Geochemistry and Potassium-Argon Ages of Plutonic Rocks in the Battle Mountain Mining District, Lander County, Nevada

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GEOCHEMISTRY AND POTASSIUM-ARGON AGES OF PLUTONIC ROCKS IN THE BATTLE MOUNTAIN MINING DISTRICT, LANDER COUNTY, NEVADA

By TED G. THEODORE, MILES L. SILBERMAN, and DAVID W. BLAKE[1]

ABSTRACT

The Battle Mountain mining district is in Lander County, north-central Nevada, at the northwest end of the Eureka–Battle Mountain mineral belt. The district is underlain predominantly by lower to upper Paleozoic sedimentary rocks, which occur in three major thrust plates and an interjacent autochthonous tectonic block. These rocks were intruded by a single Cretaceous (87 million years) pluton and subsequently by a large number of stocks and dikes in the Tertiary from 41 to 38 m.y. ago. Many of the intrusive rocks are inferred to have originally been granodiorites, now hydrothermally altered in varying degrees to more potassic K-feldspar–white mica–(biotite) assemblages. The altered plutons are chemically equivalent to quartz monzonites. These silicate alteration assemblages are commonly associated with economic sulfide deposits in the southern part of the district. In addition, increases in concentrations of Cu, Ag, Mo, and Rb in the intrusion at Copper Canyon during alteration followed increases of K_2O.

At Copper Canyon, biotite K-Ar ages for an altered granodiorite associated with the nearby porphyry copper deposit average $38.2_2 \pm 0.2_3$ m.y. The age of metallization in the porphyry copper deposit is $37.2_0 \pm 0.0_6$ m.y., as measured by whole-rock K-Ar determinations. Hypogene sulfide veins that cut the intrusion establish the post-magmatic nature of most metallization. However, the measured 1-m.y. time interval between crystallization of coarse primary biotite and metallization may be a maximum value, resulting from the much finer grain size of the hydrothermal assemblage rather than from an actual age difference. During cooling of the ore, its retentivity of argon was probably less than that of the coarse primary biotites.

INTRODUCTION

The Battle Mountain mining district is in the Antler Peak quadrangle (15 min) and at the northwest end of the Eureka–Battle Mountain mineral belt—a northwest-southeast alinement of metal mining districts inferred to be localized by deep-seated Precambrian (?) structural features (Roberts, 1966) (figs. 1 and 2). The district produces the most copper in north-central Nevada and includes the Copper Canyon porphyry copper deposit (Sayers and others, 1968) and additional potentially economic porphyry-type deposits. Over $13 million in copper, gold, silver, lead, and zinc was produced through 1961, mostly from the Copper Canyon area in the southern part of the district (Roberts and Arnold, 1965, p. B40). Noble (1970) estimated that proved copper reserves in the Battle Mountin mining district totaled $300 million before Duval Corp. began large-scale mining operations in 1967.

This report serves three purposes: it (1) dates plutonism in the mining district, (2) describes the chronology of igneous activity and metallization at the Copper Canyon porphyry copper deposit, and (3) provides a basic geochemical framework (including data and interpretation) for more detailed studies of the Copper Canyon deposit (Theodore and Blake, 1973).

Acknowledgments.—The cooperation of F. H. Howell and A. E. Shiell, Duval Corp., made possible those aspects of this study dealing with the Copper Canyon porphyry copper deposit. T. J. Armbrustmacher, R. J. Roberts, and C. T. Wrucke, all with the U.S. Geological Survey, helped to collect many of the samples. Chemical and spectrographic analyses were made in the laboratories of the U.S. Geological Survey.

GENERAL GEOLOGY OF THE BATTLE MOUNTAIN MINING DISTRICT

The Battle Mountain mining district is underlain predominantly by Paleozoic rocks that form a complex sequence of thrust plates (Roberts, 1964). Much of this part of Nevada was underlain by siliceous and

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[1] Duval Corp., Battle Mountain, Nev.

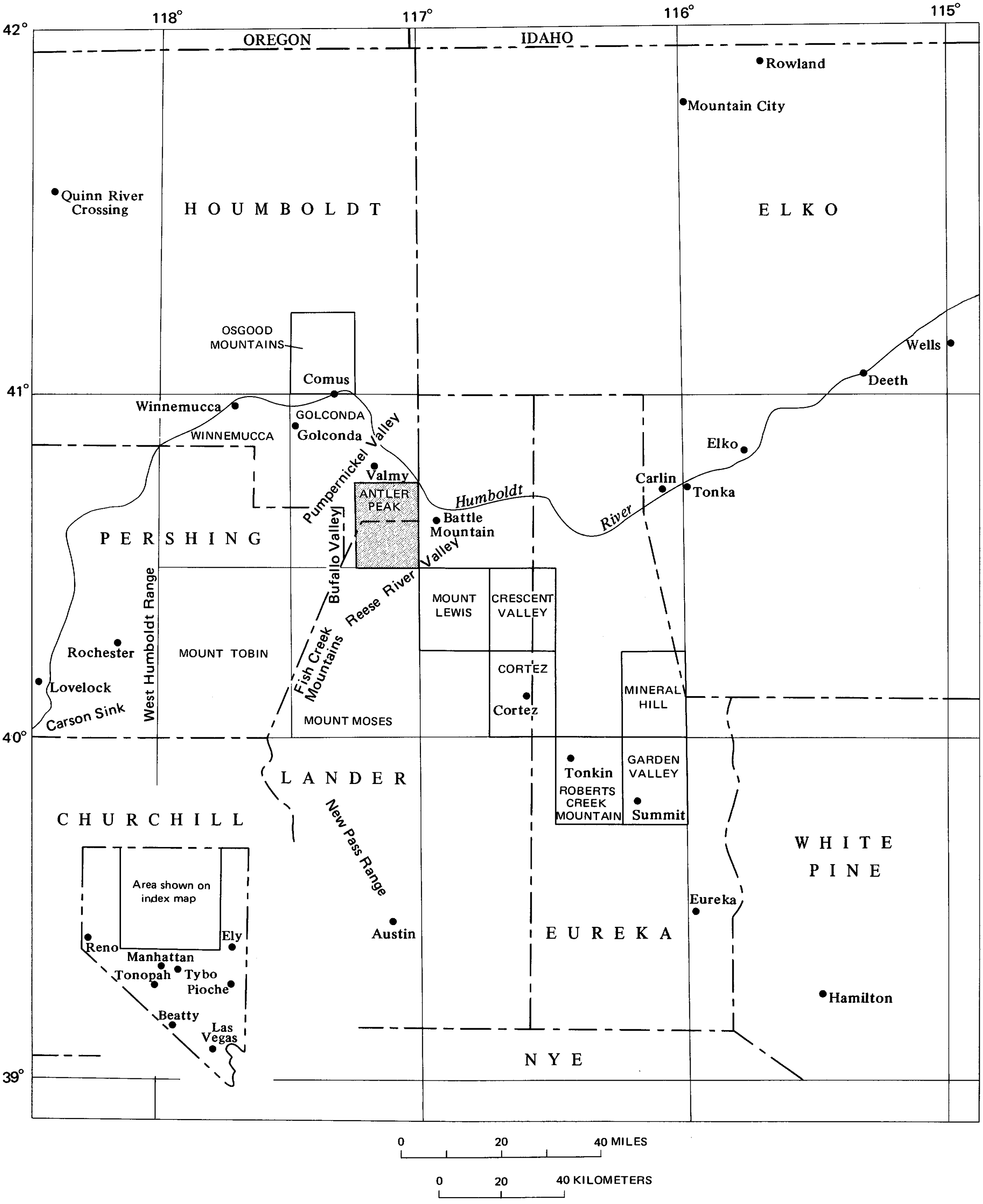


FIGURE 1.—North-central Nevada.

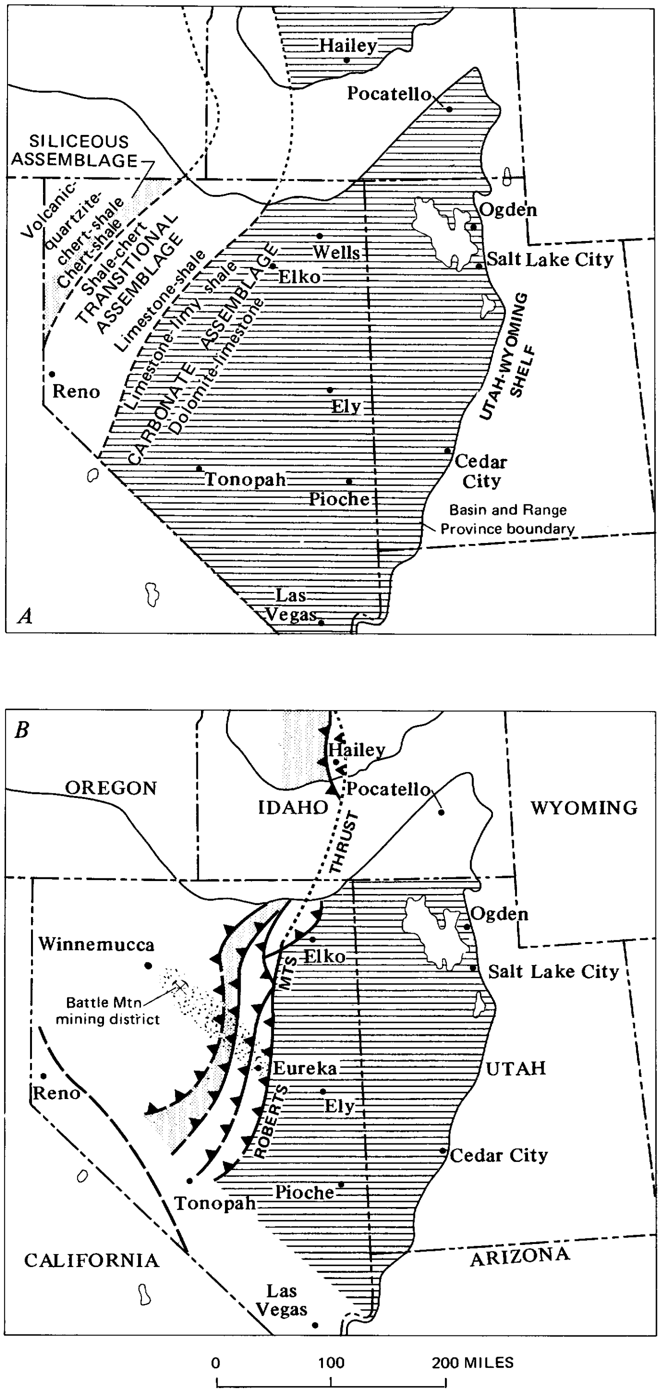


FIGURE 2.—Facies maps. *A*, distribution of facies in the Cordilleran geosyncline, Cambrian through Devonian time. *B*, distribution of facies after Late Devonian and Early Mississippian thrusting (Roberts and others, 1971) and the location of the Battle Mountain mining district (Roberts, 1966).

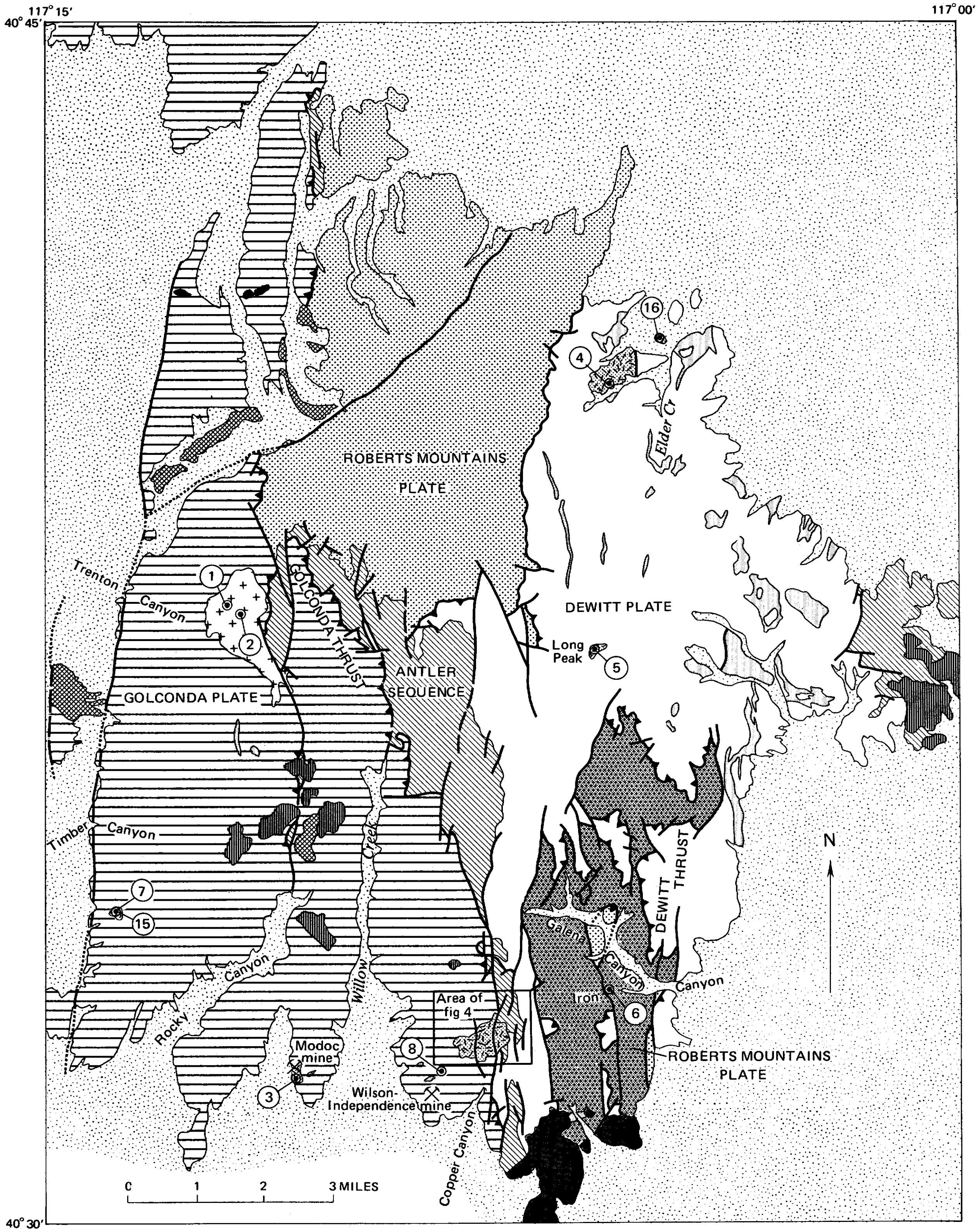
volcanic rocks in the upper plate of the Roberts Mountains thrust (fig. 2), which moved volcanic rocks, chert, shale, and quartzite of early and middle Paleozoic age eastward over a lower plate consisting of carbonate rocks of an equivalent age (Roberts and others, 1958; Roberts, 1966). This thrust does not crop out in the mining district (Roberts, 1964), but it probably passes beneath the area at depths greater than about 1,400 m (Theodore and Roberts, 1971). In addition to rocks in the upper plate of the Roberts Mountains thrust, the district is underlain by rocks belonging to two other structurally higher major thrust plates, the Dewitt and Golconda plates, and an interjacent autochthonous block, the Antler sequence (fig. 3).

About 35 stocks and dikes, each generally less than 3 sq km in outcrop area, intrude this complex of tectonic blocks. They range from gabbros to granites, with quartz monzonites and granodiorites predominating. Complete descriptions of many of these rocks are included in the report by Roberts (1964). Texturally, many are hypidiomorphic-granular, although porphyritic facies are also common. As part of a broader regional investigation by Silberman, K-Ar age determinations were made on 14 mineral separates from nine different intrusive bodies in the Antler Peak quadrangle. Two whole-rock age determinations were made also on hydrothermal biotite–white mica–K-feldspar intergrowths from two pyrite- and chalcopyrite-bearing rocks in the Copper Canyon porphyry copper deposit.

GEOLOGY OF THE COPPER CANYON AREA

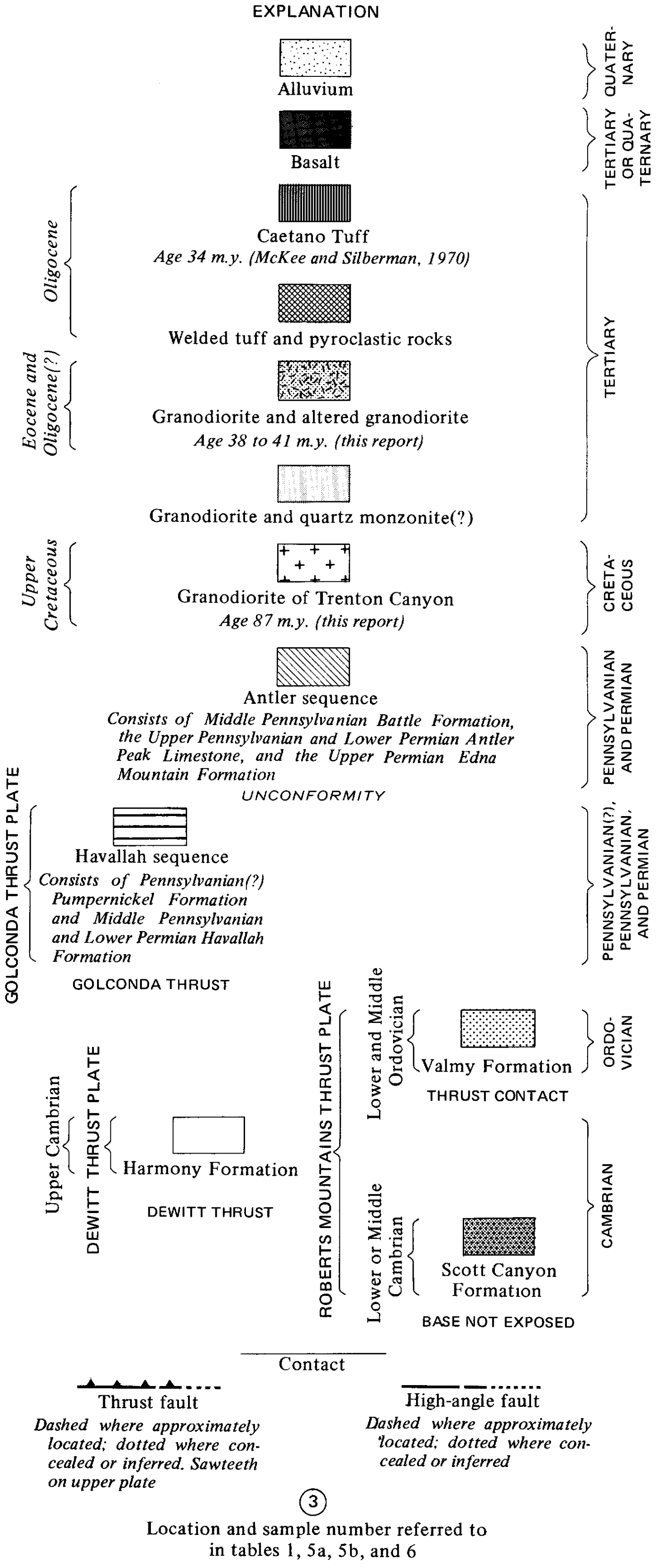
A 1,200-m-wide intrusive body crops out at Copper Canyon (fig. 4), in the southern part of the mining district. Drill holes into the body have shown it to be sill-like or laccolithic (Blake, 1971; Theodore and Blake, 1973). Peripheral to it, base- and precious-metal deposits are arranged in fairly systematic zones for a distance of about 8 km outward from the center (Roberts and Arnold, 1965). The Copper Canyon porphyry copper deposit (the east and west ore bodies) is in a central copper-gold-silver zone, just north and east of the intrusive body, primarily in conglomerate of the lower member of the Battle Formation (fig. 4) but also in sandstone of the Harmony Formation and tactite provisionally assigned to the Pumpernickel Formation.

Locally, metamorphism and metasomatism of rocks belonging to the Pumpernickel Formation in the west ore body (fig. 4) produced anhydrous tactite silicate assemblages (Nash and Theodore, 1971), most likely concomitant with the intrusion's crystallization from a magma. The intrusive rock is predominantly porphyritic. A remnant "quenched" groundmass texture (fig. 5*A*) has been detected in a few samples. We interpret inclusion of K-feldspar and quartz groundmass crystals along the margins of plagioclase phenocrysts (fig. 5*A*) as reflecting continued growth of the plagioclase (although more albitic) at hypersolidus conditions fol-



Geology modified from Roberts (1964, pl. 1)

FIGURE 3.—Generalized geologic map of the Antler Peak quadrangle and Battle Mountain mining district, Lander County, Nev. Localities of chemically and (or) K-Ar analyzed samples also shown. Location numbers same as tables 1 and 7. Localities 9–14, 17, 18 are shown in figure 4.



lowing emplacement of the intrusion. Both the anhydrous metamorphic assemblages in the wallrock and much of the matrix in the intrusive rock subsequently were metasomatically recrystallized to an even finer grained (fig. 5*B*), highly sutured assemblage of quartz–K-feldspar–white mica–(biotite). The average grain size of the matrix is now about 0.01 mm. This superposition of potassic alteration on an earlier anhydrous contact assemblage was also recognized by Roberts and Arnold (1965, p. B26). Both the pluton and the porphyry copper ore zones are characterized by potassic alteration assemblages similar to those described by Creasey (1966) and Meyer and Hemley (1967). Very little sulfide ore has been found in the altered granodiorite of Copper Canyon itself, although several of the samples collected for the K-Ar study contain pyrite, and the pluton is at the core of a broad pyritic halo that encompasses most of the southern part of the mining district (Roberts and Arnold, 1965; Theodore and Blake, 1969). The altered granodiorite is anomalously rich in copper, compared with unaltered rocks in the district (as described below) and rocks of similar composition elsewhere, but much of this copper is contained in altered plagioclase phenocrysts and is secondary, or supergene.

There is further evidence in the rocks that alteration and metallization followed primary crystallization of the intrusive body. Fluid inclusions of the dense, brine type occur both in the ore zones and, especially, along microfractures through quartz phenocrysts in the intrusive rock (Nash and Theodore, 1971). These relations strongly suggest that most hydrothermal potassic alteration and attendant metallization took place after the intrusive rock had solidified. Nevertheless, metallization must have occurred soon after the body was emplaced, with magmatic heat as a possible driving mechanism. Additional petrographic descriptions of rocks from this intrusive body are included in the sections on the chemistry of the plutons and their biotites.

CHEMISTRY OF THE GRANODIORITES

MAJOR ELEMENTS

Twelve samples (table 1) of intrusive rocks representing 11 different plutonic bodies from throughout the mining district were chemically analyzed for major and minor elements, and eight of these samples were dated by the K-Ar method. The samples include both fresh, unaltered rock and rock hydrothermally altered by fluids associated with the development of nearby hypogene sulfide deposits.

Five analyses of unaltered rocks are similar to the "average biotite granodiorite, average hornblende-biotite granodiorite, and average granodiorite" of Nock-

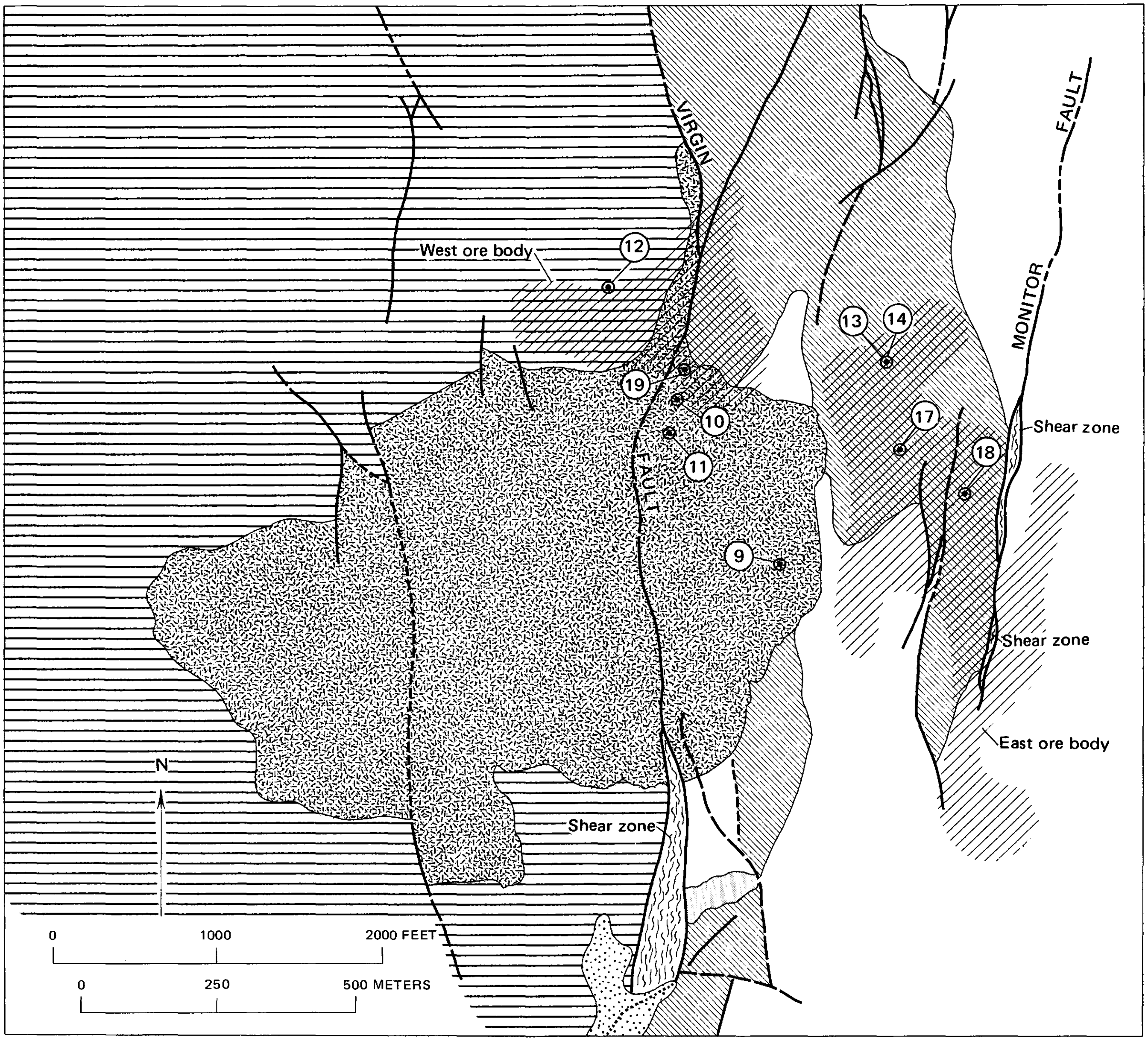


FIGURE 4.—Generalized geologic map of Copper Canyon area, Lander County, Nev., showing location of K-Ar age-dated and chemically analyzed samples. Geology modified from Roberts (1964) and Theodore and Blake (1973). Explanation same as for figure 3.

olds (1954, p. 1014), listed in table 1 for comparison. However, our samples are slightly richer in MgO—probably reflecting the high magnesian content of biotites, as found in one of the intrusive bodies. Furthermore, the rocks are generally also slightly lower in Na_2O than the three "average" granodiorite analyses of Nockolds (table 1). Finally, specimens 3, 4, and 15 (all of which contain notable modal hornblende) are slightly richer in CaO than Nockolds' average for 65 hornblende-biotite granodiorites. These analyses suggest slightly more modal hornblende in these three rocks than in Nockolds' "average hornblende-biotite granodiorite."

The differentiation index (sum of normative orthoclase, quartz, and albite) for the five unaltered igneous rock specimens ranges from 61 to 75; the average is 67. The differentiation indices for Nockolds' (1954) "average biotite granodiorite, average hornblende-biotite granodiorite, and average granodiorite" are 67, 70, and 73, respectively. Normative Q, Ab, An, and Or in molecular proportions for five unaltered specimens are included on the accompanying ternary diagram (fig. 6). The triangular plot indicates that these five unaltered specimens (collected from four widely separated intru-

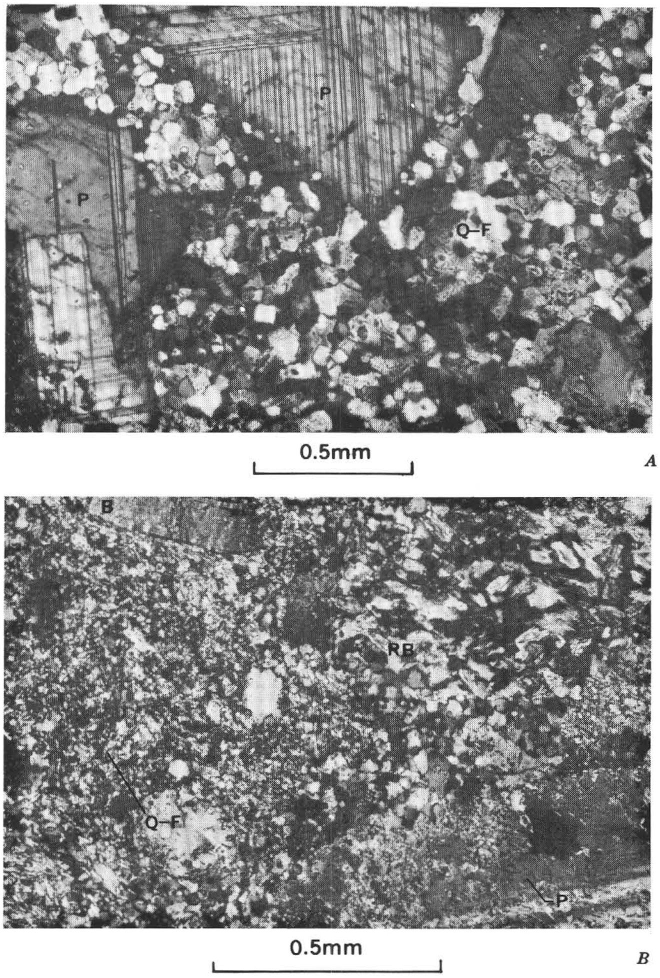


FIGURE 5.—Textures in the altered granodiorite of Copper Canyon. *A*, Photomicrograph of "quenched" groundmass texture. Crossed nicols. P, plagioclase phenocryst; Q-F, quartz–K-feldspar. *B*, Photomicrograph of hydrothermally altered rock from the granodiorite of Copper Canyon. Crossed nicols. B, primary phenocrystic biotite; RB, secondary recrystallized biotite; P, partly sericitized plagioclase phenocryst; Q–F, quartz–K-feldspar hydrothermally altered groundmass.

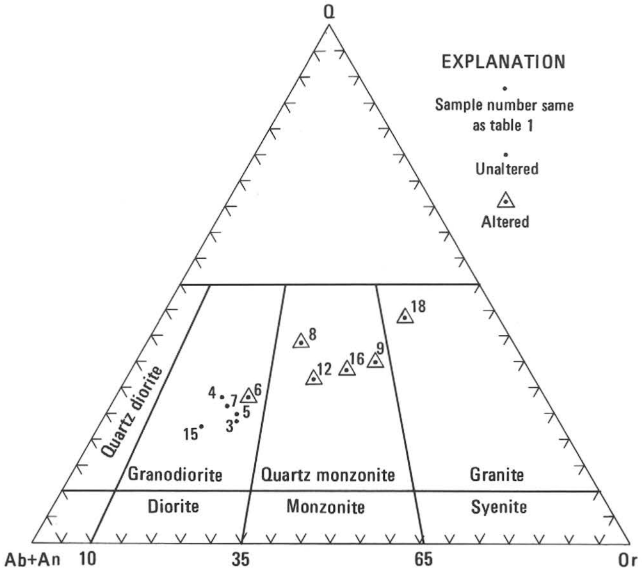


FIGURE 6.—Distribution of normative quartz (Q), plagioclase (Ab+An), and orthoclase (Or) in 11 chemicially analyzed specimens (table 1) of intrusive rocks from the Battle Mountain mining district, Lander County, Nev. Bateman's classification (1961).

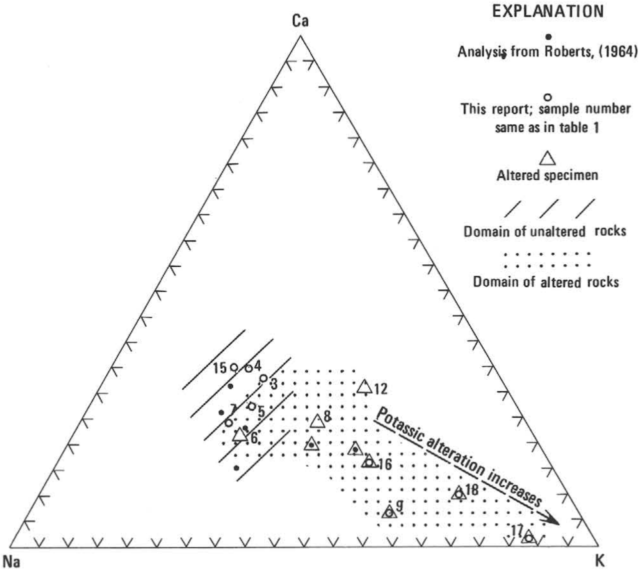


FIGURE 7.—Distribution of Ca, Na, and K in 18 specimens of plutonic rocks (both altered and unaltered) from the Battle Mountain mining district.

sive bodies, fig. 3) form a fairly tight cluster of points within what Bateman (1961) defines as the granodiorite part of the diagram.

On a triangular plot of Na, Ca, and K in atomic proportions for all available chemical analyses of igneous rock specimens from the Battle Mountain district (fig. 7), the unaltered and altered rocks appear to define two partially overlapping domains. Most of the effects of hydrothermal alteration are found in the matrix, where alteration is indicated by complexly recrystallized quartz, K-feldspar, and white mica intergrowths, with some newly grown hydrothermal biotites. Furthermore, magmatic plagioclase and K-feldspar phenocrysts are sericitized and "clouded" to varying degrees, and hornblende is commonly partly altered to biotite. The most intensely altered rocks (specimens 17 and 18, table 1 and fig. 7) are samples of two dikes, 4.5 and 6.0 meters wide, emplaced into the Battle and Harmony Formations, respectively, in the east ore body of the Copper Canyon porphyry copper deposit. Eight of the nine altered specimens shown in figure 4 are from the general area of Copper Canyon; the remaining sample of altered rock (specimen 16) is from the Elder Creek area, at the north end of the mining district. The

TABLE 1.—*Analyses of intrusive rocks*

[------, not detected or calculated; N.A., not analyzed. Biotite from Nos. 3-9 was subjected to K-Ar analysis for age

Specimen and location number, same as table 7, and figs. 3, 4 Field number (MB–)	3 20	4 12	5 16	6 21	7 9	8 19
Rapid rock chemical analyses (weight percent)[4]						
SiO_2	64.5	66.3	65.6	64.4	68.4	69.1
Al_2O_3	15.4	15.2	16.2	16.3	15.6	15.0
Fe_2O_3	1.3	.62	.81	.50	.73	.43
FeO	2.7	2.8	2.9	3.0	1.7	1.7
MgO	2.9	3.0	1.8	2.5	1.5	2.2
CaO	4.7	4.5	3.8	4.1	3.6	2.7
Na_2O	3.1	3.0	3.4	3.3	3.9	2.1
K_2O	3.2	2.6	3.2	3.0	3.0	3.7
H_2O^-	.43	.09	.20	.00	.09	.41
H_2O^+	.87	1.0	.73	.91	.75	1.3
TiO_2	.46	.54	.51	.58	.35	.38
P_2O_5	.11	.10	.17	.11	.08	.07
MnO	.06	.05	.08	.08	.03	.03
CO_2	.09	$<.05$	$<.05$	1.2	.10	$<.05$
Total	100	100	99	100	100	99
S as SO_3	----------	----------	----------	----------	----------	----------
CIPW norms						
Q	19.7	23.7	21.8	22.9	24.0	33.2
c	----------	----------	.8	3.2	----------	2.8
or	18.9	15.4	19.0	17.7	17.8	22.1
ab	26.3	25.4	28.9	27.9	33.1	17.9
an	18.7	20.4	17.3	12.0	16.2	13.1
Normative an	(An_{42})	(An_{45})	(An_{38})	(An_{30})	(An_{33})	(An_{42})
wo	1.4	.6	----------	----------	.2	----------
en	7.2	7.5	4.5	6.2	3.7	5.5
fs	3.2	3.8	4.0	4.3	2.0	2.2
mt	1.9	.9	1.2	.7	1.1	.6
il	.9	1.0	1.0	1.1	.7	.7
ap	.3	.2	.4	.3	.2	.2
cc	.2	----------	.2	2.7	.3	----------
Total	98.7	98.9	99.1	99.0	99.3	98.3
Niggli numbers						
Al	33.9	34.9	38.6	----------	40.0	----------
Fm	28.4	28.5	23.4	----------	18.4	----------
C	18.8	18.8	16.5	----------	16.8	----------
Alk	18.9	17.8	21.6	----------	24.8	----------
Si	241.0	250.5	265.2	----------	297.1	----------
Ti	1.3	1.6	1.6	----------	1.2	----------
P	.17	.16	.29	----------	.15	----------
H	16.2	14.2	12.5	----------	12.2	----------
K	.40	.36	.38	----------	.34	----------
Mg	.57	.61	.46	----------	.53	----------
Q	65.6	87.1	78.9	----------	98.6	----------
Semiquantitative spectrographic analyses (weight percent)[6]						
Ag	0.00007	----------	----------	----------	----------	0.0007
B	----------	----------	----------	----------	----------	.0007
Ba	.15	0.1	0.1	0.07	0.15	.2
Be	.00015	.00015	.0002	.0002	.0002	.0003
Co	.001	.0015	.001	.001	.001	.0007
Cr	.015	.015	.002	.01	.005	.007
Mo	----------	----------	----------	----------	----------	.001
Nb	.0007	.0007	.001	----------	.0007	.001
Ni	.005	.005	.0005	.003	.001	.003
Sc	.0015	.0015	.001	.0015	.0007	.001
Sn	----------	----------	----------	----------	----------	----------
Sr	.07	.07	.05	.05	.07	.05
V	.007	.01	.01	.01	.005	.007
W	----------	----------	----------	----------	----------	----------
Y	.001	.0015	.002	.001	.001	.0015
Zr	.015	.01	.01	.01	.01	.015
Ga	.0015	.0020	.0015	.0015	.0015	.0015
Yb	.00015	.00015	.0002	.00015	.0001	.00015
La	----------	----------	----------	----------	----------	----------
Ce	----------	----------	----------	----------	----------	----------
Chemical analyses (ppm)[7]						
Au	0.07	<0.05	<0.05	<0.05	<0.05	0.4
Cu	6.6	120.	7.6	4.2	4.8	900.

See footnotes at end of table.

in the Battle Mountain mining district

determination. Specimens 6, 8, 9, 12, and 16–18 were hydrothermally altered; Niggli Nos. were not calculated for them]

9 18	12 40	15 10	16 11	17 17	18 28	Biotite granodiorite[1]	Hornblende-biotite granodiorite[2]	Average granodiorite[3]
Rapid rock chemical analyses (weight percent)[4]								
70.5	64.0	62.5	70.5	66.9	67.2	68.97	65.50	66.88
14.5	15.1	16.9	14.5	14.7	15.8	15.47	15.65	15.66
1.0	2.0	1.6	.90	.92	1.2	1.12	1.63	1.33
.16	3.1	3.4	1.0	1.6	1.5	2.05	2.79	2.59
1.5	3.5	2.9	1.5	2.7	2.5	1.15	1.86	1.57
.95	3.5	4.8	2.2	.29	.94	2.99	4.10	3.56
2.1	1.5	3.3	2.1	.53	.93	3.69	3.84	3.84
6.1	4.3	2.4	5.6	6.6	5.5	3.16	3.01	3.07
.50	.44	.25	.26	.93	1.2	....	....	....
1.5	1.5	.85	.84	2.2	2.5	.70	.69	.65
.47	.51	.75	.43	.78	.47	.45	.61	.57
.00	.16	.18	.07	.07	.14	.19	.23	.21
.00	.02	.09	.00	.00	.01	.06	.09	.07
<.05	<.05	.14	<.05	<.05	<.05	....	....	....
100	100	100	100	98	100	100	100	100
....	....	....	....	1.5	....	....	....	....
CIPW norms								
31.2	25.2	18.6	30.2	....	35.0	26.2	20.0	21.9
3.2	2.0	.9	1.5	....	7.0	.7	....	....
36.0	25.5	14.2	33.0	....	32.5	18.9	17.8	18.3
17.7	12.7	27.9	17.8	....	7.9	31.4	32.5	32.5
3.4	16.4	21.7	9.6	....	3.7	14.2	16.4	16.4
(An$_{16}$)	(An$_{56}$)	(An$_{44}$)	(An$_{35}$)	....	(An$_{32}$)	(An$_{31}$)	(An$_{34}$)	(An$_{34}$)
....	....	....	....	....	....	....	.9	....
3.7	8.7	7.2	3.7	....	6.2	2.9	4.6	3.9
1.3	3.2	3.8	.6	....	1.0	2.2	2.9	2.9
1.2	2.9	2.3	1.3	....	1.7	1.6	2.3	1.9
.9	1.0	1.4	.8	....	.9	.8	1.2	1.1
.2	.4	.4	.2	....	.3	.4	.6	.5
.3	....	.3	.3	....	....	....	....	....
[5]99.2	98.0	98.7	99.0	....	96.2	99.3	99.2	99.4
Niggli numbers								
....	....	35.2	....	....	....	....	....	....
....	....	29.9	....	....	....	....	....	....
....	....	18.2	....	....	....	....	....	....
....	....	16.7	....	....	....	....	....	....
....	....	221.0	....	....	....	....	....	....
....	....	2.0	....	....	....	....	....	....
....	....	.27	....	....	....	....	....	....
....	....	13.0	....	....	....	....	....	....
....	....	.32	....	....	....	....	....	....
....	....	.51	....	....	....	....	....	....
....	....	54.1	....	....	....	....	....	....
Semiquantitative spectrographic analyses (weight percent)[6]								
0.0002	0.0005	....	0.0001	0.0007	0.001	....	....	....
.0007	....	....	.0007	.0007	....	....	....	....
.15	.3	0.07	.07	.2	.5	....	....	....
.0002	....	.00015	.0002	....	....	....	....	....
.001	.002	.0015	.0003	.005	.0005	....	....	....
.01	.02	.005	.007	.02	.015	....	....	....
.003	....	....	.0005	.0003	....	....	....	....
.001	.0007	.001	.0007	.0007	.0007	....	....	....
.005	.005	.0002	.002	.007	.0015	....	....	....
.001	.0015	.0015	.0007	.0015	.0015	....	....	....
....	.0007	....	....	.0007	....	....	....	....
.03	.05	.07	.05	.02	.03	....	....	....
.01	.01	.01	.005	.01	.01	....	....	....
....	....	....	.015	....	....	....	....	....
.0007	.0015	.002	.001	.001	.003	....	....	....
.01	.007	.015	.007	.01	.01	....	....	....
.002	.002	.0015	.0015	.0015	.002	....	....	....
.00001	.00015	.0002	.0001	.00015	.0002	....	....	....
....	.003	....	....	....	.005	....	....	....
....	.007	....	....	....	.01	....	....	....
Chemical analyses (ppm)[7]								
0.1	N.A.	<0.05	<0.05	0.3	N.A.	....	....	....
1500.	990.	16.	460.	6600.	555.	....	....	....

See footnotes at end of table.

TABLE 1.—*Analyses of intrusive rocks in the*

Specimen and location number, same as table 7, and figs. 3, 4	3	4	5	6	7	8
Field number (MB–)	20	12	16	21	9	19
Chemical analyses (ppm)[7]—Continued						
Pb	14.	20.	20.	28.	20.	22.
Zn	44.	140.	29.	50.	43.	160.
U	2.3	3.6	4.7	4.2	2.4	4.3
Th	8.0	8.2	7.2	6.9	9.6	6.9
Hg	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
Rb	102	119	126	111	120	147
Sr	640	590	490	540	570	414
(Rb:Sr)	(.159)	(.202)	(.257)	(.206)	(.211)	(.356)
(K:Rb)	(259)	(220)	(215)	(223)	(222)	(217)

[1] Average of 36 biotite granodiorites from Nockolds (1954, p. 1014).

[2] Average of 65 hornblende-biotite granodiorites from Nockolds (1954, p. 1014).

[3] Average of 137 granodiorites from Nockolds (1954, p. 1014).

[4] Chemical analyses by rapid rock method; analysts: P. L. D. Elmore, Lowell Artis, J. L. Glenn, Gillison Chloe, J. Kelsey, and Hezekiah Smith. Methods used are those described in Shapiro, L., and Brannock, W. W., 1962, Rapid Analysis of silicate, carbonate, and phosphate.

[5] Includes 0.1 percent normative hematite.

changes due to alteration, depicted diagrammatically in figure 7, primarily reflect potassic metasomatism —the K-feldspar, white mica (biotite) facies of Creasey (1966)— in the general area of the porphyry copper deposit at Copper Canyon (Roberts and Arnold, 1965; Nash and Theodore, 1971; Theodore and Blake, 1973). The trend shown by the altered rocks (fig. 7) is one of progressive leaching of CaO and addition of K_2O concomitant with increasing intensity of potassic alteration. Alteration of specimen 6 (table 1; fig. 7) appears to have consisted primarily of groundmass recrystallization, with negligible addition of K_2O.

From the data plotted in figures 6 and 7, we infer that, before alteration, the intrusive rocks at Copper Canyon were granodiorites. Truly unaltered specimens of these rocks have not been found at Copper Canyon. Modally the rocks are now quartz monzonites (Roberts, 1964; Clement, 1964; Blake, unpub. data). To emphasize further the chemical contrasts between the altered and unaltered plutonic rocks, we have also shown in figure 6 plots of normative Q, Ab + An, and Or ratios in molecular proportions for the altered specimens analyzed. These plot as normative quartz monzonites and granites. Similar chemical contrasts between altered and unaltered intrusive bodies associated with porphyry copper deposits have been reported elsewhere (see Moore, 1970b). Creasey (1966, p. 52) found that the norms of unaltered porphyries associated with seven of the Arizona porphyry copper deposits cluster in the granodiorite field, near the granodiorite-quartz monzonite boundary.

For each of the recognized intrusive sequences in the Sierra Nevada batholith, Bateman and Dodge (1970) found a systematic (almost linear) decrease in the $K_2O:SiO_2$ ratio with decreasing SiO_2. They showed that K_2O-SiO_2 plots define trends that intersect zero K_2O at about 40–45 weight percent SiO_2. Similar K_2O-SiO_2 plots from the granodiorite analyses of Battle Mountain define a remarkably similar trend whose projection intersects zero K_2O at about 45 weight percent SiO_2. However, chemical data available from plutons across much of north-central Nevada (M. L. Silberman, unpub. data) suggest a slightly different average trend for the region: zero K_2O would be intersected at about 50 weight percent SiO_2.

MINOR ELEMENTS

Trace elements in the plutons are typical of those commonly associated with granodiorites or potassic-altered granodiorites. The trace element contents of the specimens selected for rapid rock analyses are shown in table 1. As an aid to estimate better the areal variations of metallic trace elements in the stocks, concentrations across nine of the intrusive bodies (both altered and unaltered) are listed in table 2. The samples in table 2 were collected from localities spanning the entire exposed plutons. Each sample is a composite weighing a total of about 1 kilogram collected over an outcrop area of about 10 sq. m; sample group 6 (AEH–926, AEH–927), however, represents composite drill core samples.

Estimates by Vinogradov (1962) and Turekian and Wedepohl (1961) of average abundances of minor elements in selected rock types are shown in table 3. Compared with these estimates, unaltered granodiorite from the Battle Mountain mining district is generally poorer in Nb, Y, Zr(?), La, and Hg, and generally slightly richer in Sc. In addition, many of the granodiorite plutons display individual differences. The granodiorite of Trenton Canyon, for example, is richer in Cu and Mo. The granodiorite of the Elder Creek area is richer in Cu, Cr, and W. (W occurs as very sparse disseminated grains of scheelite.) Granodiorite of the Long Peak area is richer in Mo, and granodiorite of the

Battle Mountain mining district—Continued

9 18	12 40	15 10	16 11	17 17	18 28	Biotite granodiorite[1]	Hornblende-biotite granodiorite[2]	Average granodiorite[3]
			Chemical analyses (ppm)[7]—Continued					
20.	33.	17.	14.	21.	18.	....	....	....
110.	245.	59.	26.	31.	39.	....	....	....
9.0	1.9	1.7	2.3	5.1	2.1	....	....	....
5.4	6.0	7.4	6.6	6.3	15.	....	....	....
<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	....	....	....
215	140	87	121	274	175	....	....	....
319	348	570	429	209	204	....	....	....
(.675)	(.403)	(.153)	(.283)	(1.31)	(.857)	....	....	....
(245)	(255)	231)	(382)	(203)	(261)	....	....	....

[6] Analyst: Chris Heropoulos. Results are reported to the nearest number of the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, ..., which represent approximate midpoints of interval data on a geometric scale. The precision of a reported value is approximately plus or minus one series interval at 68 percent confidence. Looked for but not found: As, Au, Bi, Cd, Pd, Pt, Sb, Te, U, Zn, Ge, Hf, In, Li, Re, Ta, Th, Tl. Also looked for but not found in samples 12 and 18: Pr, Nd, Sm and Eu.

[7] Au was determined by a combined fire-assay atomic absorption technique; analyst: Carroll L. Burton. Cu, Pb, and Zn were determined by atomic absorption spectroscopy; analyst, Carroll L. Burton. U was determined fluorimetrically; analyst, Joseph Budinsky. Th was determined by instrumental neutron activation analysis; analysts: Carroll L. Burton and F. O. Simon. Hg was determined spectrophotometrically by a Penfield-dithizone method; analyst: Jesse J. Warr. Rb and Sr were determined by x-ray spectroscopy; analysts: B. P. Fabbi and L. F. Espos.

Timber Canyon area is slightly richer in Cu.

Additional data for whole-rock Ba, Rb, and Sr in the five unaltered granodiorites provide background levels with which to compare these elements in altered rocks (table 1). Ba concentrations are in the 700–1,500 ppm range; Rb, 87–126 ppm; and total Sr, 490–640 ppm. These Ba and Sr values are slightly higher than the tabulated crustal abundances for rocks of this composition (table 3). Also, the average K:Rb ratio for these five specimens (229) is nearly identical with that for crustal rocks (230) (Heir and Adams, 1964), and well within the range of reported K:Rb ratios for "granitic" rocks (fig. 8). Ba:Rb ratios for the five granodiorites are about 10, and Rb:Sr ratios are in the 0.153–0.257 range. The geochemical data (table 1) for the unaltered granodiorites of Battle Mountain also indicate a direct relationship between silica content and both K_2O and Rb. Furthermore, a K:Rb versus Rb:Sr variation plot for these unaltered granodiorites is consistent with the results obtained in plutonic rocks over a broad area of north-central Nevada (M. L. Silberman, unpub. data).

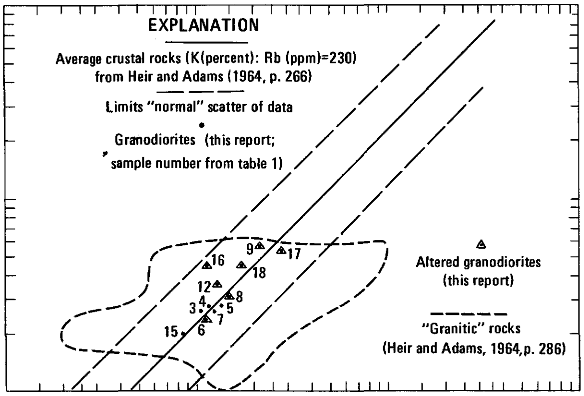


FIGURE 8.—Plots of K (in percent) : Rb (in ppm) for average crustal rocks, "granitic' rocks (modified from Heir and Adams, 1964), and five specimens of unaltered granodiorite from the Battle Mountain mining district.

Percentages of several minor elements in altered granodiorite of the Copper Canyon area are significantly different from those in the unaltered granodiorites. The altered rocks are enriched in Cu. However, because of the extreme mobility of Cu during supergene processes, it is very difficult to use these data to evaluate overall levels of Cu enrichment that occurred during potassic alteration in the granodiorites. The geochemical data (tables 1 and 2) also suggest that alteration resulted in widespread but relatively low level increases in Ag, Mo, and possibly B contents. The altered granodiorite of the Copper Canyon area (sample location 9, table 2) also appears to be somewhat more enriched in As and Zn than the other granodiorites. The altered granodiorite of the Iron Canyon area (sample location 6, table 2) contains relatively high concentrations of As (300 and 2,000 ppm). Also, increases in the Rb:Sr ratios of the altered rocks (table 1) correlate remarkably well with increasing potassic alteration. (Compare table 1 with figure 6.) These results are not unexpected, as Rb closely follows K, and Sr follows Ca. K (+Rb) was apparently added to the rocks during alteration whereas Ca (+Sr) was lost. The most intensely altered specimen (17, table 1) appears to contain more than twice as much Rb as the unaltered granodiorites, and about one-third as much Sr.

The average K:U ratio for all Battle Mountain plutonic rocks, altered and unaltered, is 1.1×10^4, about the same as for most igneous rocks (Heir and Rogers, 1963; Tilton and Reed, 1963). The average K:U ratio for the seven altered rocks is 1.5×10^4.

BIOTITE COMPOSITIONS

In an attempt to resolve ambiguities of age determinations on primary phenocrystic biotites in hydro-

TABLE 2.—*Analyses for selected minor metals in plutonic rocks in the Battle Mountain mining district*

[Spectrographic analyses: Ag, Co, Cr, Cu, Mo, Ni, Pb. Results are reported in ppm to nearest number in the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1, 0.07, ...; these numbers represent approximate midpoints of group data on a geometric scale; analyst, E. F. Cooley. Gold and zinc were determined by an atomic absorption technique; analysts, H. D. McBride and J. G. Viets. Antimony and arsenic were determined by a colorimetric technique; analysts, S. I. Hoffman, H. D. McBride, M. S. Rickard, and A. W. Wells. Mercury was determined instrumentally; analyst, C. A. Cortis. ...., not detected]

Granodiorite of Trenton Canyon (Location No. 1 and 2, fig. 3)

Sample No. (AHW–)	179	180	181	182	183	184	185	186	187	188	189
Ag	....	....	1.0	....	....	....	....	1.0	<0.5	<0.5	<0.5
As	....	....	<10	....	10.0	10.0	40.0	....	10	20	10
Au	<0.02	<0.02	<.02	<0.02	.02	<.02	<.02	<.02	<.02	<.02	<.02
Co	5	10	10	5	5	5	5	5	5	5	5
Cr	5	10	10	5	5	5	<5	5	<5	5	5
Cu	50	50	50	100	70	100	70	100	30	50	100
Hg	.02	.03	.02	.03	.04	.05	.06	.02	.28	.24	.22
Mo	<5	<5	<5	<5	7	5	<5	10	<5	70	70
Ni	10	10	5	10	5	5	5	5	5	5	5
Pb	10	20	20	20	10	10	<10	15	10	10	10
Sb	<1	<1	<1	<1	<1	<1	<1	<1	<1	7	6
Zn	60	50	70	45	50	50	<25	45	55	<25	<25

Granodiorite of Modoc mine area (Location No. 3, fig. 3)

Sample No. (AHW–)	114	115	116	117	118	119	120	121	122	123	124	125	126
Ag	2.0	1.0	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
As	10	20	....	<10	<10	....	<10	....	....	....	....	....	10
Au	.1	.1	.1	.12	.04	.02	.06	.06	.06	.28	.08	.06	.06
Bi	....	....	....	....	....	....	....	....	....	....	....	....	10
Cr	150	150	150	150	150	150	150	150	150	150	150	150	150
Cu	10	20	10	50	30	20	30	30	30	30	50	30	30
Hg	.09	.04	.04	.03	.03	.03	.02	.03	.03	.02	.06	.03	.03
Mo	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Ni	30	30	20	30	30	30	30	20	30	30	30	30	30
Pb	200	150	100	10	10	10	10	10	10	10	10	10	10
Sb	16	8	9	<1	<1	<1	2	<1	<1	<1	2	<1	<1
Zn	1500	2500	300	50	30	30	40	<25	30	30	65	75	75

Granodiorite of Elder Creek area (Location No. 4, fig. 3)

Sample No. (AHW–)	157	158	159	160	161	162	163	164	165	166	167	168
Ag	....	2.0	....	....	....	....	....	....	....	5.0	3.0	1.5
As	20.0	60	20.0	10.0	....	20.0	10.0	10.0	10.0	80	120	40
Au	.02	<.02	<.02	.02	0.02	.02	<.02	<.02	<.02	<.02	.02	<.02
Bi	....	....	....	....	....	....	....	....	....	10	....	....
Cr	200	<5	100	70	<5	100	150	150	70	50	50	70
Cu	50	20	100	100	30	50	50	50	200	500	200	200
Hg	.02	.01	.04	.03	.03	.01	.03	.07	.02	.02	.03	.06
Mo	5	5	10	5	<5	10	5	20	20	5	20	5
Ni	50	10	20	20	5	20	20	20	20	15	15	20
Pb	30	10	15	20	<10	20	20	15	20	70	20	30
Sb	<1	12	<1	2	<1	<1	<1	<1	<1	<1	20	9
W	150	200	100	....	....	....	....	....	....	50	100	....
Zn	40	<25	25	30	<25	40	40	30	30	30	200	50

Granodiorite of Long Peak (Location No. 5, fig. 3)

Sample No. (AHW–)	210	211	212	213	214	215	216	217	218	219	AEH–926[1]	AEH–927[1]
Ag	....	....	....	0.5	....	....	0.5	0.5	0.5	0.5	0.5	0.5
As	....	40.0	10.0	10	<10.0	60.0	<10	40	<10	20	300	2000
Au	0.02	.02	<.02	.04	<.02	.02	<.02	.06	.02	.02	.02	.06
Cr	20	15	15	10	20	15	10	10	15	10	100	100
Cu	30	30	20	30	20	70	70	20	20	20	100	50
Hg	.03	.03	.02	.03	.01	.02	.02	.03	.02	.04	.06	.07
Mo	15	5	5	10	5	20	10	15	7	<5	....	....
Ni	10	20	10	15	15	15	10	10	10	10	70	20
Pb	15	10	15	20	20	30	20	20	30	20	200	150
Sb	<1	<1	2	<1	1	<1	<1	<1	<1	<1	<100	<100
Zn	230	420	40	50	45	70	25	30	35	140	<200	<200

Granodiorite of Timber Canyon area (Location No. 7 and 15, fig. 3)

Sample No. (AHW–)	169	170	171	172	173	174	175	176	177	178
Ag	....	....	0.5	....	....	....	0.5	....	0.5	....
As	....	10.0	....	....	....	....	....	....	....	....
Au	<0.02	.02	.04	<0.02	<0.02	<0.02	<.02	<0.02	<.02	<0.02
Cr	15	20	30	30	50	20	20	20	30	20
Cu	50	200	200	100	70	50	70	50	50	50
Hg	.02	.02	.03	.03	.05	.03	.04	.04	.04	.04
Mo	<5	5	<5	<5	<5	<5	<5	<5	<5	<5
Ni	10	10	10	10	10	10	10	10	10	10
Pb	20	20	20	20	15	30	30	20	30	30
Sb	1	2	<1	2	2	<1	<1	<1	<1	<1
Zn	55	55	75	45	55	55	55	60	70	55

TABLE 2.—*Analyses for selected minor metals in plutonic rocks in the Battle Mountain mining district*—Continued

Altered granodiorite of Wilson-Independence mine area (Location No. 8, fig. 3)

Sample No. (AHW-)	137	138	139	140	141	142	143	144	145	146
Ag	1.0	2.0	1.0	5.0	5.0	1.0	1.0	1.5	1.0	1.0
As	10	10	10	10	10	10	20	<10	20	20
Au	.14	.16	.08	.14	.40	.40	.28	.42	.30	.22
Cr	70	100	70	70	70	100	100	100	100	70
Cu	500	500	500	1000	1000	300	200	500	700	300
Hg	.02	.04	.03	.02	<.01	.03	.03	.04	.04	.05
Mo	5	10	10	<5	<5	20	5	5	5	7
Ni	20	20	20	20	30	30	30	30	30	20
Pb	20	20	15	20	15	20	20	15	20	20
Sb	4	4	3	3	3	5	<1	<1	<1	<1
Zn	70	95	140	170	200	270	170	320	150	400

Altered granodiorite of Copper Canyon area (Location No. 9, fig. 4)

Sample No. (AHW-)	127	128	129	130	131	132	133	134	135	136
Ag	5.0	5.0	3.0	2.0	1.0	2.0	2.0	1.0	5.0	1.0
As	20	40	10	40	120	20	60	20	40	20
Au	1.6	.12	.1	.06	.08	.16	.1	.26	.48	.14
Cr	30	50	50	50	30	50	50	50	50	100
Cu	500	500	200	1500	1000	100	1000	500	200	1500
Hg	.02	.03	.06	.03	.04	.03	.04	.03	.02	.03
Mo	<5	10	5	20	10	20	50	10	10	15
Ni	10	10	15	15	15	15	50	30	20	20
Pb	10	10	30	15	50	20	10	10	10	10
Sb	<1	<1	<1	<1	20	16	<1	2	2	16
Zn	110	170	130	70	700	70	420	200	60	60

Altered granodiorite of Elder Creek area (Location No. 16, fig. 3)

Sample No. (AHW-)	147	148	149	150	151	152	153	154	155	156
Ag	2.0	1.0	1.0	1.0	....	....	1.0	1.0	1.0	0.5
As	<10	10	<10	10	....	....	....	....	....	....
Au	<.02	<.02	<.02	<.02	<.02	0.02	<.02	.02	.02	.02
Cr	70	70	70	50	10	20	70	70	70	70
Cu	500	700	1000	1500	200	300	700	700	700	500
Hg	.04	.03	.02	.04	.02	.04	.02	.03	.03	.03
Mo	15	5	5	20	<5	5	<5	<5	50	<5
Ni	20	20	20	20	<2	10	30	30	30	30
Pb	200	20	20	10	10	10	10	10	10	10
Sb	18	25	16	<1	<1	<1	<1	2	<1	<1
W	50	50	100	50	50	100	50	150	200	500
Zn	230	230	230	35	<25	<25	30	25	30	30

[1] Altered granodiorite of Iron Canyon area, Location No. 6, fig. 3.

thermally altered rocks (to be described below), we selected five biotites from three intrusive bodies for further investigation.

ALTERED GRANODIORITE OF THE COPPER CANYON AREA

Biotite was separated from three different samples of altered granodiorite from the Copper Canyon area. Typically, these biotites are medium-grained (somewhat greater than 1 mm across), "hexagonal," red-brown plates that are optically homogeneous (fig. 9). The plates are single crystals and do not appear to have recrystallized during the later potassic alteration. Alteration of biotite phenocrysts more than 1 mm across is minimal; only a small number show thin rinds of bleaching with some marginal chloritization. Some of the smaller biotite phenocrysts are somewhat more pervasively bleached, with the concomitant development of very fine clusters of sphene. However, these more altered biotites were excluded from the final separates by size-sieving. Compositions and calculated structural formulas of the three biotites are shown in table 4. Implications for pressure-temperature stabilities of their compositions are discussed by Theodore and Blake (1973). The first of the three was separated from a hand specimen collected from a roadcut (fig. 4;

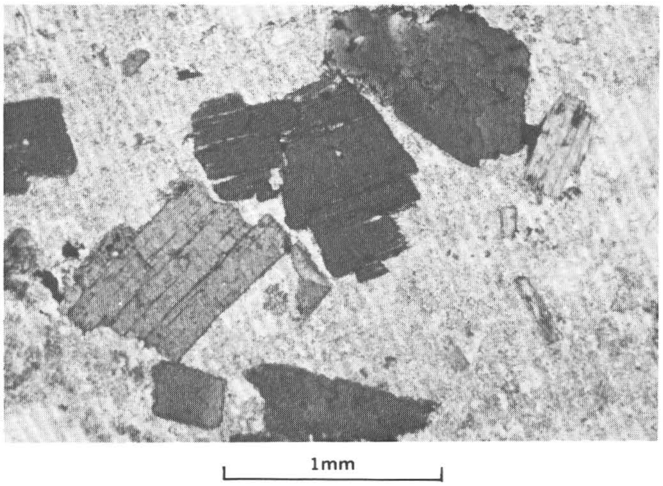


FIGURE 9.—Photomicrograph of primary biotite from altered granodiorite of the Copper Canyon area. Plane polarized light.

TABLE 3.—*Abundance of minor elements in "granitic" rocks*

[Reported in ppm]

Element	Intermediate rocks[1]	Felsic granites and granodiorites[1]	Granites[2]	
			High calcium	Low calcium
Ag	0.07	0.05	0.051	0.037
B	15.	15.	9.	10.
Ba	650.	830.	420.	840.
Be	1.8	5.5	2.	3.
Co	10.	5.	7.	1.
Cr	50.	25.	22.	4.1
Mo	.9	1.	1.	1.3
Nb	20.	20.	20.	21.
Ni	55.	8.	15.	4.5
Sc	2.5	3.	14.	7.
Sn	....	3.	1.5	3.
V	100.	40.	88.	44.
W	1.	1.5	1.3	2.2
Y	....	34.	35.	40.
Zr	260.	200.	140.	175.
Ga	20.	20.	17.	17.
Yb	....	4.	3.5	4.
La	....	60.	45.	55.
Ce	....	.5	2.	4.
Au	....	.004	.004	.004
Cu	35.	20.	30.	10.
Pb	15.	20.	15.	19.
Zn	72.	60.	60.	39.
U	1.8	3.5	3.	3.
Th	7.	18.	8.5	17.
Hg	....	.08	.08	.08
Rb	100.	200.	110.	170.
Sr	800.	300.	440.	100.
Sb	.2	.26	.2	.2

[1] Vinogradov, 1962.

[2] Turekian and Wedepohl, 1961.

TABLE 4.—*Compositions and structural formulas of biotites from granodiorite of the Copper Canyon, Long Peak, and Timber Canyon areas*

[Major elements shown in weight percent; analyses of Copper Canyon area by Sarah T. Neil, U.S. Geological Survey, using classical methods, and methods of Ingamells (1962, 1966), Suhr and Ingamells (1966), and Medlin, Suhr, and Bodkin (1969); analyses of Long Peak and Timber Canyon areas by P. Elmore, H. Smith, G. Chloe, J. Kelsey, and J. Glenn using rapid rock methods. Minor elements shown in weight percent; semiquantitative spectrographic analyses by R. E. Mays and Chris Heropoulos, U.S. Geological Survey; results are reported in percent to the nearest number in the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1, 0.07, ...; these numbers represent approximate midpoints of group data on a geometric scale. The precision of a reported value is approximately plus or minus one interval about 68 percent of the time or two intervals 95 percent of the time. Elements looked for but not found: As, Au, B, Be, Bi, Cd, Ce, Ge, Hf, Hg, In, La, Li, Mo, Pb, Pd, Pt, Re, Sb, Sn, Ta, Te, Th, Tl, U, W, Y, Yb, Zn. Structural formulas calculated on the basis of 24 (O, OH, Cl, F) anions per formula unit. $X_2Y_{4-6}Z_8O_{20}$ (OH, F, Cl)$_4$ is assumed to be the general structural formula]

Specimen and loc. No.	Copper Canyon area			Long Peak area	Timber Canyon area
(figs. 3, 4)	9	10	19	5	7
Lab No.	M109678	M109679	M109681	W174693	W174694
Field No.	MB–18	MB–23	MB–31	MB–16	MB–9
Major elements					
SiO_2	37.81	37.51	36.49	35.8	37.2
Al_2O_3	15.30	14.70	15.79	14.6	14.1
Fe_2O_3	1.69	.51	.35	.70	2.7
FeO	10.97	14.49	14.49	20.1	17.0
MgO	15.72	15.12	15.91	10.9	11.5
CaO	.21	.36	.16	.68	1.6
Na_2O	.10	.15	.10	.15	.44
K_2O	8.73	9.12	8.48	8.3	7.6
H_2O^+	4.05	3.59	4.11	3.8	3.0
H_2O	.32	.08	.02	.00	.00
TiO_2	2.93	2.69	2.91	3.5	3.4
P_2O_5	.18	.32	.21	.32	.28
MnO	.02	.09	.04	.36	.34
Cl	.4	.5	.4	....	....
F	1.59	1.17	1.29	....	....
Cr_2O_3	.1	.1	.1	.02	....
BaO	.33	.37	.34	....	....
V_2O_5	.1	.1	.1	.05	....
Subtotal	100.6	101.0	101.3		
Less O=F, Cl	.75	.61	.63		
Total	99.8	100.4	100.7	99.3	99.2
Minor elements					
Ag	0.0007	....	....	....	....
Co	.002	0.005	0.003	0.005	....
Cu	.2	.03	.01	.0007	....
Mo	.003	....	....	....	....
Nb	.003	.003	.003	.003	....
Ni	.015	.02	.015	.003	....
Sc	.005	.003	.003	.001	....
Sr	.001	....	....	.0015	....
Zr	.003	.005	....	.007	....
Ga	....	....	....	.003	....

Structural formulas

		9		10		19		5		7	
Si	Z	5.54	8.00	5.59	8.00	5.36	8.00	5.52	8.00	5.72	8.00
Al^{iv}		2.46		2.41		2.64		2.48		2.28	
Al^{vi}	Y	.18	5.46	.18	5.71	.10	5.74	.17	5.81	.27	5.84
Fe^{+3}		.19		.06		.04		.08		.31	
Ti		.32		.30		.32		.41		.39	
Mg		3.43		3.36		3.49		2.51		2.64	
Fe^{+2}		1.34		1.80		1.78		2.59		2.19	
Mn		....		.01		.01		.05		.04	
Ca	X	.03	1.69	.06	1.83	.03	1.65	.11	1.79	.26	1.88
Na		.03		.04		.03		.05		.13	
K		1.63		1.73		1.59		1.63		1.49	
OH		3.96	4.80	3.57	4.25	4.03	4.73	3.91		3.08	
F		.74		.55		.60		....		....	
Cl		.10		.13		.10		....		....	

No. 9). The other two were separated from composite drill core samples (about 100 m below ground surface) from two different drill holes in the intrusive body. K-Ar age determinations were made on two of the biotites (Nos. 9 and 10, table 4), and the rock bulk chemistry was also determined for one (No. 9, tables 1 and 4). Purity of the three analyzed biotite separates was visually estimated to exceed 99 percent. (No magnetite was observed in grain mounts of final separates.) However, the anomalously high Cu content (0.2 weight percent) of specimen 9 (table 4) suggests the presence of minute inclusions of chalcopyrite in this sample. If we then assume that about 0.18 (that is, 0.2−[0.03+0.01]/2) weight percent Cu in this specimen is due to the presence of chalcopyrite ($CuFeS_2$), the specimen must be contaminated by about 0.5 weight percent chalcopyrite, which implies, in turn, that the actual Fe_2O_3 content of biotite in specimen 9 is about 0.2 weight percent less than the reported value, because iron in chalcopyrite is in the Fe^{+3} state (Donnay and others, 1958).

Limited optical and X-ray data were obtained from the biotites analyzed (table 4). Their strong pleochroic scheme ($X<Y=Z$) is typical of most biotites; optic axial angles are 0° or very nearly. This suggests the absence of interleaved polymorphs. We assume that the biotites belong to the single layer (1 M) polymorph of Hendricks and Jefferson (1939)—a polymorph common to intrusive "granitic" rocks (Smith and Yoder, 1956, p. 227; Dodge and others, 1969). From the method outlined by Wones (1963), cell volumes (table 5) were first calculated using the biotites' X-ray *d*-spacings of 005 and 060 reflections, the relation $b/a=\sqrt{3}$ (Smith and Yoder, 1956), and calculated values of β ($\beta=180°-\cos^{-1}(a_M/3c_M)$)[2]. The values calculated for specimens 9, 10, and 19 (table 4) are within 12′ of arc of the 100°β value (Deer and others, 1962, p. 53) reported common to 1 M biotite polymorphs.

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[2] *a*, *b*, and *c* are unit translations in angstroms along a crystal's lattice; the angle between *a* and *c* directions is β.

TABLE 5.—*X-ray* d-*spacings of 005 and 060 reflections, calculated unit cell volumes, and densities of biotites from granodiorite of the Copper Canyon and Long Peak areas*

[Ni-filtered Cu radiation ($\lambda K\alpha$=1.54178A). Si (a_0=5.4307 A, calibrated against diamond by Steve Huebner), internal standard. 1° and 0.010 slits. Oscillated 2 cycles with interposed 180° rotation of unoriented smear mount. ¼° 2 θ per min scan speed]

Specimen (same as table 4)	Locality	*d* (005) (A)	*d* (060) (A)	Cell volume[1] (A^3)	Cell volume[2] (A^3)	Calculated density[3] (g/cc)	Measured density (g/cc)
9	Copper Canyon	2.014	1.541	489.8	489.9	2.946	2.945±0.005
10	do	2.015	1.543	491.2	494.4	3.009	2.990± .005
19	do	2.015	1.542	490.6	493.0	2.985	2.970± .005
5	Long Peak	2.017	1.545	493.0	498.8	3.085	3.049± .005

[1] From $Vc = a\ b\ c \sin \beta$.

[2] From $\rho c = \frac{GN}{10^{-24} A V_0}$ (see text).

[3] From $Vc = \frac{GN}{10^{-24} A \rho_0}$ (see text).

However, there is some uncertainty regarding use of the 060 reflection as a measure of *b*, because of the possibility of an overlapping $\bar{3}31$ reflection (Wones, 1963, p. 1305). Accordingly, unit cell volumes were also calculated by the relation,

$$Vc = \frac{GN}{10^{-24} A \rho_0},$$

where *Vc* is the calculated cell volume in cubic angstroms, *G* the formula weight in grams, *N* the number of formulas per unit cell, *A* Avogradro's number, and ρ_0 the measured density in grams per cubic centimeter (Jackson and others, 1967, p. C26). Uncertainties (±0.005) in measured densities (table 5) primarily reflect density variations in the biotites. Nevertheless, the close agreement of the unit cell volumes calculated from the X-ray-determined *d*-spacings with those calculated from the formula weights and measured densities (table 5), seems to confirm the biotites' assumed polytype and the use of the 060 reflection as a measure of *b*. Lastly, the unit cell dimensions and densities (both calculated and measured) of the sample collected from the roadcut in the stock (No. 9, table 5) are all slightly less than those of biotites from drill holes in the pluton (Nos. 10 and 19, table 5). These differences may be due to higher concentrations of "oxybiotite" or ferric component in this biotite, because Wones (1963) has shown that the *c* axis of the unit cell contracts as "oxybiotite" increases.

Structural formulas were calculated from the biotite analyses using the computer program described by Jackson, Stevens, and Bowen (1967). We assumed 24 (O + OH + F + Cl) anions per formula unit and a minimum of eight cations in fourfold coordination as in the general trioctahedral mica formula.

Interlayer, 12-coordinated cation positions are not fully occupied in these biotites. In fact, K, Ca, and Na fill only 1.65–1.83 of the available 2.00 sites. Of these filled positions, more than 95 percent are occupied by K. Ca and Na fill very few, as CaO and Na_2O each make up less than 0.4 weight percent of the three biotites. The interlayer positions in these biotites have unusually low occupancy, compared with published structural formulas (Foster, 1960; Dodge and others, 1969; Lee and Van Loenen, 1970; Moore, 1970a) but are not outside the range others have reported.

In the biotites from the intrusive body at Copper Canyon, octahedral Y group cations occupy from 5.46 to 5.74 sites, or over 90 percent of the 6.00 octahedral sites in the general trioctahedral mica formula (table 4). Mg makes up about 60 percent of the total Y group cations in these micas, and Fe^{+2} about 30 percent. According to Foster's classification (1960), these biotites would all be termed magnesian biotites (fig. 10), although specimen 9 (table 4) is more intermediate between the magnesian biotite and phlogopite fields than specimens 10 and 19. Similar high Mg contents in biotites from the early-stage porphyry at the Ely, Nev., porphyry copper deposit suggested to Fournier (1967, p. 71) a relatively high ratio of sulfur to oxygen fugacity during the magmatic stage. Lesser amounts of Al, Fe^{+3}, Ti, and Mn fill the remaining occupied Y group sites of the Copper Canyon biotites. TiO_2 contents and $Fe_2O_3/(Fe_2O_3 + FeO)$ ratios for these biotites are comparable with those of other red-brown biotites (Hayama, 1959).

Almost all Al occurs in the presumably filled, tetrahedrally coordinated Z group cation sites (table 4).

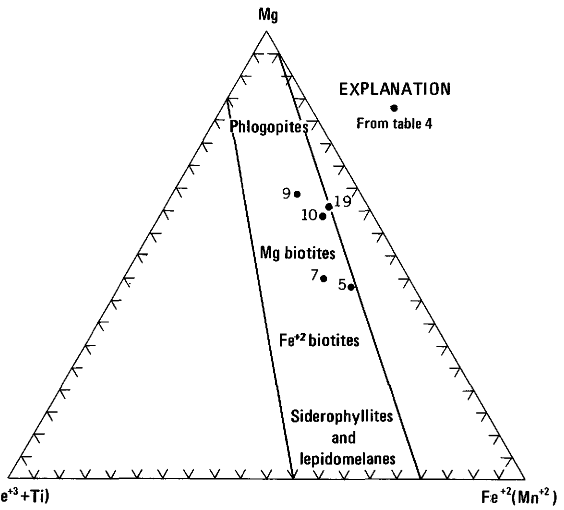

FIGURE 10.—Relation among Mg, $Fe^{+2}(Mn^{+2})$, and Al Fe^{+3}, Ti) in biotites from the Battle Mountain mining district. Biotite classification from Foster (1960).

And, in all three biotite specimens, OH, F, Cl anions total more than the four available positions—primarily an effect of the high F contents (more than 0.55 ions per formula) of these biotites. These biotites are much richer in F than biotites from the Sierra Nevada batholith (Dodge, Smith, and Mays, 1969). They are also slightly richer in F than magnesian biotite in latitic dike rocks in the Bingham mining district (Moore, 1970a) and generally richer in F than biotites from the Snake Range, Nev. (Lee and Van Loenen, 1970). However, Foster (1960) in her extensive compilation of biotite analyses lists several biotites, with appropriate Mg contents, whose F concentrations are comparable to those at Copper Canyon.

Compositions of phenocrystic biotites in the pluton at Copper Canyon, together with several other factors, may have helped to preserve them during metallization. Certainly the brine-type fluids ascribed to the metallization processes there circulated through much of the intrusion (Nash and Theodore, 1971). Quartz phenocrysts and groundmass quartz are abundantly filled with prominent postmagmatic fluid inclusions characterized by NaCl and KCl daughter mineral assemblages. Studies of fluid inclusions yielded filling temperatures in the 310°–380°C range in the east ore body. We suggest that some of the pluton's original biotite was preserved at these temperatures owing to a combination of several factors:

1. The ferrous (Fe^{+2}) nature of most iron in the original biotite. Fluids initially in equilibrium with pyrrhotite in the system Fe-S-O at 250°C are typified by maximum oxygen fugacities of about 10^{-45} atm in a slightly acidic environment (Barnes and Czamanske, 1967). Biotites similar in composition to those at Copper Canyon (table 4) probably crystallized initially at prevailing oxygen fugacities higher than that suggested by the later pyrrhotite assemblages (see below; Wones and Eugster, 1965). Accordingly, these biotites may have been "less reactive" to fluids with lower oxygen fugacities because their Fe was already reduced. Alternatively, subsequent removal of any of the biotites' buffers would stabilize the biotite to oxygen fugacities lower than those prevailing during its crystallization.
2. Failure of Fe^{+2} in the biotites in these samples to be sulfidized suggests domains of relatively "low" sulfur fugacity in the intrusive body at the magmatic stage, and also during the hydrothermal stage. The samples collected from the intrusion for this study are from the "least altered" appearing rock. This in turn implies that fluids with relatively high sulfur fugacities were not freely circulating.
3. Reaction rates may have been lower at the temperatures prevailing during the bulk of the metallization. Perhaps the metal-bearing fluids were locally quenched by mixing with cooler ground waters.
4. Locally high Mg/H ratios in the fluids. As pointed out by Rose (1970, p. 921), there are two critical ratios involved in potassic alteration: "***K/H high enough in the ore fluid to stabilize and form biotite or orthoclase, and in the case of biotite, Mg/H high enough to avoid removal of Mg." K-feldspar–quartz veins with hydrothermal vein chlorite do occur locally through the intrusion and in the porphyry copper deposit.

GRANODIORITES OF THE LONG PEAK AND TIMBER CANYON AREAS

Many of the K-Ar ages of plutonic rocks from the Battle Mountain district were determined from grain concentrates of medium-grained, euhedral to subhedral biotite, seemingly unaltered, yet set in rock samples hydrothermally altered to varying degrees. Chemical and X-ray study of biotites from unaltered granodiorites (the stocks at Long Peak and Timber Canyon) was therefore undertaken in order to learn more about the effects of hydrothermal alteration. These data have a bearing on the age determinations at Copper Canyon, where completely unaltered intrusive rocks have not been found.

The main compositional difference between unaltered biotite from the granodiorite at Copper Canyon and biotite from the Long Peak stock is in MgO content (see fig. 10), and $Mg/Mg+Fe^{+2}$ distribution ratios between biotite and whole-rock analyses suggest that the differences shown in figure 10 may result from contrasts in original (prealteration) bulk chemical compositions, not from alteration.

The overall fabric of the granodiorite at Long Peak is remarkably similar to that of the altered granodiorite of the Copper Canyon area. Phenocrysts of hornblende, plagioclase, and quartz (as much as about 6 mm across), and generally euhedral biotite laths and plates (about 1 mm across), are set in a groundmass of quartz, K-feldspar, and accessory minerals. Groundmass grains are about 0.2 mm across. The plagioclase crystals (calcic oligoclase to sodic andesine) are clear and complexly zoned in an oscillatory manner, with slightly more albitic rims. Quartz in the phenocrysts and groundmass is remarkably free of fluid inclusion and, most importantly, does not contain any brine-type fluid inclusions. Biotites are strongly pleochroic ($X<Y=Z$), with optic axial angles close to 0°. They are reddish brown ($Y=Z$) but a paler red than those from the intrusive body at Copper Canyon. In addition, they typically include sparse needles of rutile oriented parallel to the (001) cleavage direction, and about 1 percent of the biotite grains are partly rimmed by chlorite.

Granodiorite of the Timber Canyon area is also porphyritic, with groundmass grains about 0.01 mm across. Biotites from this intrusive body are dark brown (Y=Z), with a slight greenish hue. They also include minute rutile needles and some magnetite, and their optic axial angles are very nearly 0°.

Structural formulas of both biotites (Nos. 5 and 7, table 4) and unit cell dimensions of one (No.5, table 5) were determined as described in the preceding section. Cl and F contents of these biotites were not determined (because of sample size), and it is probably because these data were not available that the discrepancies in cell volumes and densities of sample 5 are as large as they are.

Occupancy of the 12 coordinated cation positions by K, Ca, and Na in these biotites (Nos. 5 and 7, table 4) is about the same as in the biotites at Copper Canyon. However, octahedral Y group cation sites are slightly more fully occupied, and Mg makes up about 45 percent of the total Y group cations. Again, using Foster's (1960) classification, these biotites are intermediate between Mg biotites and Fe^{+2} biotites (fig. 9). Moreover, the iron in these two biotites from the unaltered granodiorite samples is largely Fe^{+2} (table 4). This is especially so in the biotite from the stock at Long Peak, which is texturally very similar to the intrusive body at Copper Canyon. Most Al in the biotites from the Long Peak and Timber Canyon intrusive bodies is tetrahedrally coordinated in the Z group cation sites (table 4).

K-Ar AGES

K-Ar ANALYTICAL PROCEDURE AND PRECISION

Bulk rock samples were prepared for mineral separation by crushing and sieving to retain the 1–0.1-mm-size fraction. An electrostatic mineral separator, heavy liquids, and an inclined vibrating table were used to prepare the mineral concentrates for K-Ar analysis. The mineral concentrates were split with a Jones microsplitter, and separate aliquots were analyzed for Ar and K. The purity of mineral separates was usually 99 percent or better, with the exception of several separates whose biotites were partially chloritized. Detailed sample locations and purity estimates for the mineral separates are listed in table 6. Potassium analyses were

TABLE 6.—*Sample locations and descriptions of* K-Ar *age-dated specimens from the Battle Mountain mining district*

Loc. No. (figs. 3 and 4)	Field No.	Description
1	MB–25	Granodiorite of Trenton Canyon. SW¼ sec. 24, T. 32 N., R. 42 E., from outcrop adjacent to road along Trenton Canyon. Sparse pyrrhotite along joint surfaces. Medium-grained hypidiomorphic-granular hornblende-biotite granodiorite. Very slightly porphyritic with some zoned andesine phenocrysts ranging up to 7 mm across. K-feldspar and plagioclase slightly to moderately sericitized, and brown biotite (Y=Z) slightly chloritized. Accessory minerals: sphene, apatite, magnetite, zircon, allanite (trace), and epidote group (trace).
2	MB–26	Granodiorite of Trenton Canyon. SW¼ sec. 24, T. 32 N., R. 42 E., from outcrop adjacent to road along Trenton Canyon. Medium-grained hypidiomorphic to xenomorphic-granular biotite-hornblende granodiorite. Slightly porphyritic with subhedral brown (Y=Z) biotite, and andesine phenocrysts ranging up to 6 mm across. K-feldspar and plagioclase slightly sericitized; biotite slightly chloritized. Accessory minerals: magnetite, zircon, apatite, sphene, epidote group, pyrrhotite (trace) and allanite (trace).
3	MB–20	Granodiorite of Modoc mine area. SW¼ sec. 30, T. 31 N., R. 43 E. Fine-grained porphyritic hornblende-biotite granodiorite. Hornblende phenocrysts (averaging about 0.75 mm in their longest dimension), and dark-reddish brown (Y=Z) biotite phenocrysts (about 0.5 mm across) set in a predominantly quartz–K-feldspar matrix whose grains average about 0.02 mm across. Tabular euhedral to subhedral sodic labradorite phenocrysts (averaging about 1 mm in length but ranging up to 5 mm) sparsely altered to white mica. Accessory minerals: apatite, magnetite, zircon, pyroxene(?, trace), and chlorite (trace).
4	MB–12	Granodiorite of Elder Creek area. SE¼ sec. 2, T. 32 N., R. 43 E.; from outcrop about 500 feet from southwestern contact of intrusive body. Medium-grained porphyritic biotite-hornblende granodiorite. Biotite (red-brown, Y=Z), hornblende, plagioclase, and quartz phenocrysts (average about 2 mm across) set in a predominantly quartz–K-feldspar matrix whose grains average about 0.08 mm across. Biotite sparsely chloritized. Accessory minerals: hematite, sphene, apatite, magnetite(?), and zircon(?).
5	MB–16	Granodiorite of Long Peak area. NE¼ sec. 26, T. 32 N., R. 43 E., from outcrop about 15 m below summit of Long Peak. Medium- to fine-grained biotite-hornblende granodiorite that is slightly porphyritic. Hornblende, quartz, and zoned plagioclase (calcic oligoclase to sodic andesine) phenocrysts (about 1 mm across) set in a quartz–K-feldspar–accessory mineral groundmass whose grains average about 0.2 mm across. Reddish-brown biotites (Y=Z) include some rutile and are sparsely chloritized. Accessory minerals: zircon, apatite, magnetite, sphene, hematite, and pyrrhotite(?).
6	MB–21	Altered granodiorite of Iron Canyon area. NE¼ sec. 23, T. 31 N., R. 43 E. Composite sample collected from porphyritic dike penetrated by DDH–2 (Theodore and Roberts, 1971) between 871.1 and 876.9 m below ground surface. Phenocrysts of quartz, plagioclase, and K-feldspar are unaltered, but the matrix has recrystallized to a sericite, quartz, and K-feldspar intergrowth. Accessory minerals: apatite, zircon, pyrrhotite, bornite, chalcopyrite (trace), calcite (trace), and ilmenite(?).
7	MB–9	Granodiorite of Timber Canyon area. NE¼ sec. 15, T. 31 N., R. 42 E. Sample col-

TABLE 6.—*Sample locations and descriptions of* K-Ar *age-dated specimens from the Battle Mountain mining district*—Continued

Loc. No. (figs. 3 and 4)	Field No.	Description
		lected from outcrop about 50 m from perimeter of stock, in relatively leucocratic core area of compositionally zoned granodiorite. Medium- to fine-grained porphyritic biotite-hornblende granodiorite. Euhedral plagioclase, biotite (dark-brown, Y=Z), hornblende, and quartz phenocrysts (about 1 mm across) set in a chiefly quartz–K-feldspar matrix whose grains average 0.01 mm across. Accessory minerals: apatite, zircon, and magnetite.
8	MB–19	Altered granodiorite of Wilson-Independence mine area. NW¼ sec. 28, T. 31 N., R. 43 E., sample from outcrop. Medium-grained altered porphyritic granodiorite. Subrounded, partially resorbed quartz phenocrysts; biotite phenocrysts (about 1 mm across, and partially recrystallized); intensely sericitized plagioclase and K-feldpar phenocrysts; all set in a quartz–K-feldspar–white mica–biotite matrix (grains about 0.01 mm across). Accessory minerals: sphene, apatite, zircon, chlorite, and sulfides.
9	MB–18	Altered granodiorite of Copper Canyon area. SW¼ sec. 22, T. 31 N., R. 43 E. Hand specimen collected from roadcut in intrusive body, 50 m northeast of Duval's primary crusher. Medium- to coarse-grained altered porphyritic granodiorite. Quartz phenocrysts (up to 1 cm across), variably sericitized plagioclase and K-feldspar phenocrysts, red-brown (Y=Z) biotite phenocrysts, quartz - K-feldspar - white mica–chlorite (trace) matrix. Biotite very sparsely chloritized with trace amounts of included chalcopyrite(?) (see text). Accessory minerals: zircon, sphene, apatite, hematite, magnetite(?), and sulfide.
10	MB–23	Altered granodiorite of Copper Canyon area. SW¼ sec. 22, T. 31 N., R. 43 E. Composite sample of nine drill core splits from depths of 74.7 to 131.1 m below ground surface. Rock typically coarse- to medium-grained porphyritic altered biotite granodiorite. Quartz phenocrysts (subangular, locally recrystallized, up to 2 cm across); moderately sericitized plagioclase phenocrysts; biotite phenocrysts (red-brown, Y =Z, tabular, averaging slightly greater than 1 mm long, sparsely chloritized); predominantly quartz–K-feldspar–white mica–biotite (trace) matrix whose grains are about 0.01 mm across. Accessory minerals: sphene, apatite, chlorite, amphibole (trace), and sulfides.
11	MB–30	Altered granodiorite of Copper Canyon area. SW¼ sec. 22, T. 31 N., R. 43 E. Composite sample of eight drill core splits from depths of 57.9 to 86.9 m below ground surface. Rock description same as MB–23, except chlorite (trace) typically in narrow veinlets and amphibole absent.
12	MB–40	Altered granodiorite sill. SE¼ sec. 21, T. 31 N., R. 43 E. Composite sample of nine drill core splits from depths of 115.8 to 123.4 m below ground surface. Intensely sericitized and pyritized porphyritic granodiorite. Remnant quartz, clouded plagioclase, and primary biotite phenocrysts set in a fine predominantly white mica matrix with minor pyrite. Primary biotite phenocrysts (0.5 to 1.0 mm across, red-brown Y=Z, and optically homogeneous) are only sparsely chloritized and sericitized. Some chlorite along veinlets. Accessory minerals: apatite, sphene, rutile, and amphibole (trace).
13	MB–6500	Metallized matrix of Battle Formation. SW¼ sec. 22, T. 31 N., R. 43 E., hand specimen from 6500 bench of Copper Canyon porphyry copper deposit. Almost schistose facies of metamorphosed rock belonging to lower member of Battle Formation. Rock consists of very fine, 0.01 mm and less, intergrowths of hydrothermal red-brown (Y=Z) biotite, K-feldspar, quartz, pyrite, chalcopyrite, sericite (trace), and sphene(?). Some relict plagioclase.
14	MB–52	Metallized matrix of Battle Formation. SW¼ sec. 22, T. 31 N., R. 43 E., description same as MB–6500.

TABLE 6.—*Sample locations and descriptions of* K-Ar *age-dated specimens from the Battle Mountain mining district*—Continued

performed by Lois Schlocker (U.S. Geological Survey) by flame photometer using lithium metaborate fusion, the lithium serving as an internal standard. Argon analyses were performed in the U.S. Geological Survey laboratory in Menlo Park, Calif., using standard isotope dilution procedures (Dalrymple and Lanphere, 1969). A Neir-type, 6-inch, 60° sector, mass spectrometer and a Reynolds 4½-inch, 60° sector, mass spectrometer, both operated in the static mode, were used for mass analyses. Analytical precision of the reported ages is approximately 2 percent and is based on statistical analysis of a large number of replicate potassium analyses and duplicate argon analyses run during the course of earlier studies (McKee and Silberman, 1970; Silberman, unpub. data). Constants used are:

$$\lambda\varepsilon = 0.585\text{x}10^{-10}\ \text{yr}^{-1}$$

$$\lambda\beta = 4.72\text{x}10^{-10}\ \text{yr}^{-1}$$

$$\text{K}^{40}/\text{K} = 1.22\text{x}10^{-4}\ \text{gm/gm}$$

The analytical data are tabulated in table 7.

CRETACEOUS GRANODIORITE OF TRENTON CANYON

The oldest K-Ar ages in the mining district, 87.2 and 87.0 m.y. (million years) (Late Cretaceous), were determined for biotite from two samples of the granodiorite of Trenton Canyon (table 8, Nos. 1 and 2; fig. 3, Nos. 1 and 2). The samples (medium-grained biotite-hornblende granodiorites) were collected approximately 0.4 km apart and are within the porphyritic outer margins of the pluton that intrudes argillite and chert of the Pumpernickel Formation, chert of the Havallah Formation, and conglomerate of the Battle Formation. This pluton, with an outcrop area of about 2.5 sq km, is the largest exposed igneous body in the district. Sample 2 has some pyrrhotite both as disseminated grains and as fracture coatings; the groundmass and phenocrysts appear to be unaltered.

Following emplacement of the granodiorite of Trenton Canyon, there was a gap of about 46 m.y. in

TABLE 7.—K-Ar *analytical data*

Location No., figs. 3, 4	Mineral	K_2O Weight percent	Radiogenic Ar^{40} mole/gm$\times 10^{-10}$	$\frac{Ar^{40}}{K^{40}} \times 10^{-3}$	$\frac{\text{Radiogenic } Ar^{40}}{\text{Total } Ar^{40}}$	Age $\times 10^6$ yrs
	Outside of Copper Canyon area					
1	Biotite, 3 percent chlorite (−20+60 mesh)	7.38	9.729	5.219	0.791	87.2±1.7
2	Biotite, $<$1 percent chlorite (−20+140 mesh)	8.20	10.78	5.206	.762	87.0±1.7
3	Hornblende, $<$1 percent pyroxene (−100+150 mesh)	.685	.4205	2.429	.232	41.1±1.4
3	Biotite, 2 percent chlorite, matrix (−50+150 mesh)	7.20	4.209	2.315	.622	39.2±0.8
4	Biotite, $<$1 percent chlorite (−48+80 mesh)	8.43	4.691	2.204	.663	37.3±0.7
5	Biotite, $<$1 percent chlorite (−42+60 mesh)	8.45	4.699	2.201	.739	37.3±0.7
6	Biotite, $<$1 percent sericite (−35+60 mesh)	8.82	4.939	2.217	.601	37.5±0.8
7	Biotite, $<$1 percent adhering matrix (−80+100 mesh)	7.78	4.532	2.307	.828	39.0±0.8
7	Hornblende, 10 percent biotite (−80+100 mesh)	2.80	1.620	2.290	.799	38.8±0.8
8	Biotite, 1 percent chlorite (−60+150 mesh)	7.92	4.518	2.258	.787	38.2±0.8
	Copper Canyon area					
9	Biotite, $<$1 percent chlorite (−60+100 mesh)	8.54	4.900	2.273	0.865	38.5±0.8
10	Biotite, no visible impurities (−40+80 mesh)	9.05	5.155	2.256	.820	38.2±0.8
11	Biotite, no visible impurities (−80+100 mesh)	9.38	5.318	2.246	.634	38.0±0.8
12	Biotite, 2 percent chlorite (−42+65 mesh)	9.00	5.048	2.220	.782	37.6±0.8
13	Whole rock matrix of Battle conglomerate, biotite, sericite, K-feldspar, quartz, relict plagioclase (−100+150 mesh).[1]	9.51	5.283	2.200	.814	37.2±0.7
14	do.[1]	2.55	1.411	2.195	.521	37.2±0.7

[1] Sample prepared by crushing to 60 mesh and settling sulfides in methylene iodide. Light fraction was reground to −100+150 and mixed thoroughly.

TABLE 8.—K-Ar *ages of rocks from the Battle Mountain mining district*

Location No. (figs. 3, 4)	Name	Mineral	K-Ar age ($\times 10^6$ yr)
1	Granodiorite of Trenton Canyon	Biotite	87.2
2	Granodiorite of Trenton Canyon	Biotite	87.0
3	Granodiorite of Modoc mine area	Hornblende[1]	41.1
3	Granodiorite of Modoc mine area	Biotite[1]	39.2
4	Granodiorite of Elder Creek area	Biotite	37.3
5	Granodiorite of Long Peak area	Biotite	37.3
6	Altered granodiorite of Iron Canyon area.[2]	Biotite	37.5
7	Granodiorite	Biotite[1]	39.0
7	Granodiorite	Hornblende[1]	38.8
8	Altered granodiorite of Wilson-Independence mine area	Biotite	38.2
9	Altered granodiorite[3] of Copper Canyon area	Biotite (I)	38.5
10	Altered granodiorite[2] of Copper Canyon area	Biotite (II)	38.2
11	Altered granodiorite[2] of Copper Canyon area	Biotite (III)	38.0
12	Altered granodiorite sill[2 3]	Biotite	37.6
13	Matrix of mineralized conglomerate, Battle Formation, Copper Canyon porphyry copper deposit.[4]	Whole rock (I)	37.2
14	Matrix of mineralized conglomerate, Battle Formation, Copper Canyon porphyry copper deposit.[4]	Whole rock (II)	37.2

[1] Mineral pair from same bulk sample.

[2] Drill core.

[3] See text.

[4] Biotite–K-feldspar–white mica–quartz–(plagioclase)–bearing matrix separated from pyrite-chalcopyrite-rich rock specimen collected from 6500 bench. Copper Canyon porphyry copper deposit. Samples 13 and 14 are from different locations on the bench.

the intrusive igneous record. All 14 remaining K-Ar ages on intrusive rocks in the district fall between 37 and 41 m.y., placing them in the latest Eocene and earliest Oligocene(?) Epochs. Thus, the K-Ar ages in the district span a 50-m.y.-time interval from Late Cretaceous to late Eocene or early Oligocene (table 8).

TERTIARY GRANODIORITE AND ALTERED GRANODIORITE

SAMPLES COLLECTED OUTSIDE THE COPPER CANYON AREA

Six intrusive bodies outside the Copper Canyon area yielded K-Ar ages of 41.1 to 37.3 m.y. from biotite and hornblende mineral concentrates. K-Ar ages of 41.1 m.y. and 39.1 m.y. were obtained from hornblende and biotite, respectively, separated from a sample of porphyritic biotite-hornblende granodiorite intrusive into chert and calcareous sandstone of the Havallah Formation at the Modoc mine, in the southern part of the district (No. 3, table 8 and fig. 3). Biotite separated from samples of porphyritic granodiorite intruding sandstone and arkose of the Harmony Formation in the upper plate of the Dewitt thrust, at Elder Creek, and at Long Peak (fig. 3, Nos. 4 and 5), both gave 37.3-m.y. ages (table 8, Nos. 4 and 5).

Medium-grained biotite (greater than 1 mm across) separated from a composite sample of a porphyritic granodiorite dike, intruding chert and argillite of the Scott Canyon Formation intersected in a drill hole, approximately 1,050 m beneath the present erosion surface (fig. 3, No. 6), yielded a 37.5-m.y. age (table 8, No. 6). Phenocrysts of biotite, quartz, plagioclase, and K-feldspar are unaltered in this sample, but the groundmass has recrystallized to an intergrowth of white mica, quartz, and K-feldspar. Ages of 39.0 and 38.8 m.y., respectively, were obtained from a biotite and a composite hornblende-biotite concentrate separated from the core of a small porphyritic biotite-hornblende granodiorite stock intruding chert and quartzite of the Havallah Formation near the southwest corner of the district (fig. 3, No. 7). Biotite separated from an altered granodiorite plug near the Wilson-Independence mine, about one-third km southwest of the main intrusion at Copper Canyon (fig. 3, No. 8), yielded an age of 38.2 m.y. The remaining six K-Ar age determinations in the district come from the Copper Canyon area.

COPPER CANYON AREA

Biotites from the altered granodiorite of the Copper Canyon area have been described above. They gave

K-Ar ages of 38.5, 38.2, and 38.0 m.y. (Nos. 9–11, table 8 and fig. 4).

An altered sill emplaced along the Golconda thrust was intersected in a drill hole (collared about 150 m north of the Copper Canyon intrusive body) at a depth of 116–125 m below ground surface. Feldspar phenocrysts and groundmass minerals of the sill are extensively altered to white mica, and the rock contains pyrite plus some chlorite, mainly along microfractures. Red-brown biotite plates are again optically homogeneous and contain minute amounts of quartz and magnetite. An age of 37.6 m.y. was obtained on biotite separated from a composite sample of the sill (No. 12, table 8 and fig. 4).

Finally, two samples of metallized rocks from the Battle Formation were collected from the 6500 bench of the porphyry copper deposit at Copper Canyon. Attempts to obtain a clean biotite separate were not successful at first, because the grains are so small (<0.01 mm, fig. 11). However, a sample suitable for dating was acquired first by crushing the rocks to 60 mesh and then by settling the sulfides in methylene iodide. The light fraction (which consisted of quartz–biotite–white mica and K-feldspar with some relict plagioclase) was reground to 100–150 mesh, thoroughly mixed, and then analyzed for K and Ar. The two separates varied in K content by a factor of 5, due to differing proportions of K-feldspar and quartz, but both yielded ages of 37.2 m.y. (Nos. 13 and 14, table 8 and fig. 4).

SIGNIFICANCE OF THE DATA

Metallization at Copper Canyon occurred during a hydrothermal stage that closely followed the emplacement of the Copper Canyon intrusion. The hydrothermal fluid(s) giving rise to the wallrock ore also were responsible for alteration and recrystallization of the groundmass of the intrusive body. The relative ages of granitic host rocks and porphyry-type copper deposits have been the subject of considerable investigation. Most of the studies that have been done using the K-Ar method have shown that the age of mineralization as determined on hydrothermal biotite or muscovite is the same within analytical uncertainty as the age of the granitic host rock (Creasey, in Anderson, 1968; McDowell and Kulp, 1967; Livingston and others, 1968; Damon and Mauger, 1966; Laughlin and others, 1969). Damon and Mauger (1966, p. 106) summarized these relations in stating that the age data require that the processes of mineralization are restricted in time to the cooling history of the genetically associated porphyry. However, two recent detailed studies using the K-Ar method have indicated that the time interval between emplacement of granitic host rocks and some stages of mineralization may be large enough to resolve (Moore and Lanphere, 1971; Page, 1971). The K-Ar age relations of the Copper Canyon intrusive body and ore deposits have some bearing on this problem.

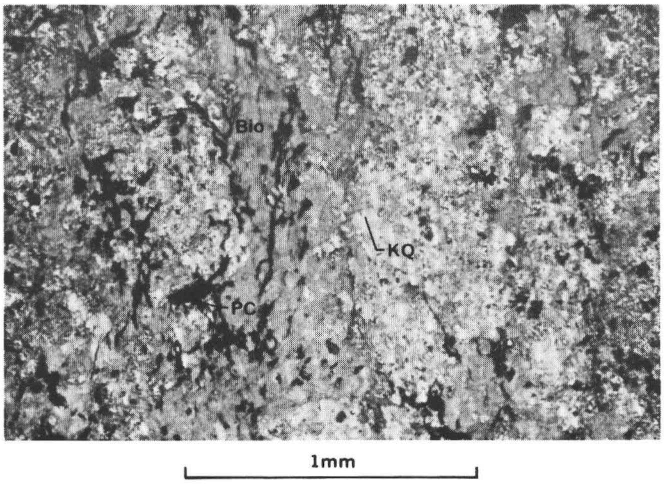

FIGURE 11.—Photomicrograph of hydrothermal biotite (Bio), K-feldspar and quartz (KQ), and pyrite and chalcopyrite (PC) from the Middle Pennsylvanian Battle Formation, 6500 bench, Copper Canyon porphyry copper deposit. Plane polarized light.

The data in table 8 show that the ages of the biotites in the intrusive body and the ages of the ore zone matrix overlap within the analytical uncertainty (0.7 m.y.) when individual age determinations are considered, essentially confirming the close relation in time between the intrusion and the ore deposit. However, when the results are averaged, the age of the intrusion is $38.2_2 \pm 0.02_3$ m.y., and the age of the ore deposit, as measured by the age of recrystallization of the Battle Formation's matrix, is $37.2_0 \pm 0.0_6$ m.y. The averages differ significantly at the 85-percent confidence level, according to the critical value test of McIntyre (1963). The measured age difference between the intrusion and the ore deposit is thus statistically resolvable; however, it is premature to say that this age difference has genetic validity because of two problems in interpreting the ages.

The first problem is whether the biotite ages from the intrusive body give a true picture of their age of magmatic crystallization at the exposed levels of the intrusive body. No unaltered samples of the intrusive rock were found during this study, and it might well be argued that the biotite ages were reduced by alteration from their true age. As described earlier, 310°–380°C fluid-inclusion temperatures were determined in the ore zones at the Copper Canyon porphyry copper deposit by Nash (Nash and Theodore, 1971). Study of Ar retention of biotite in contact metamorphic zones (Hart, 1964) has demonstrated that biotite loses Ar at temperatures much lower than these. Converging lines of evidence at Battle Mountain, however, strongly suggest that the biotite ages of the Copper Canyon intrusive body give accurate estimates of its age of emplacement:

1. The biotite K-Ar ages for the altered granodiorite of the Copper Canyon area are the same, within the analytical uncertainty, as the K-Ar ages from minerals of texturally similar rocks that are unaltered elsewhere in the district (table 8). The porphyritic granodiorite of the Long Peak area, for example, closely resembles granodiorite of the Copper Canyon area and gives a K-Ar age of 37.3 m.y.
2. Petrographic evidence suggests that some alteration may have occurred during late-stage crystallization of the intrusive body, when the temperatures would normally be high. Roberts and Arnold (1965, p. 11) suggested that the ore deposits formed during an alteration episode that could be considered a late hydrothermal phase of the igneous activity. Some cooling, however, of the primary biotites must then have continued after most of the alteration had ceased.

Two other factors suggest that these biotites were not affected by the alteration in a way that might make them lose argon subsequent to cooling:

3. The studied biotites are optically homogeneous and have apparently not recrystallized during the alteration, the physical conditions for which must have been well within their stability field.
4. Oxygen isotopic analysis of biotite sample 10 (table 4) by James O'Neil of the U.S. Geological Survey gave a δO^{18} of + 7.17°/oo, which is within the range of normal magmatic biotite (James O'Neil, written commun., 1970).

For these reasons, particularly the first, we conclude that the 38.2 m.y. age given by the biotites of the Copper Canyon intrusive body is an accurate estimate of their age of crystallization.

The second problem concerning the genetic validity is in interpreting the ages of the matrix of the Battle Formation in the ore zone. The samples contain disseminated sulfides, and the metasomatic recrystallization of the matrix to a potassium silicate alteration assemblage took place during ore deposition. Ore deposition, however, appears to have occurred over a period of time, because both the intrusion and the ore zone are cut by similar quartz–K-feldspar veins that contain sulfides. Some time must have elapsed between intrusion and veining in order for the igneous rock to have sustained brittle fracture and for the fractures to have then become filled with the sulfide-bearing veins. As the ore zones are veined, fluids at temperatures possibly up to 400°C (see Theodore and Blake, 1973) must have circulated there. The very fine grained material dated (K-feldspar–white mica–biotite, 0.01 mm and less) would not retain Ar at these temperatures. A study of grain size versus Ar retentivity for micas was conducted by Hanson and Gast (1967), who compared K-Ar and Rb-Sr ages of samples of the Snowbank stock in Minnesota at varying distances from the contact with the Duluth Gabbro Complex, a lopolith. The stock, a granitic body of varying composition, is 2.6×10^9 years old, and the lopolith is 1.05×10^9 years old. The effect of grain size of the biotite from one locality on the retentivity of Ar is illustrated in table 9 (modified from Hanson and Gast, 1967, p. 1132) and figure 12. The data illustrate that the retentivity of Ar varies as a function of grain size. The maximum temperature at 2.9 km from the contact with the lopolith was estimated at about 450°C. The study also demonstrated that biotite lost Ar in a range of temperature from 500° to 350°C. A similar study of K-Ar ages in a

TABLE 9.—*Effect of grain size on retentivity of argon, biotite from Snowbank stock, 2.9 km from contact with Duluth Gabbro Complex (sample is 5240a)*

[Modified from table 4, Hanson and Gast (1967, p. 1132)]

Grain size (mm)	K-Ar age[1]	K-Ar age[2] —1.05×10^9 yr	Fraction of argon retained[3]
1.8 ±0.3	2.07×10^9 yr	1.02×10^9 yr	0.65
.95± .28	2.10×10^9 yr	1.05×10^9 yr	.67
.41± .11	1.90×10^9 yr	$.85 \times 10^9$ yr	.54
.17± .04	1.52×10^9 yr	$.47 \times 10^9$ yr	.30
.41 (ground to 0.18)	1.91×10^9 yr	$.86 \times 10^9$ yr	.55

[1] Apparent age of biotite from sample 5240a from Snowbank stock, 2.9 km from Duluth Gabbro contact. Age of emplacement of stock is 2.61×10^9 yr.

[2] Age of Duluth Gabbro Complex=1.05×10^9 yr. The Duluth Complex was thus emplaced 1.56×10^9 yr after the Snowbank stock.

[3] After emplacement of Duluth Gabbro Complex, at 1.05×10^9 yr b.p., fraction=$\frac{\text{apparent age}-1.05 \times 10^9 \text{ yr.}}{1.56 \times 10^9 \text{ yr}}$

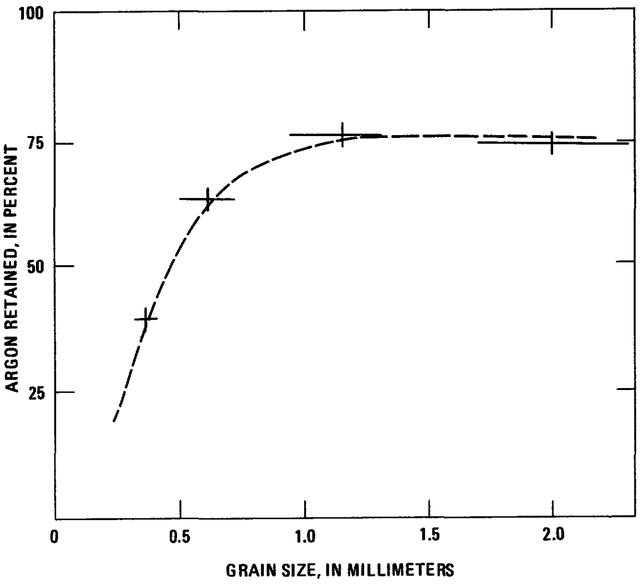

FIGURE 12.—Effect of grain size on Ar retentivity of biotite from Snowbank stock intruded by the Duluth Gabbro Complex (from Hanson and Gast, 1967).

contact metamorphic zone adjacent to the Eldora stock in the Front Range of the Colorado Rockies indicated that biotite lost Ar in the temperature range 500°–200°C (Hart, 1964) and also indicated a grain-size effect on the retentivity of Ar similar to that demonstrated by Hansen and Gast (1967).

The temperatures in the ore zones at Copper Canyon were generally in the 300°–400°C range during the early stages of sulfide deposition, but it is difficult to compare the two cases of Ar loss mentioned previously to that at Copper Canyon because of the mixed nature and the metasomatic aspects of the biotite and K-feldspar assemblages dated in this study. The ore-zone matrix, because of its very fine grain size, probably lost Ar until the ambient temperature dropped to perhaps 200°C, the lowest probable temperature for which Ar loss occurred in the contact zone of the Eldora stock (Hart, 1964). The coarse biotite of the Copper Canyon intrusive body, on the other hand, probably became closed to statistically significant Ar loss at some higher but again unknown temperature.

The K-Ar age of the matrix of the Battle Formation thus measures the time at which this assemblage dropped below some low but unspecified temperature and, similarly, the age of the coarse biotites in the granodiorite measures the time at which its ambient temperature dropped below some higher value. The difference of 1 m.y. between the coarse biotites of the granodiorite and the fine-grained matrix of the Battle Formation, which is statistically resolvable, cannot therefore be interpreted as indicating that a comparable interval of time occurred between emplacement of the intrusion and the initiation of hydrothermal mineralization. The apparent age difference may simply be due to the grain-size effect. Coarse biotite, or K-feldspar of grain size comparable to the coarse biotite in the intrusion, has not been found in the ore zone. K-Ar ages on such material would yield more accurate data on any time interval that may have occurred.

At Bingham Canyon, Utah, Moore and Lanphere (1971) found age relations similar to those of Battle Mountain between the magmatic biotite from unaltered parts of the Last Chance and Bingham stocks and hydrothermally recrystallized fine-grained aggregate biotite from altered rocks in the ore zone. They demonstrated that coarse, late-stage biotite deposited with quartz and sulfides on fracture coatings was younger (35.8±0.2 m.y.; average of two determinations on a single sample) than magmatic biotite from the Last Chance and the Bingham stocks (38.6±0.2 m.y. and 37.6±0.1 m.y., respectively; both ages are averages of three samples). However, this age difference has much greater validity than that suggested by the K-Ar data at Battle Mountain, because the minerals are of comparable grain size. Their data suggest that the magmatic-hydrothermal system responsible for the igneous rocks and ore deposits of Bingham had a lifetime of about 3 m.y. We infer, however, the lifetime of the system at Battle Mountain to be less than 1 m.y. Suitable coarse-grained material for K-Ar age determination in the ore zone might refine this estimate.

The age relations of altered granodiorite of the Copper Canyon area and ore deposits agree with the generalization made by Damon and Mauger (1966) that the processes of ore deposition in the porphyry-copper deposits are restricted in time to the cooling history of the associated igneous rock.

SUMMARY

Intrusive bodies were first emplaced in the Battle Mountain mining district during the Late Cretaceous (87 m.y. ago). There was then a quiescent gap of about 46 m.y. in the intrusive history, and intrusive activity finally culminated in late Eocene or early Oligocene time (41–38 m.y. ago). The magmatic composition of all these intrusions appears to be granodioritic—with remarkable major element chemical coherence across the entire district. Many of the intrusive bodies in the southern part of the district have been altered by fluids associated with hydrothermal sulfide deposits. Changes in concentrations of many minor elements reflect relative intensities of alteration. We infer no differences in major element chemistry before post-magmatic hydrothermal alteration between the intrusive body at Copper Canyon and intrusive bodies throughout the district not associated with economic copper deposits. However, primary magnesian biotites with most of their iron as Fe^{+2} have not everywhere been notably affected by the alteration. K-Ar ages of biotite in altered granodiorite of the Copper Canyon area are different from K-Ar ages in nearby disseminated ore, but this difference may be primarily a grain-size effect.

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