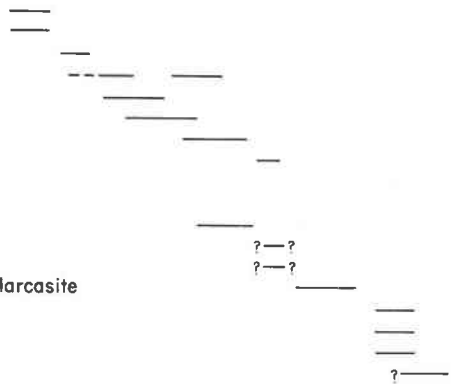


FIG. 7. Paragenesis of the ore minerals, Cotopaxi, Colorado.

grained quartz and/or lime-silicate rock at the apexes of folds, and other evidences of plastic deformation.

Late Laramide deformation in Fremont County has developed large, north trending block faults. The block faults are slightly displaced in the area of the Cotopaxi mine by east-west striking vertical faults. A large number of subsidiary faults and shear zones accompany the major faults. The strike of the north-south faults in general coincides with the north-south trend of the Precambrian foliation and fold axes.

PETROLOGY

Rock Descriptions. In deposits of this type, the silicate and oxide minerals generated by metasomatism and reorganization during the formation of

the "skarn-like" pegmatoid are generally more indicative of the depositional environment than are the subsequent ore minerals. A study of the gangue minerals has a further instructive advantage in that these species are much less likely to reflect post-depositional responses to a changing environment, *i.e.*, crystallographic inversions, redistribution of trace elements, complete unmixing, etc. than are many sulfide minerals. With this in mind, a description of the unmineralized equivalents of the high grade metamorphic rocks that comprise the gangue of the Cotopaxi deposit is in order if the successive mineralogical, chemical, and textural transitions that occurred during mineralization are to be reconstructed.

Not all rock types have shared equally in the mineralization, but all are involved to some extent. The major rock units present in the Cotopaxi area are:

(1) biotite schist, (2) amphibolite-hornblende gneiss, (3) nodular sillimanite schist, (4) biotite gneiss, and (5) lime-silicate rocks. Post-ore rock units include: (1) granite, (2) pegmatite and (3) tonalite (Laramide?).

Biotite schist.

1. *General Description:* Biotite schist is not a common rock type in the mine area. It is closely associated with sillimanite-bearing schist, generally as a thin border separating sillimanite schist and biotite gneiss. The schistosity is pronounced and the foliation conforms closely to the enclosing rocks.

2. *Petrography:*

Biotite forms discontinuous trains of well oriented flakes. Quartz and oligoclase are the other essential minerals. The rock is uniformly fine-grained with all essential and accessory minerals rarely greater than one millimeter in diameter. Accessory minerals include magnetite, sphene, garnet, microcline and apatite. Alteration products include sericite, hematite, limonite, leucoxene, and chlorite-magnetite.

Nodular sillimanite schist.

1. *General Description:* Nodular sillimanite schist occurs as separated lenses and irregular masses interlayered with biotite gneiss, amphibolite and hornblende gneiss, and commonly possesses a "selvage" of biotite schist. Minerals visible on fresh surfaces are quartz, biotite, sillimanite and muscovite. There is a marked tendency for sillimanite, minor quartz and later muscovite to be concentrated into ellipsoidal nodules which are flattened parallel to the foliation and range in size from 2 millimeters to 4 centimeters. Biotite and quartz are the essential matrix minerals. The contrast of the speckled dark gray matrix surrounding the gray-white nodules imparts a distinct augen texture to the coarser facies of the rock. The rock has a singular weathering pattern; sillimanite-rich nodules pro-

trude above the weathered surface and impart a pseudoconglomeratic appearance to the rock (Fig. 8A).

2. Petrography:

Biotite is principally responsible for the schistose texture. Sillimanite generally lies parallel to biotite and contributes to the foliation. However, where sillimanite is present as

TABLE 1. MODES OF REPRESENTATIVE UNMINERALIZED ROCKS NEAR THE COTOPAXI MINE, FREMONT COUNTY, COLORADO

	(1)	(2)	(3)	(4)	(5)	(6)
Hornblende	28.7	50.7				
Plagioclase	9.7 (Ab ₈₅)	26.8 (Ab ₅₀)	10.5 (Ab ₈₁)		26.0 (Ab ₇₅)	28.2 (Ab ₈₉)
Microcline			32.2			31.6
Quartz	16.5	4.2	42.0	56.1	47.8	30.6
Biotite	7.9		11.5	12.2	22.8	5.3
Muscovite				tr		2.2
Magnetite	5.7				1.3	
Diopside		7.5				
Sphene		4.5				
Garnet			3.8		1.1	
Sillimanite				29.2		
Epidote Group	30.0	6.0				
Other Accessories	1.6	0.3		2.4	0.9	2.2
	100.1	100.0	100.0	99.9	99.9	100.1

- (1) Tonalite.
- (2) Amphibolite.
- (3) Biotite gneiss.
- (4) Nodular sillimanite schist.
- (5) Biotite schist.
- (6) Fine-grained granite.

clusters and knots, it commonly transects the schistosity. The matrix is normally fine-grained and consists of quartz interlocking with oriented biotite. Essential minerals are quartz, biotite, sillimanite, and muscovite. Accessory minerals generally average less than two per cent of the rock and include zircon, garnet, microcline, magnetite, and apatite. Clinozoisite, sericite, leucoxene, albite, hematite and limonite are alteration products.

Amphibolite and hornblende gneiss.

1. *General Description:* Diverse types of amphibole-bearing rocks are widespread within the Cotopaxi area. They occur as scattered, generally lensoid bodies of irregular extent that intergrade with one another or with biotite-bearing rocks, lime-silicate rocks and migmatite. Both field relations and petrographic evidence indicate that most amphibole-bearing

rocks are likely metasediments, but some appear to represent metamorphosed intrusive basic igneous rocks. Two general types are recognizable. The distinction is petrographic: with essential quartz (>5%) the rock is hornblende gneiss; without, it is amphibolite. Most hornblende gneiss is more foliated than amphibolite, but not conspicuously so, and does not possess well developed mineralogic banding.

2. Petrography:

In general, hornblende gneiss has a granoblastic texture in which hornblende is only slightly elongate. A crude planar orientation of hornblende crystals is responsible for most of the gneissic texture. Individual crystals lying within the foliation planes exhibit only a weak lineation.

Essential minerals are hornblende, plagioclase, and subordinate quartz. One or more members of the epidote group and locally magnetite are also present in essential amounts. Sphene and apatite are ubiquitous and along with zircon and minor garnet comprise the accessory minerals. In hornblende gneiss that has been penetrated with quartzo-feldspathic material biotite, microcline, minor tourmaline, and allanite are present. Uralitized pyroxene is extremely scarce and confined to ragged patches in the centers of non-poikilitic hornblende. Sericite, chlorite, calcite and hydrated iron oxides are secondary in origin.

Amphibolite is the most widespread and diversified amphibole-bearing rock in the area. Hornblende-plagioclase amphibolite constitutes about 90 per cent of the exposed amphibolite. Present as rare conformable lenses within amphibolite is a feldspar-free, high calcium rock composed of about equal parts of clinozoisite, diopside and hornblende (γ = light green to blue-green). The texture is fine-grained and distinctly granoblastic. Microscopically there is no evidence whatsoever that clinozoisite formed at the expense of plagioclase. These three species in mutual contact likely represent the original equilibrium assemblage.

Of 20 representative amphibole-bearing rocks sectioned, 14 contained only accessory quartz. Although the mineralogy and texture are similar, several differences other than lack of essential quartz help to distinguish amphibolite from hornblende gneiss. Plagioclase in amphibolite tends to be more calcic, ranging from calcic labradorite (Ab_{34}) to andesine (Ab_{60}) with an average about (Ab_{50}). Diopside is commonly present as uraltized remnants, and epidote minerals are much more prevalent, particularly as coarse-grained replacements of plagioclase. Garnet is absent in the examined amphibolites; otherwise the accessory minerals of the two rocks are identical.

Biotite gneiss.

1. *General Description:* Biotite gneiss constitutes the bulk of the metamorphic rocks in the immediate vicinity of the mine. It is typically a poorly-banded pink to gray quartzo-feldspathic rock in which biotite rather than hornblende is the ferromagnesian mineral. Ptygmatic dikelets of aplite to pegmatite are locally abundant. A characteristic feature of the gneiss is local concentrations of biotite deficient haloes surrounding magnetite euhedra (Fig. 8B).

Quartz, microcline, oligoclase, biotite and commonly magnetite are essential minerals. Microscopically visible accessory minerals include

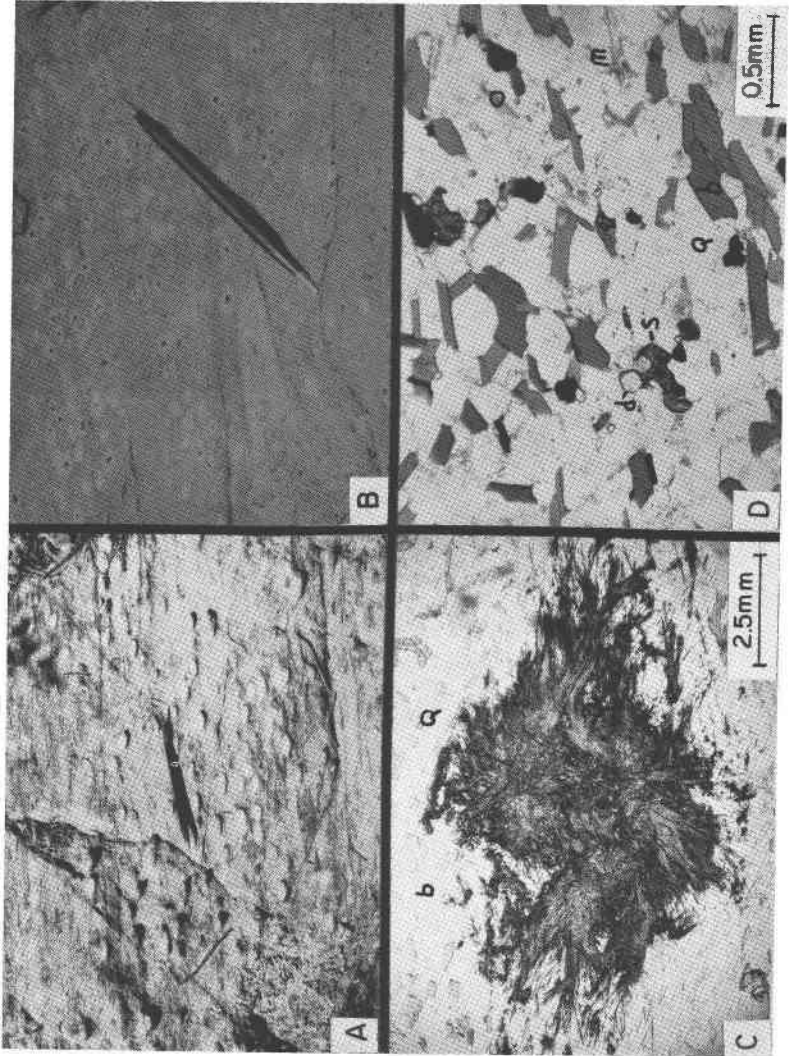


FIG. 8.

- A) Nodular sillimanite schist in which protuberant nodules of resistant sillimanite-quartz produce a distinctive pseudo-conglomeratic appearance to the weathered outcrop. Henthorn Gulch, Cotopaxi mine area, Colorado.
- B) Poorly banded biotite gneiss with quartz-feldspar envelopes containing single grains of magnetite. Henthorn Gulch, Cotopaxi mine area, Colorado.
- C) Fibrolitic sillimanite nodule showing the finely felted texture of individual sworls. A biotite-poor (b) quartz (q) halo surrounds the sillimanite nodule. Photomicrograph of rock shown in A. Plane polarized light. Henthorn Gulch, Cotopaxi mine area, Colorado.
- D) Biotite gneiss in which poorly defined biotite (b) layers alternate with quartz (q) and

muscovite, garnet, sphene, and zircon. Sericite, hematite, limonite, and rare chlorites occur as alteration minerals.

2. Petrography:

Under the microscope, biotite gneiss exhibits many of the textural features common to biotite schist. The fabric is granular, composed of quartz and feldspar with dispersed sub-parallel biotite responsible for the foliation. Quartz generally exceeds 50 per cent of the rock and is commonly fractured and granulated at grain edges. The plagioclase is strongly sericitized oligoclase. Magnetite is commonly an essential mineral, rare in the matrix, but occurring as euhedral porphyroblasts surrounded by a roughly circular felsic envelope in which biotite is conspicuously absent. Garnet is the commonest accessory mineral, but rarely exceeds 1 per cent of the rock. Sphene and magnetite are closely associated. Zircon is not as plentiful as in sillimanite schist, and muscovite is rare.

Lime-silicate rocks. Lime-silicate rocks are scarce in the vicinity of the Cotopaxi mine. Two types can be distinguished on the basis of whether calcite is an essential or an accessory mineral. The common variety, which contains only accessory calcite, is non-foliated, fine- to medium-grained, dull green to light waxy brown, and is confined to the crests of small, tight, nearly isoclinal folds in biotite gneiss.

Under the microscope lime-silicate rock with accessory calcite is seen to consist of green diopside, epidote, zoisite, quartz, garnet and scapolite (dipyre). Calcite, sphene, clinozoisite and rare apatite are accessory minerals. Sericite, which replaces scapolite, is the only alteration product. Epidote, zoisite and scapolite are poikiloblastic and enclose granular diopside and less commonly garnet. Quartz and minor calcite fill interstices between grains.

Lime-silicate rocks with essential calcite are associated with amphibolite and form small lensoid bodies commonly gradational to normal amphibolite. Essential minerals are scapolite, calcite, epidote, quartz and chlorite. Accessory minerals include serpentine, sphene and rare chalcopyrite and tourmaline.

If lime-silicate rocks were included in the mineralized zone, they have been so altered that their original character is no longer identifiable. In any event, they would constitute only a small part of the mineralized volume of rock.

STRUCTURE

The Cotopaxi mine is located in a small gulch one-half mile northwest of the bridge at Cotopaxi in the southwest quarter, Sec. 25, T.48N., R.11E., Fremont County, Colorado. It lies in the northeast corner of a one and one-half by two mile xenolith of intermediate to high-grade

feldspar (microcline (m) and oligoclase (o) layers. Oligoclase shows sericitization along alternate albite twins. Magnetite (opaque) and accessory sphene (s) and small almandine (d) euhedra complete the field. Plane polarized light. Cotopaxi mine area, Colorado.

metamorphic rocks enclosed in granite. Near the mine the granite is a fine-grained, almost aplitic, reddish rock. The ore is erratically distributed in a sulfide-impregnated amphibolitic rock that is generally confined between hanging wall sillimanite schist and footwall biotite gneiss. The footwall biotite gneiss is more or less mineralized and locally intensely silicified for some distance below the contact; the hanging wall sillimanite schist is relatively unmineralized. The strike of the metamorphic foliation is quite variable, but dominantly it is N-S to NW-SE and dips 35-45 E.

The ore body is bounded by two NE-SW striking faults and by a NW-SE striking cross fault, all of which are essentially vertical. A number of steeply dipping auxiliary-faults, striking N-S, EW complicate the major fault pattern (Fig. 2). The age of the faulting is uncertain. However, mineralogic and structural evidence indicate two periods of faulting. The NE-SW striking faults are likely Precambrian in age and appear contemporary with the waning phase of mineralization; all other faults probably are Laramide in age.

The easternmost of the Precambrian (?) faults is represented by a fine-grained reddish rock that varies from 5 to 15 feet in width and shows strong evidence of shear flow. Under the microscope the rock consists almost entirely of chessboard albite and very subordinate chlorite. Where best exposed this shear zone represents completely altered biotite gneiss. The westernmost of the Precambrian (?) fault zones is composed of sheared biotite gneiss and amphibolite. Biotite gneiss has been chloritized, partly albitized, and silicified; amphibolite has been entirely chloritized. The alteration was highly pervasive, and many original textures remain some distance from the shear zones. The Precambrian (?) fault zones are barren of ore minerals or gossan material.

The faults assigned a Laramide age differ significantly from the Precambrian (?) faults in that they are tight narrow faults. The entire fault zone is rarely over three inches in width. They are characterized by relatively small displacements, and intensely slickensided and fractured walls. Retrograde mineralogical alteration is absent; only minor secondary thin films of calcite, gypsum and iron-manganese staining are present.

The metamorphic foliation surrounding the mine shows the effects of plastic deformation, but little evidence of local folding. Ore control by pre-existing fold structures, if any, has been obscured by post-ore faulting. The sulfide-impregnated amphibolite layer was undoubtedly chemically reactive to ore deposition. However, it is possible that the biotite gneiss-amphibolite-sillimanite schist sequence is not an original order. It may be that a bedding surface separating incompetent, sillimanite schist from more competent biotite gneiss acted as an incipient fracture and

localized first Mg-Ca-Fe-Al silicates, which in turn were replaced by sulfide minerals. The coarse pegmatoid appears to have been a local development confined to that part of the deposit now nearest the surface and occupied by the glory hole. More or less surrounding the amphibolite is an alteration envelope of coarse-grained biotite locally rich in euhedral garnet. It is especially well developed along the hanging wall contact, and commonly forms a selvage on late transecting sulfide veinlets in the amphibolite.

Small isolated pods of granite occur within the mineralized area. They are barren of sulfide minerals and lithologically similar to the fine-grained granite that borders the xenolith. A large simple unzoned quartz-feldspar pegmatite south of the deposit transects the metamorphic foliation; this pegmatite is likewise barren. A small body of milky quartz stands in erosional relief immediately west of the ore outcrop. It contains scattered euhedral gahnite and rare boxworks suggestive of original ore minerals. This quartz pod is cut by the westernmost of the Precambrian (?) faults. A thin tabular tonalite dike lies along one of the younger Laramide faults. The dike has chilled margins and is unmineralized.

ORE DEPOSIT

Silicate and oxide pegmatoid. Within the pegmatoid are unaltered relicts of country rock. These relicts maintain their stratigraphic positions and mineralogically and texturally grade into pegmatoid.

The rock types formed during the silicate and oxide pegmatoid phase chemically, and to a lesser extent mineralogically, closely reflect the compositions of the metamorphic parent rocks. This strongly suggests that reorganization of the already existing rocks was a prominent factor in the genesis of the pegmatoid. Unquestionably the formation of the pegmatoid was more than an example of paramorphism. However, only zinc (gahnite) and possibly fluorine (clinochumite) need to have been added in significant quantities. Boron (tourmaline), tungsten (scheelite), and molybdenum (molybdenite), although likely additions, are present in such minor amounts that the possibility of their generation through a concentration of original material released during reorganization cannot be precluded. Particularly if one considers that lime-silicate rocks may have been among the pre-mineralized rocks. Cotopaxi clinochumite contains 2 per cent fluorine whereas mineralogically typical unmineralized amphibolite near the mine contains 0.5 per cent fluorine (Table 2). If the source material of the actinolite-anthophyllite mine rock were such an amphibolite, the relatively small volume of clinochumite to that of amphibole requires that only a small part of the fluorine in the original

TABLE 2. CHEMICAL ANALYSES OF AMPHIBOLITE, ACTINOLITE, GAHNITE, AND CLINOHUMITE COTOPAXI MINE, COLORADO

	A Unmineralized amphibolite	B Matrix actinolite	C Gahnite	D Clinohumite
SiO ₂	49.11	53.97		37.0
Al ₂ O ₃	16.68	4.18	60.76	0.26 ¹
TiO ₂	1.02	0.20		2.8
Fe ₂ O ₃	2.46	1.60	0.58	8.7 ^{1,2}
FeO	8.09	6.25	4.56	
MnO	0.46			1.8 ¹
MgO	6.56	24.65	10.33	Major
ZnO			23.77	
CaO	9.82	6.19		0.32 ¹
Na ₂ O	2.72	0.20		
K ₂ O	1.33			
H ₂ O	0.38	1.86		
H ₂ O	0.03	0.17		1.4 (total)
P ₂ O ₅	0.30			
F	0.6	0.04		2.0
Sr	*			
Ba	*			
	99.56	99.31	100.00	

A. * Appreciable amounts. C. O. Ingemalls, Analyst. Alkali determinations, E. Martinec. P₂O₅, M. Bailey. Sample obtained approximately one-quarter mile from Cotopaxi Mine, Colorado.

B. Law and Company, Analyst. Cotopaxi Mine.

C. Keller, analyst in Genth. Cotopaxi Mine.

D. C. O. Ingemalls Analyst. 1. Spectrographic value courtesy of N. Suhr. 2. Total iron calculated to Fe₂O₃, Cotopaxi Mine.

amphibolite would need to have been released during reorganization to account for the formation of clinohumite.

1. *Recrystallized Biotite Gneiss*: Pegmatoid derived from biotite gneiss is not conspicuously developed. It is difficult to distinguish the coarse-grained alteration of the more aluminous biotite gneiss from pegmatoid formed from low-alumina sillimanite schist. Most glassy massive quartz was once biotite gneiss. The transition from biotite gneiss through sugary granular quartz largely leached of feldspar and mica, to massive glassy quartz speckled with minute bubbles, shreds of weakly pleochroic amphibole, epidote, garnet, pale biotite, fluorite, rhombohedral carbonate, rare tourmaline and sulfide minerals, is clearly evident in many subsurface exposures. The alteration of biotite during the transition from

biotite gneiss to glassy quartz is readily traced. The biotite was first bleached so that the pleochroism is sharply reduced and the optical indices generally are lower. With further alteration the biotite flakes develop ragged edges until only shreds and bits remain. Presumably the alteration of the optical properties indicate a decrease in iron.

The minerals are distributed in several closely associated groups. Biotite books up to 2 centimeters in diameter, euhedral molybdenite up to 1 centimeter, rare coarsely crystalline albite 5–10 cm, and garnet in masses of interfering subhedrons less than 0.5 mm occur as small concentrations in sugary quartz. Euhedral gahnite, pinitized cordierite and quartz concentrations are relatively common. Microcline remnants are found only in weakly silicified rock and here they are commonly corroded and embayed by quartz.

2. *Reorganized Sillimanite Schist*: Within the pegmatoid, sillimanite schist has been thoroughly recrystallized. Much of the massive gahnite clearly replaces sillimanite (Fig. 9B) in altered sillimanite schist. Quartz-gahnite-cordierite with minor pale biotite is a relatively common rock type. Undoubtedly the high alumina content of the parent rock favored this association. Microcline, commonly the variety amazonite, in anhedral crystals up to one and one-half inches replaces sillimanite nodes in nodular sillimanite schist. The texture of the original rock is preserved and many microcline crystals still retain sillimanite cores. Whether microclinization preceded, was contemporaneous with, or followed the pegmatoid stage is indeterminate. The microclinized sillimanite schist was found only as dump samples. This part of the dump contains only unmineralized country rock, and for this reason it appears likely that microclinization may have occurred only at the fringes of the pegmatoid development.

Garnet is poorly developed in altered sillimanite rocks; here it occurs as small (<0.5 mm) widely scattered anhedra generally in association with biotite clusters. Zircon shows no increase in grain size and is still restricted to the centers of pleochroic haloes in biotite. Nests of "sunburst" tourmaline are locally developed, but are not nearly as prominent as they are in biotite gneiss pegmatoid.

3. *Amphibolite*: Pegmatoid texture is best developed in rocks of amphibolitic composition. The dominant rock type is an actinolite matrix with large (10 cm) slender anthophyllite laths as phenocrysts. Gahnite, clinohumite, phlogopite, and rarely forsterite are present in trace to major amounts. Diopside is rare, but isolated coarsely-twinned crystals weighing up to 25 pounds are present in a relatively fine-grained actinolite matrix.

Actinolite and anthophyllite appear to be essentially contemporane-

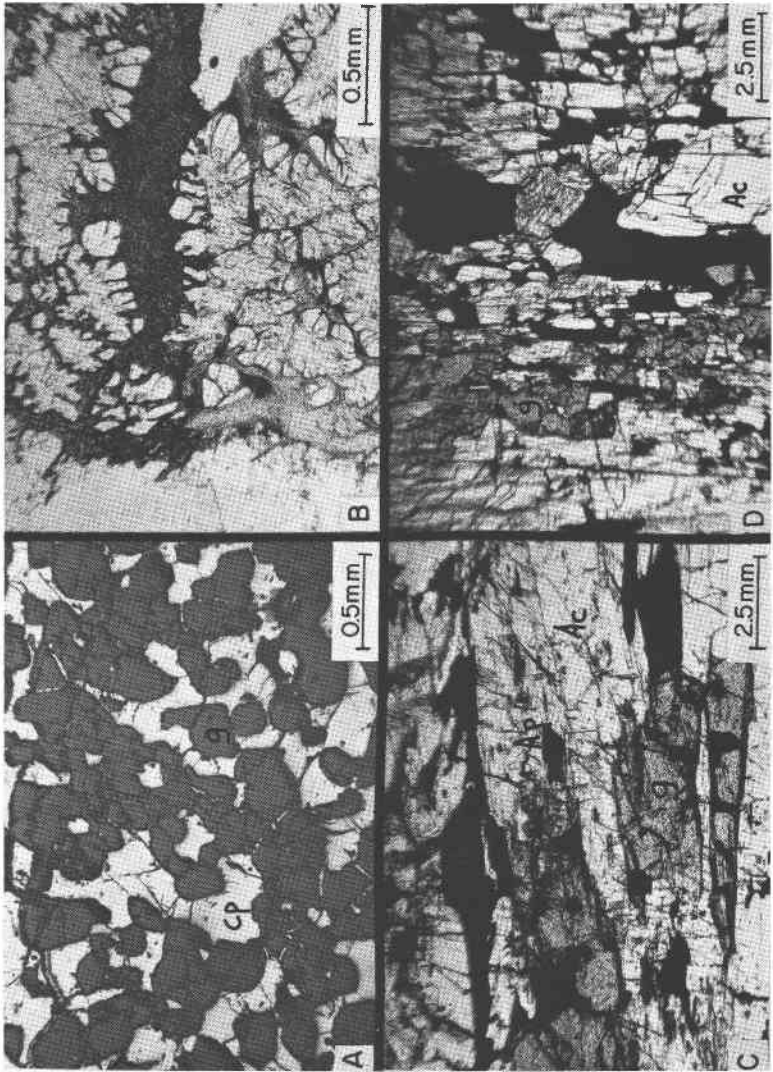


FIG. 9.

- A) Corroded but unaltered gahnite (g) surrounded by chalcopyrite (cp). Plane reflected light. Cotopaxi mine, Fremont County, Colorado.
- B) Gahnite (dark gray) replacing sillimanite (light gray) in quartz matrix. Altered nodular sillimanite gneiss. Plane polarized light, Cotopaxi mine, Fremont County, Colorado.
- C) Gahnite (g) replacing actinolite (ac) along the cleavage and in turn being replaced by galena (opaque). The paragenetic relation of the small subhedral apatite (ap) is in-

ous; minor high-magnesium garnet and phlogopite are generally later but in part overlap actinolite-anthophyllite. Gahnite is earlier than clinohumite, which commonly transects it, but later than the previously mentioned silicates.

Most gahnite is massive to subhedral, although a number of smaller specimens (<3 cm) show octahedral faces. Some gahnite exists as small subhedrons in a glassy quartz matrix. The two phases are sharply separated and the gahnite is commonly unaltered. Cotopaxi gahnite is a magnesian variety, however, the substitution of considerable zinc for magnesium must have extended the stability field of the spinel to allow it to coexist with quartz at elevated temperatures and pressures.

Forsterite and clinohumite show some evidence of simultaneous crystallization, but most clinohumite has replaced forsterite. Scheelite is associated with, and commonly surrounds, small, euhedral, lime-rich garnet. A coarse-textured garnet-biotite border separates amphibolite and hanging wall sillimanite schist. It is particularly well developed near the structurally higher part of the amphibolite and "mantles" the ore body. Here it is several feet thick and most of the biotite is altered to chlorite—the garnet is entirely unaltered. Petrographic and field evidence indicate that the garnet-biotite selvage has formed through a hydrothermal alteration of the actinolite amphibolite.

Figure 6 is a generalized paragenesis of the reorganized amphibolite.

Ore Minerals.

1. *General Statement:* Unquestionably the development of the ore species is a part of the total mineralization sequence, however, with the exception of scheelite and possibly minor molybdenite, they appear to be distinctly later than the minerals of the pegmatoid stage. The bulk of the ore minerals are intimately combined with amphibolite. Considerable ore mineralization is located as irregular grains and euhedra in silicified biotite gneiss; a minor amount occurs as late irregular, attenuated veinlets with an accessory gangue of quartz, sideritic to calcitic carbonate, and rare fluorite and apatite. These veinlets transect all rock types including those previously mineralized. The ore mineralogy and paragenesis are relatively simple, particularly when compared to the oxides and silicates

determinate. Mineralized amphibolite. Plane reflected light, Cotopaxi mine, Fremont mine, Fremont County, Colorado.

D) Gahnite (g) and galena (opaque) replacing actinolite (ac). Galena is much more controlled by the amphibole cleavage than is gahnite. Plane reflected light, Cotopaxi mine, Fremont County, Colorado.

of the pegmatoid stage. Ore deposition began and ended with oxides; intermediate species are all sulfides. In general, sulfides of Mo, Fe, Zn, Cu, and Pb were sequentially deposited. Figure 7 is a summary of the paragenetic sequence.

2. *Mineral Descriptions:* a. *Early Euhedral Magnetite:* Early magnetite is present sparingly as slightly corroded, commonly fractured euhedra in a sulfide groundmass (Fig. 12D). The rock matrix is coarse-grained actinolite-anthophyllite-gahnite-clinohumite in which magnetite and sulfide are subordinate.

b. *Scheelite:* Scheelite is irregularly distributed as small (<1 mm) very rare patches in gahnite-anthophyllite-actinolite-clinohumite pegmatoid, the amount present is so little and inconspicuous that if it were not for its fluorescence it would probably have gone unnoticed. Small, lime-rich, garnet euhedra are common associates. Scheelite appears to be post-pegmatoid, but the relations are not diagnostic and it may be a late pegmatoid mineral. Veinlets of late chalcopyrite and galena fill fractures in scheelite, however, the relation between scheelite and early ore minerals was not observed. Scheelite is confined to the silica-poor pegmatoid; molybdenite conversely, is primarily present in what appears to be younger garnet-quartz-biotite rock. On this basis scheelite is presumably pre-molybdenite.

c. *Molybdenite:* Molybdenite is scarce in the Cotopaxi deposit. Whether molybdenite preceded, was contemporaneous with, or followed magnetite is not directly evident. In general, molybdenite is associated with garnet-quartz-biotite rock as scattered subhedral to euhedral flakes up to one-half inch in width. Rare molybdenite occurs as crystallographically oriented microscopic laths in sphalerite. A binocular examination of foliated amphibolite specimens reveals small molybdenite flakes oriented with their *c* axis perpendicular to the foliation. The writer concludes that the molybdenite laths are quite separate in origin from the sphalerite, the sphalerite having subsequently replaced the original molybdenite-impregnated amphibolite. In support of this view similarly oriented amphibole remnants are also found scattered throughout the sphalerite.

d. *Pyrite:* Euhedral pyrite is scarce and appears to be older than most pyrrhotite. These older pyrite euhedra are in general free from inclusions, take a good polish and are isotropic to weakly anisotropic.

Anhedral to subhedral pyrite is widespread throughout the deposit, but subordinate to sphalerite or chalcopyrite. Most pyrite has formed by replacing earlier pyrrhotite. Replacement pyrite occurs as pseudomorphs after pyrrhotite (Fig. 11B), as anhedral to subhedral masses commonly

TABLE 3. SUMMARY OF THE RETROGRADE ALTERATIONS IN MINERALIZED ROCK TYPES, COTOPAXI MINE, FREMONT COUNTY, COLORADO

Original Assemblage	Type of Transformation	Present Assemblage
Biotite Gneiss K Feldspar Sillimanite	Sericitization	Sericite and/or muscovite
Plagioclase	Saussuritization	Epidote, sericite, albite
Gahnite Biotite	Chloritization	Chlorite (ripidolite, rare diabantite)
Biotite gneiss	Albitization	Albite+minor biotite (chlorite)
Sillimanite schist K feldspar Sillimanite Codierite	Sericitization	very fine-grained muscovite
Gahnite Biotite	Chloritization	Chlorite (ripidolite)
Amphibolite Clinohumite	Serpentinization	Antigorite+amesite? rare talc
Gahnite	Chloritization	Chlorite
Amphiboles	Serpentinization Epidotization	Antigorite, magnetite, clacite Epidote, quartz, chlorite (ripidolite)
Phlogopite	Chloritization	Chlorite (ripidolite)
Garnet+Biotite	Chloritization	Chlorite+garnet

with irregular patches of unreplaced crystallographically oriented pyrrhotite (Fig. 11A), or intimately associated with magnetite as a replacement of pyrrhotite (Fig. 11C, D).

e. *Pyrrhotite*: Pyrrhotite, was once far more prevalent than it now appears. It has persisted only where it was insulated from subsequent chemical attack, and is present as separated, rounded grains with similar crystallographic orientations within pyrite, sphalerite, chalcopyrite, and rarely marcasite; all of which, at least in part, have formed by the replacement of pyrrhotite. Pyrrhotite is more consistently associated with

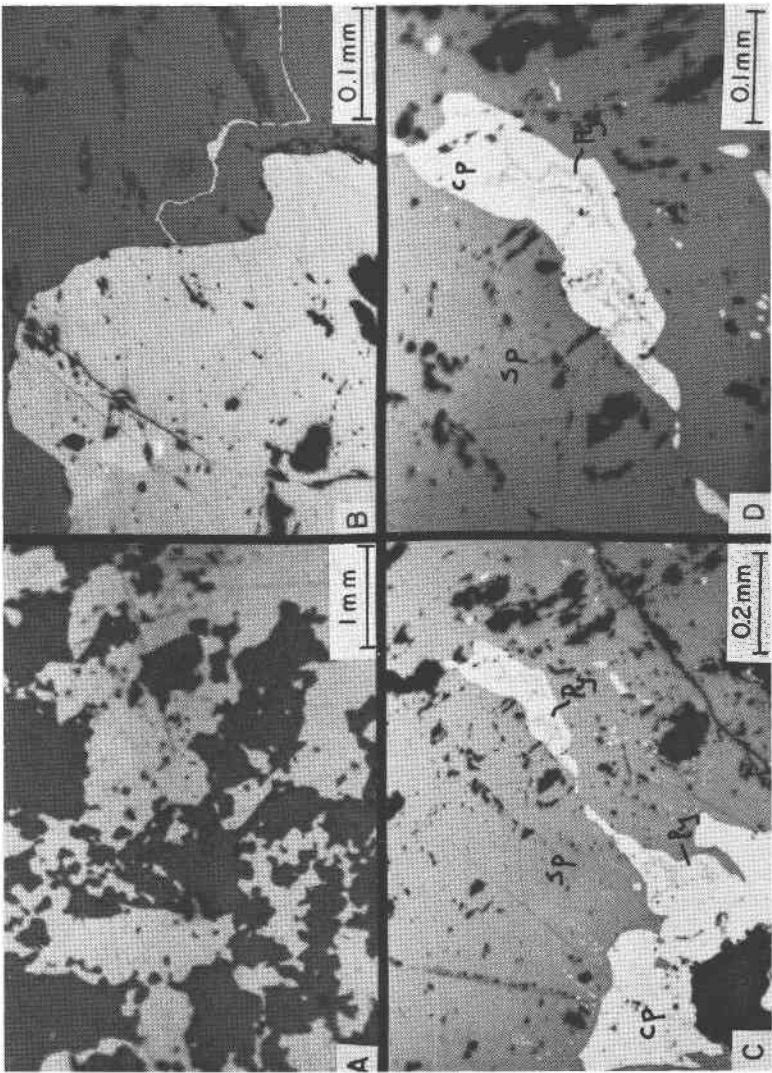


FIG. 10.

- A) Chalcopyrite (light gray) and sphalerite (dark gray) exhibiting a "mutual texture." Plane reflected light, Cotopaxi mine, Fremont County, Colorado.
- B) Highly magnified "mutual texture" boundary between chalcopyrite (light gray) and sphalerite (dark gray). Here chalcopyrite is clearly post-sphalerite. Plane reflected light, Cotopaxi mine, Fremont County, Colorado.
- C) Chalcopyrite (cp) preferentially absorbing pyrite (py) remnants in sphalerite (sp). Plane reflected light, Cotopaxi mine, Fremont County, Colorado.
- D) Enlarged view of C showing details of the developing boundary between chalcopyrite

sphalerite and to a lesser extent with chalcopyrite. Many excellent examples of pyrite, complex intergrowths of magnetite and pyrite, and marcasite pseudomorphs after pyrrhotite are evident (Figs. 11C, D).

f. *Sphalerite*: Sphalerite is the most prevalent ore mineral within the deposit. It is dark brown to almost black and coarsely twinned. Most sphalerite intimately replaces amphibolite. Actinolite appears to have been more readily replaced than was anthophyllite. Where gahnite and sphalerite appear in the same section, sphalerite is invariably later and fills fractures in gahnite. The contact between the two is very sharp. Irregular sphalerite veins up to several inches in width extend from the mineralized amphibolite into biotite-poor locally sugary-textured foot-wall biotite gneiss. Within the vein, individual crystallographically continuous areas of sphalerite up to $1\frac{1}{2}$ inches are set in what superficially appears to be a "crushed" sphalerite-chalcopyrite-subordinate pyrite matrix. Close examination of the matrix shows that the matrix sphalerite is crystallographically continuous within the individual sphalerite areas. What first appeared to be small scale mechanical brecciation is a "solution breccia" formed by the replacement of very coarsely crystalline sphalerite by chalcopyrite.

In general, sphalerite is post-pyrrhotite. Small crystallographically oriented grains of pyrrhotite are so common in sphalerite throughout the deposit that they preclude any interpretation other than that sphalerite has largely formed at the expense of pyrrhotite. Additional evidence that sphalerite is mainly post-pyrrhotite is found where sphalerite completely surrounds fractured gangue and small fractures in the center of the gangue are filled by pyrrhotite.

g. *Chalcopyrite*: Chalcopyrite is the second most abundant sulfide at Cotopaxi. Characteristically it is intimately associated with sphalerite in what has been described as "a mutual texture" (Fig. 10A). A careful examination of the "mutual texture" clearly shows that chalcopyrite is mainly post-sphalerite and has formed by replacement of rather than co-formation with sphalerite (Fig. 10B). Early chalcopyrite appears to have been localized by pyrrhotite or pyrite inclusions in sphalerite, and as replacement progressed absorbed the iron sulfide cores (Figs. 10C, D).

and sphalerite. If the pyrite were consumed, chalcopyrite and sphalerite would show a "mutual texture" with no indication of its complex origin. Plane reflected light, Cotopaxi mine, Fremont County, Colorado.

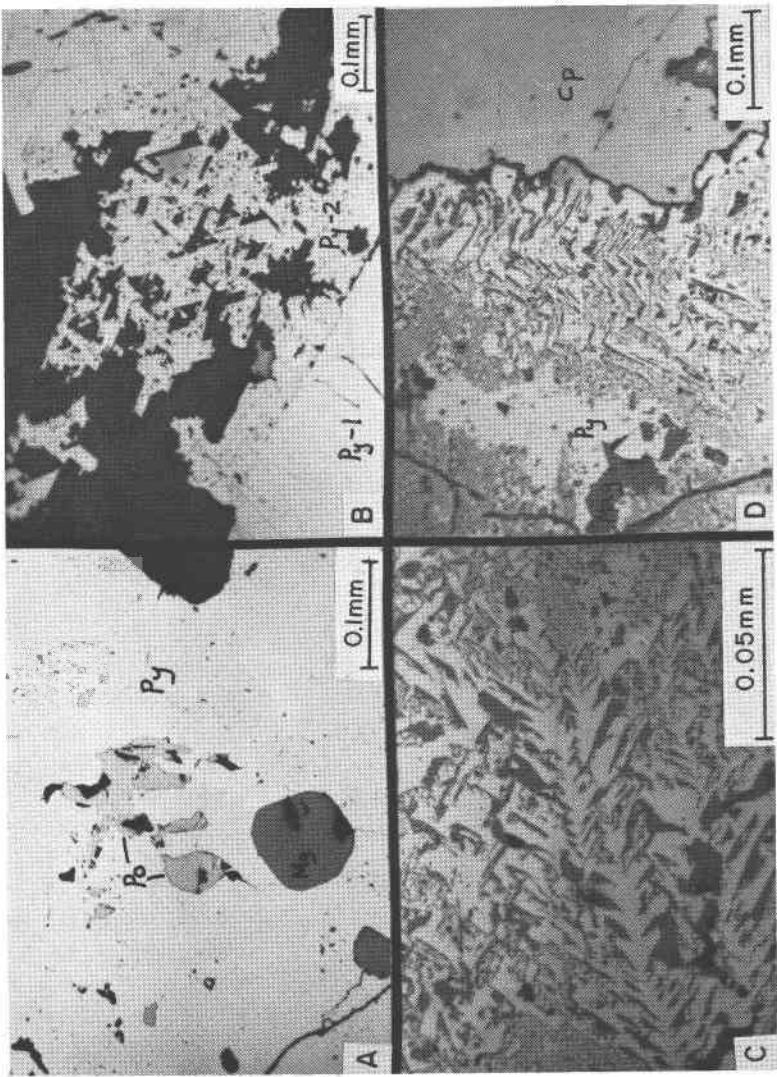


FIG. 11.

- A) Early euhedral magnetite (mg) and crystallographically oriented fragments of pyrrhotite (po) surrounded by pyrite (py). The sequence here is magnetite followed by pyrrhotite and the conversion of most of the pyrrhotite to pyrite. Plane reflected light. Cotopaxi mine, Fremont County, Colorado.
- B) Two generations of pyrite. Early euhedral pyrite (py-1) and a second generation of pyrite (py-2). Second generation pyrite pseudomorphous after skeletal pyrrhotite. The dark inclusions in second generation pyrite are not magnetite but a carbonate mineral. Plane reflected light, Cotopaxi mine, Fremont County, Colorado.

Much of the chalcopyrite is coarsely twinned. Very minor rounded grains of chalcopyrite are associated with some pyritized pyrrhotite and may represent chalcopyrite that was completely exsolved from early pyrrhotite. The textural evidence here; however is only suggestive not diagnostic. In none of the observed specimens did chalcopyrite contain exsolved sphalerite, nor was there any indication of complete unmixing.

h. *Galena*: Galena is the youngest sulfide mineral. It characteristically occurs as a fine-grained replacement of amphibolitic gangue and rarely of earlier sulfides, particularly chalcopyrite. Galena is irregularly distributed throughout the deposit and only locally is it plentiful. With the exception of traces of tetrahedrite (?) it is relatively free of other ore minerals. An interesting aspect to the galena mineralization is its highly pervasive nature. Galena-impregnated areas nearly a foot across show parallel cleavage faces. Stereoradiographic examination of these areas shows that the galena is not entirely interconnected in depth, but that it is highly skeletal (Hamblin and Salotti, 1964).

Minor galena is present along the small veinlets that have originated as a result of an alteration of pre-existing silicates. This galena shows no evidence of having been "rearranged" and appears to be primary.

i. *Pyrite + Magnetite*: Under low to medium magnification some "pyrite" appears to have a rough surface and low reflectivity. Examination under high magnification shows that "pyrite" to be an intimate mixture of subhedral pyrite and magnetite (Figs. 11C, D). Diffractometer patterns suggest that a rhombohedral carbonate may be the minor gangue in some intergrowths. The intergrowths are generally irregular in outline and strongly suggest that massive pyrrhotite was the original mineral. Pyrite-magnetite is best developed in early pegmatoid rocks, particularly those high in clinohumite and gahnite, but even here it is subordinate. The intergrowths show no evidence of replacement by other sulfides, but are cut by later anhedral magnetite-bearing veinlets (Fig. 12A, C).

j. *Marcasite*: Marcasite is a widely distributed microscopic component. It is most consistently associated with pyrite. In general, where pyrite and marcasite occur together, pyrrhotite inclusions in pyrite are

C) Highly magnified mixture of pyrite (light gray) and magnetite (dark gray) after pyrrhotite. The mottled areas are very fine grained mixtures of pyrite and magnetite. Plane reflected light. Cotopaxi mine, Fremont County, Colorado.

D) Intimate mixture of pyrite (py) and magnetite (mag) after pyrrhotite. Completely unaltered chalcopyrite (cp) and gangue (very dark gray) complete the field. Plane reflected light. Cotopaxi mine, Fremont County, Colorado.

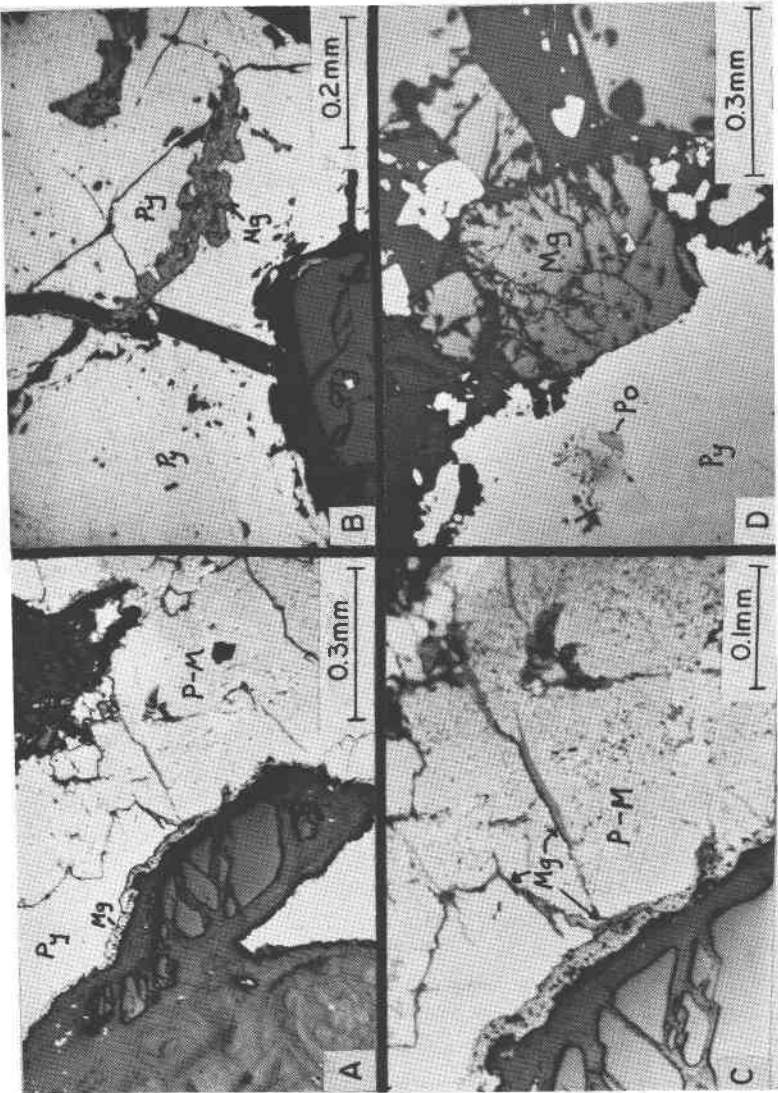


FIG. 12.

- A) Late anhedral magnetite (mg) associated with the serpentinization of amphibole. Pyrite (py) and an epitaxial aggregate of pyrite-magnetite (p-m) complete the field. Plane reflected light, Cotopaxi mine, Fremont County, Colorado.
- B) Late anhedral magnetite (mg) in serpentine veinlet transecting pyrite (py). Fractured quartz (qtz) completes the field. Plane reflected light, Cotopaxi mine, Fremont County, Colorado.
- C) Enlarged view of A. The late anhedral magnetite (mg) clearly cuts across the pyrite-

most prevalent. Texturally most marcasite appears as an irregularly shaped mosaic of fine-grained granules, but some marcasite is coarse-grained and well twinned. There is a complete lack of colloform textures, and the associated ore minerals are unaltered. A careful search failed to disclose any marcasite whatsoever in specimens showing surficial weathering.

k. *Anhedral-Subhedral Magnetite*: Most anhedral magnetite is included in serpentine veinlets along with minor calcite in mineralized amphibolite. This magnetite formed during the waning phases of mineralization and may properly be separated into a sub-stage, which is characterized by the absence of sulfide deposition and the pervasive hydration of essentially anhydrous silicate and oxide minerals. However, rare anhedral-subhedral magnetite-bearing veinlets with mainly quartz for gangue and containing traces of galena are present, and likely mark the end of primary ore deposition.

l. *Gangue Minerals*: Gangue minerals deposited with the ore minerals are few and with the exception of quartz are quantitatively unimportant. Quartz is a major component of the early pegmatoid that developed in siliceous gneiss and schist. This early quartz may have been supplied in part from the country rock; however, irregular quartz-gahnite-minor phlogopite veins transect partly silicified gneiss and indicate that silica was introduced, and/or strongly mobilized. Quartz-sphalerite-chalcopyrite veins cut mineralized amphibolite, and quartz is a prominent gangue mineral in late magnetite-bearing veinlets.

Microscopic euhedral to subhedral apatite is rare but widely distributed. Most apatite is spatially associated with galena, but its position within the sequence cannot be fixed certainly.

Siderite clearly belongs to the main sulfide stage. It is best developed in late chalcopyrite veinlets as individual rhombohedrons up to 1 centimeter. The rare rhombohedral carbonate associated with the inversion of some pyrrhotite to pyrite-magnetite is likely siderite. Very little siderite is associated with sphalerite or galena.

magnetite mixture (p-m) indicating that pyrrhotite had altered to pyrite-magnetite before the serpentinization. Plane reflected light. Cotopaxi mine, Fremont County, Colorado.

D) Early fractured euhedral magnetite (mg), pyrite (py), small remnants of crystallographically oriented pyrrhotite (po), and gangue minerals. The sequence is magnetite, pyrrhotite, and the conversion of pyrrhotite to pyrite. Plane reflected light, Cotopaxi mine, Fremont County, Colorado.

Calcium-garnet, epidote, and fluorite are confined to strongly silicified biotite gneiss. Here they occur as highly irregular elongate patches along with minor sphalerite, rare chalcopyrite, and shreds of a pale green amphibole.

PARAGENESIS

The Precambrian igneous and metamorphic rocks of south-central Colorado are structurally and petrologically complex and to date afford no compelling evidence to classify the Cotopaxi-type deposits as either metamorphic-metasomatic or magmatic. The largest of these deposits, the Sedalia mine, is cut by a 50-foot thick unmineralized simple pegmatite dike (Lindgren, 1908), and at Cotopaxi both fine-grained granite and pegmatite are post-ore. However, throughout south-central Colorado, particularly along the southern and southwestern margins of the batholith, there is evidence of more than one period of granite formation and/or of differentiation within major granite types (Salotti, 1960). The formation of a mesozone-catazone granite as large as the south-central Colorado batholith would necessitate that the same process did not operate simultaneously throughout the mass, but that fractionation was spatially as well as temporally separated. Within a major granite cycle likely some local reversals of stages would result.

Lindgren's (1908) and Boyd's (1933) position that the Sedalia and Cotopaxi deposits are regionally metamorphosed basic magmatic segregations is incompatible with the mineralogy and paragenesis of the deposits, and with the geologic setting. The term pyrometasomatic is not appropriate because it is inexpressive of a deep-seated origin, and further because many geologists think of pyrometasomatic deposits in Graton's sense—a hypothermal deposit in limestone. The writer suggests that the deposits are best described as sulfide deposits of the Mg-Al silicate gangue type. This non-genetic nomenclature seems preferable until more is known concerning the origin of these deposits.

Except for a small number of rarer minerals the textural relations among the minerals of the Cotopaxi deposit quite well delineate the paragenetic sequence. Five stages are distinguishable in the genesis of the deposit. They are the following:

- (1) formation of the actinolite-anthophyllite amphibolite, (2) development of the oxide and silicate pegmatoid, (3) appearance of the sulfide minerals, (4) retrograde alteration, and (5) weathering.

The mineralogy of each stage indicates a significantly different environment from the other stages and the paragenesis of the deposit is best outlined by a discussion of the individual stages and their sequential relations to each other.

TABLE 4. SUMMARY OF PARAGENESIS, COTOPAXI, COLORADO

Pre-Mineralized Metamorphic Rock	Original Mineralogy	Early Pegmatoid Stage (Silicate and Oxide)	Main Ore Stage	Retrograde Alteration	Surficial Alteration
Biotite Gneiss	<u>Essential</u> Quartz Biotite Plagioclase Muscovite Microcline <u>Accessory</u> Garnet (Fe) Magnetite Zircon Apatite Sillimanite Rutile	<u>Essential</u> Quartz Microcline Biotite (>Mg) Gahnite (L) Albite (L) Tourmaline (L-R) <u>Accessory</u> Zircon Garnet (Fe-Mg) Molybdenite Cordierite (L-M)	<u>Ore Minerals</u> Molybdenite Magnetite Pyrite Pyrrhotite Sphalerite Pyrite (Po+Py) Chalcocopyrite Pyrite + Magnetite (Po+Py + Mag) Pyrite + R. Carbonate (Po+Py+R Carbonate) Marcasite (Po+Mc) Galena Tetrahedrite(?) Magnetite	Fine-grained Muscovite Albite (M) Epidote group (M) Diabantite	Hematite Goethite Limonite Covellite (M) Malachite Azurite Chrysocolla Cuprite Anglesite Calcite Gypsum Strontionite (R)
Nodular Sillimanite Schist	<u>Essential</u> Quartz Sillimanite Biotite Muscovite Plagioclase Microcline <u>Accessory</u> Garnet (Fe) Zircon Rutile Magnetite Apatite	<u>Essential</u> Quartz Gahnite Cordierite Amazonite (L) Sillimanite <u>Accessory</u> Zircon Garnet Tourmaline (L)	<u>Non-ore Minerals</u> Quartz Siderite Garnet (Ca) Epidote Fluorite <u>Wall Rock Alteration</u> Amphibolite → Biotite + Garnet (Fe)	Fine-grained Muscovite Serpentine Albite (M) Epidote (M)	
Amphibolite (?)	<u>Essential</u> Hornblende Plagioclase Diopside (L) Quartz (L) Epidote group <u>Accessory</u> Biotite Allanite Sphene Garnet (Fe) Magnetite	<u>Essential</u> Mg-Aclinolite Anthophyllite Garnet (Mg) Diopside Phlogopite Gahnite Clinohumite <u>Accessory</u> Forsterite Garnet (Ca-L) Scheelite (L-M)		Talc (R) Diabantite Clinocllore Amesite ? Antigorite Fine-grained Muscovite Albite Epidote Thulite Clinozoisite Calcite Magnetite	
Lime-silicate Rock (?)	<u>Essential</u> Scapolite Garnet (Ca) Diopside Quartz Epidote group <u>Accessory</u> Calcite Sphene Apatite	(?)			

L = Local
M = Minor
R = Rare

Formation of amphibolite. The origin of the actinolite-anthophyllite rock is not known. In south-central Colorado rocks of this type are confined to mineralized areas of the Cotopaxi type. Whether they are entirely metasomatic or regional types that have been partly altered and thoroughly reorganized is indeterminate. The mineralized amphibolite of the Cotopaxi mine was compared petrographically to a number of unmineralized regional amphibolites in the area. The significant isomorphism allowed by most species involved complicates the comparison; however, the bulk compositions of the two rocks differ substantially, and the actinolite-anthophyllite rock, if reorganized amphibolite, must have undergone considerable metasomatism.

Pegmatoid stage. The development of the pegmatoid closely followed or perhaps even accompanied the later stages of amphibolite formation. It is pertinent to note that within a fifty mile radius both cordierite and gahnite (Heinrich, 1948) are late pegmatite minerals, and scheelite is a widely dispersed accessory mineral in small lime-silicate deposits (Belser, 1956; Tweto, 1960). Figure 6 illustrates a simplified paragenetic sequence of the pegmatoid. Zinc was present in quantity during the pegmatoid stage and formed not a sulfide but the zinc aluminate, gahnite. Only molybdenum, an element with a high affinity for sulfur, occurs as a sulfide. The absence of other sulfide minerals cannot be attributed to high temperatures alone, because high iron-bearing pegmatoid silicate minerals indicate the ready availability of iron and the prevailing temperatures must have been within the stability field of pyrrhotite (Kullerud, and Yoder, 1959; Arnold, 1962). The paucity of sulfide minerals within the pegmatoid more likely indicates a low sulfur content during early mineralizing. With the exception of hydroxyl-bearing clinohumite and phlogopite-biotite, minerals developed during the pegmatoid stage are anhydrous.

Ore deposition stage. The transition from pegmatoid to ore stage appears abrupt. Magnetite and molybdenite likely are common to both stages but they are dispersed constituents and this relation is not certain. The beginning of ore deposition marked a change in the system. A significant change may have been a compositional change in the fluid phase with sulfur strongly increased relative to oxygen (Salotti, 1964). The general sequence of the ore minerals is iron, zinc, copper, and lead sulfide minerals; similar to world-wide occurrences. The assemblages also follow the trends pointed out by McKinstry and Kennedy (1957, 1959) of increasing S:O and Cu:Fe. Coarse-twinning is common, etched sphalerite shows this particularly well; whereas zone or exsolution textures are prac-

tically non-existent. Minor euhedral pyrite is the first mineral that clearly initiates ore deposition. Pyrite was closely followed by and in part contemporaneous with the main period of pyrrhotite formation. Pyrrhotite changed to pyrite as the availability of sulfur increased. This conversion was both extensive and pervasive. Sphalerite formed mainly after pyrrhotite. Locally, a close spatial association suggests some overlap, but neither sphalerite nor pyrrhotite shows any exsolution relations. Sphalerite replaces both pre-existing sulfide minerals and gangue. Chalcopyrite and sphalerite are generally spatially associated and because of their "mutual" texture, Lindgren (1908) believed them to be contemporaneous. A close examination shows that most chalcopyrite replaces older sulfide minerals, commonly by a selective process (Figs. 10B, C, D), but much replaces gangue and fills irregular fractures. Chalcopyrite may be entirely post-pyrrhotite. The general rule is that elements with a higher affinity for sulfur than iron are soluble in iron monosulfide. If copper were already in the system during the formation of pyrrhotite, a solid solution should have formed and a copper-iron sulfide mineral should have exsolved upon slow cooling. A careful search of the remaining pyrrhotite failed to show any cubanite, valeriite, mackinawite or "chalcopyrrhotite." The chalcopyrite present is much later and replaces both pyrrhotite and pyrite. Either all evidence of the exsolved species is obliterated, or during the formation of pyrrhotite appreciable copper was not present in the ore fluid. Galena is the last mineral to form during the hypogene sulfide phase, and may have slightly overlapped the formation of chalcopyrite, but in general it is later than the preceding sulfide minerals. The presence of minor galena within anhedral magnetite-bearing serpentine veinlets indicates that the deposition of galena, although it occurred mainly in the late sulfide stage, was not completed until the retrograde stage had begun.

Some wall rock alteration accompanied the emplacement of the younger sulfide minerals.

Retrograde mineralization stage. Retrograde mineralization describes the accommodation of the pre-existing mineral assemblage to subsequent non-surficial (?) alteration. Both ore and gangue minerals are involved, but the retrograde adjustments are largely confined to the gangue minerals. The retrograde minerals include the ore minerals pyrite, magnetite, and marcasite; among the gangue minerals are members of the epidote group, albite, and a number of phyllosilicate minerals.

Retrograde alterations among the gangue minerals can be divided into two mineralogically and texturally defined sub-stages. The earliest alteration involved the transformation of amphibolite to a biotite-al-

mandite selvage bordering late sulfide (principally chalcopyrite) veinlets which transect previously mineralized but unaltered amphibolite. It is reasonable to assume that the biotite (chlorite)—almandite envelope that mantles the ore body also formed during this period.¹

The extent of the time lapse, if any, between the end of primary sulfide mineralization and the beginning of the retrograde stage is not evident. However, a distinct separation based upon mineralogy is present between the two stages. This division between a main sulfide stage and subsequent retrograde alteration is a common sequence in many "skarn" deposits. The cause and the time relation of the retrograde changes to the preceding minerals are little understood and controversial. Possible explanations for the alterations include the following:

- 1) hydrothermal reverberations
- 2) unloading metamorphism
- 3) circulating ground water incidental to tectonic disturbances
- 4) beginning oxidation at the current surface
- 5) true diaphoresis

Relations at Cotopaxi include:

- 1) primary galena, although largely confined to the late sulfide stage, is sparingly present along late veinlets that result from retrograde alterations.
- 2) nearby unmineralized regional amphibolitic rocks are not similarly retrograded.
- 3) nearby small Laramide sulfide-bearing non-pyrrhotitic deposits are essentially unaltered.
- 4) retrograde minerals include magnetite, serpentine, coarse-grained chlorites, rare talc, albite, and epidote minerals—an assemblage suggestive of a hydrothermal rather than a surficial origin.

The available evidence does not allow a comfortable choice. If the alteration is diaphoretic in origin, marcasite, because it along with magnetite and pyrite intimately replaces pyrrhotite, must have formed at a relatively elevated temperature and pressure. If the alteration is supergene it would require that serpentinization and the accompanying magnetite formation, as well as the development of the coarse-gained phyllosilicates, are weathering products—an equally unattractive conclusion.

It should be pointed out that mineralogically similar but geographically separated deposits, *i.e.*, Ducktown and Outokumpu, possess comparable alterations. This suggests that the alterations are a response to a common process rather than a geographically isolated phenomenon.

In general retrograde alterations involve the conversion of mainly

¹ The alteration of amphibolite to garnet-biotite (chlorite) is particularly well-developed at the Sedalia mine near Salida and is the source of the large euhedral almandite collected at this locality.

anhydrous minerals to hydrous types; as well as increased complexity in the silicate linkage—from chain to sheet structures. Based upon textural evidence retrograde alterations among the gangue minerals can be divided into two sub-stages. Again the time lapse, if any, between these sub-stages cannot be determined. The first sub-stage involved the alteration of amphibolite to biotite-almandite,² and the local transformation of hornblendic amphibole to thulite and clinozoisite and minor zoisite and epidote. Basic plagioclase was almost completely saussuritized to rather coarse mixtures of clinozoisite, albite, and very minor sericite. The albitization of biotite gneiss along one of the major faults likely belongs to the first stage of alteration. Biotite is restricted to the first alteration period, and the minor chlorite in the albitized rock contains shreds of older biotite indicating an original albite-biotite assemblage. Rare talc occurs as an alteration product of dark mica less commonly of amphibole; is almost completely replaced by serpentine.

The second sub-stage involved a greater hydration, and minerals formed during this period are all phyllosilicates. Serpentine, almost entirely antigorite with very rare small seams of fibrous chrysotile, and chlorite (mostly ripidolite with minor diabantite) are the principle alteration products of the later stages of alteration. In general chloritic alteration prevailed at the margins of the ore body whereas serpentine formed in the more central parts. Why such a distribution should prevail is not apparent. A possible explanation is that the more central parts were previously enriched in magnesium (i.e., clinohumite, anthophyllite, phlogopite, forsterite) relative to the margins.

Chlorite pervasively replaces biotite in the biotite-garnet mantle, particularly near the apex of the deposit. The garnet because of its resistance to alteration is unaffected. Along the major western fault unmineralized amphibolite has been pervasively altered to ripidolite. The transformation is markedly pseudomorphous and the original texture of the amphibolite including euhedral outlines of idioblastic anthophyllite are delicately preserved. Most gahnite has altered to chlorite rather than serpentine even though nearby clinohumite and amphiboles are serpentinized. Along some contacts between clinohumite and gahnite an intimate fine-grained mixture of antigorite and chlorite is present. This chlorite is colorless to very pale green, non-pleochroic, optically+, sensibly uniaxial, with very low birefringence. Diffractometer patterns of the mixture contain none of the prominent talc peaks, or reflections at

² Whether biotite and almandite are coeval is indeterminate. Almandite may well have developed first and the almandite-amphibole rock then altering to almandite-biotite with a subsequent alteration to almandite-chlorite—the almandite being inert to the later alteration effects.

14 Å, but strong reflections at 7 and 3.5 Å. These properties suggest that the chlorite may be the septachlorite amesite.

Serpentine is widespread throughout the amphibolitic parts of the ore body. It is best developed within the early magnesium-pegmatoid. Here large masses of clinohumite have been completely converted to serpentine. Amphibole generally shows less alteration than does clinohumite. The source of the late anhedral magnetite and calcite was likely the altering amphibole. During serpentinization of amphibole, iron and calcium were released and precipitated as magnetite and calcite. Textural evidence indicates that serpentinization and chloritization occurred simultaneously. Which mineral formed depended upon the nature of the replaced species. For example, a coarse aggregate of what was once clinohumite-gahnite-phlogopite is now serpentine after clinohumite, and chlorite after gahnite and phlogopite.

Weathering. Secondary enrichment at Cotopaxi is neither extensive nor well-exposed. Very likely a more thorough examination of the alteration would uncover more species and greater detail of their paragenesis, but because the surficial alteration is entirely separate from the origin of the primary minerals, the writer devoted little time to their study.

The Cotopaxi ore body is exposed at the surface in a small outcrop immediately north of the glory hole. Only the upper workings of the mine are in the zone of surficial alteration. The secondary ore minerals are chiefly hydrated carbonates and silicates of copper, and oxides and hydrated oxides of copper and iron. No secondary zinc minerals were found. Covellite is the only secondary sulfide and it is only present microscopically; it replaces sphalerite in preference to chalcopyrite. Rare anglesite veinlets are restricted to parts of the ore rich in galena. Very rare fine needle-like crystals of strontianite were found in the cellular gossan. Gypsum is confined to thin crusty coatings along joints or small faults. Very little cuprite is left either on the dump or in the near surface workings; however, early mine records report cuprite as the most valuable ore mineral.

SUMMARY

The ore body at Cotopaxi is an example of a distinctive and little studied type of mineralization in south-central Colorado. Deposits of this nature, although atypical in the western cordillera, have a worldwide distribution. They are at present best defined as sulfide deposits of the Al-Mg gangue type, with the presence of cordierite and anthophyllite particularly noteworthy. Sillimanite rather than andalusite is the com-

mon aluminum silicate, and there is a strong tendency for Zn to be incorporated in the structure of early silicate and spinel minerals.

The Cotopaxi deposit is included in a large xenolith of high-grade regional metamorphic rocks and conforms to the enclosing metamorphic structure. The surrounding granite transects the metamorphic foliation, is unmineralized, and is presumably younger than the deposit.

The deposit appears to be essentially the result of one overall geologic event, with separable stages during the formation of the deposit all genetically related. The following sequence of separable stages are present:

- (1) Formation of the amphibolite. Principal minerals are magnesium, calcium, iron, and minor manganese-bearing amphiboles. The composition is unusual; it may represent a partially metasomatized regional amphibolitic rock, or it may be entirely metasomatic.
- (2) Pegmatoid stage. This stage includes mainly the formation of silicate minerals, but includes some oxide, aluminate, tungstate, rare carbonate minerals, and minor molybdenite. The pegmatoid stage involved the reorganization of existing minerals, along with some metasomatism, into a coarse to giant-grained aggregate of mainly distinctive new species.
- (3) Sulfide deposition. The successive formation of pyrite, pyrrhotite, sphalerite, chalcopyrite, and galena constitute this phase. Galena is distinctly later than the other sulfide minerals.
- (4) Retrograde alterations. This appears to be the most complex stage and perhaps represent more than one episode, with an incomplete superimposition of stages. In general the alteration of the silicate gangue minerals involves an increasing complexity in the silicate linkage and an increasing water content. Alterations within the ore minerals involve the conversion of pyrrhotite to pyrite, or an intimate mixture of pyrite-magnetite, and pyrite-magnetite-marcasite. Marcasite is commonly coarsely twinned and is always non-colloform.
- (5) Surficial weathering.

The reuse of much of the same material during each succeeding stage, and the strong tendency toward equilibrium, at least within local volumes during individual stages, all indicate that the overall mineralization extended over a considerable time interval. Particularly is this evident considering the different requirements of each stage in pressure, temperature, and activities of specific components.

The source of the mineralization at Cotopaxi is not certainly determinable. The youngest granite in the area is post-mineralization; however, there is evidence of earlier igneous activity and a magmatic source cannot be precluded. Also possible is that the source volume for the Cotopaxi deposit may have been the metamorphic rocks themselves. As the rocks were slowly being reconstituted under intense metamorphism, those elements not readily incorporated into the new rock-forming silicate structures might have collected in concentrations sufficient for ore genesis. Some support for this latter view is found in the diverse composition of the deposit—mineralization derived from normal igneous rock types is not so heterogeneous in composition.

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