Chemical Characteristics of Hydrothermal Alteration at Bingham, Utah

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Abstract

Three chemical profiles, based on 31 analyses of intrusive igneous rocks, are used to characterize the relations of chemical changes to alteration mineralogy at Bingham, Utah. The chemical trends are reasonably coherent along the profiles, indicating a large-scale uniformity of alteration. Average compositions show cumulative effects of successive biotitic and sericitic alterations (slight loss of Al, substantial loss of Ca + Na, increase in Na : Ca ratios) that are similar in most respects to many porphyry copper deposits.

Biotitic alteration of quartz monzonite occurred with only small gains in K; losses of Mg and ferrous iron were also small. The replacement of clinopyroxene and amphibole by hydrothermal biotite represents a high-temperature hydrolysis reaction in which K and Mg are largely recombined rather than lost from the system.

A chemically and mineralogically distinct, northeast-trending zone of sericitic alteration was superimposed upon biotitized host rocks in the northern half of the orebody. This hydrolytic alteration occurred under conditions near the stability boundary between K-feldspar and sericite but on the mica side of the sericite-plagioclase boundary. Sulfide mineralization and alteration were integral parts of a multistage hydrothermal history confined to a broad zone of repeatedly fractured host rocks.

Introduction

UNDERSTANDING of the chemical environment of hydrothermal alteration related to porphyry copper metallization at Bingham, Utah, has been hampered by a lack of compositional data for host rocks of specified alteration type. Many petrologic characteristics of the porphyry deposit now are generally agreed upon, and major features of metal distribution and mineral associations are known reasonably well in three dimensions. Geological details of the porphyry deposit are presented in other articles in this issue and in a recent guidebook (Bray and Wilson, 1975). These results provide necessary background for a summary of chemical characteristics of the altered rocks, which is the principal objective of this report.

Published chemical data of the Bingham stock include 15 analyses of rocks identified as granite and granite porphyry by Stringham (1953, p. 977) who noted that the virtual absence of fresh rock precluded chemical documentation of "progressive alteration intensity"; these rocks are now termed quartz monzonite and quartz monzonite porphyry (Bray and Wilson, 1975). Single analyses of "dark" and "light" porphyry from Butler (1920) were used by Creasey (1959) and Burnham (1962) in discussions of relationships between alteration assemblages and bulk compositions of porphyry copper wall rocks; Burnham provided additional data on the inverse relationship between K_2O and CaO contents

of altered quartz monzonite porphyry. Average values for some major elements from zones of "differing mineral intensity" were tabulated subsequently by Peters et al. (1966), and five analyses of relatively unaltered quartz monzonite from the southeastern margin of the Bingham stock were reported by Moore (1973).

This report focuses on mineralogical and chemical features of the two major intrusive phases of the Oligocene Bingham stock: quartz monzonite and quartz monzonite porphyry. The hypidiomorphic-granular, amphibole-augite quartz monzonite is the oldest phase in the composite intrusion (Fig. 1). Petrographic features of this rock are considered elsewhere (e.g., Lanier et al., 1978; Moore, 1973). The quartz monzonite is intruded by a mass of quartz monzonite porphyry having a distinctive microgranular or "aplitic" groundmass. These phases are intruded by several types of latite and quartz latite porphyry dikes discussed by Bray (1969). Both the quartz monzonite porphyry and latitic dikes have a pronounced northeasterly trend parallel to a regional fault system that, in part, predates intrusive activity in the district (Tooker, 1971).

Petrographic examination of about 300 samples (Moore and Nash, 1974) led to the delineation of a zone of abundant high-salinity fluid inclusions in magmatic and hydrothermal quartz crystals. This zone (Fig. 2A) encompasses a central bornite-molybdenite zone (with subordinate chalcopyrite) and is congruent with limits of the (chalcopyrite-dominant)

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copper ore zone as discussed by James et al. (1961), Rose (1970), and John (1975).

Hydrothermal biotite (Fig. 2B) is a ubiquitous silicate phase in alteration mineral assemblages of the copper ore zone (Peters et al., 1966; Bray, 1969; Moore and Nash, 1974); biotite occurs in veinlets, scattered flakes, and aggregates replacing primary mafic minerals. The southern limit of biotitic alteration corresponds approximately to the southern limit of high-salinity fluids (cf. Fig. 2A, B). The Mg content of the biotite generally increases toward the center of the orebody (Moore and Czamanske, 1973; Lanier et al., 1975); modal abundance, however, is a function of the content of primary mafic minerals of the monzonitic rocks and
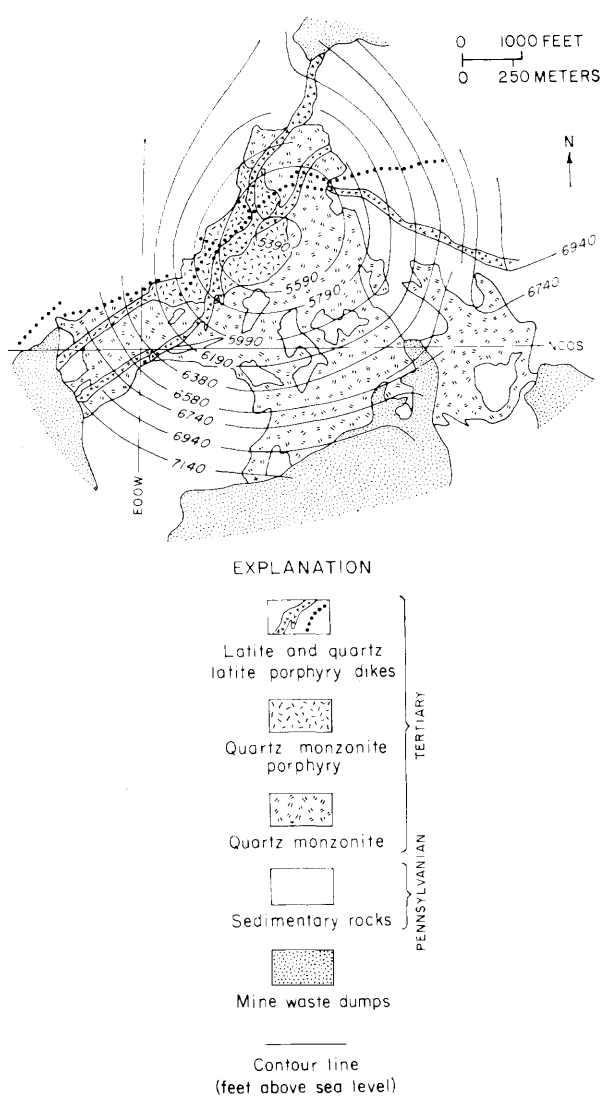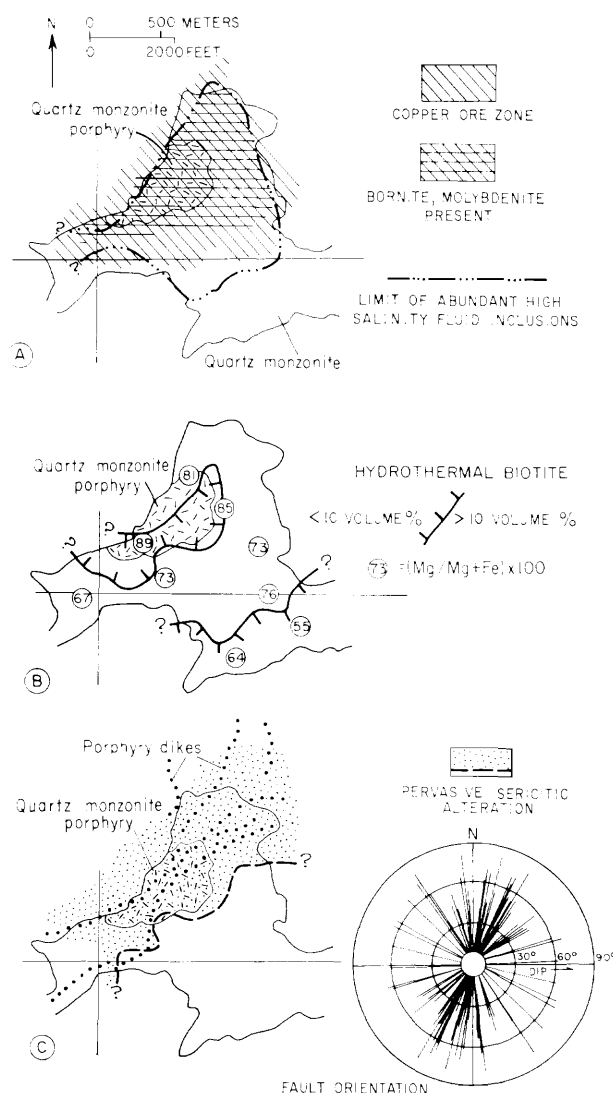

FIG. 2. Fluid inclusion and alteration mineral distribution patterns.

A. Outer limit of abundant high-salinity fluid inclusions (Moore and Nash, 1974) in relation to copper sulfide zonation adapted from John (1975).

B. Distribution of hydrothermal biotite and representative Mg:Fe values (from Moore and Czamanske, 1973).

C. Diagram illustrating similarity in northeasterly trend of sericitic alteration boundary and porphyry dikes. Rose diagram constructed from map of Smith (1969).

FIG. 1. Sketch map of the Bingham stock; adapted from Smith (1969) and John (1975).

shows no apparent relation to the roughly concentric zonation of ore mineral assemblages.

The similarity of distribution patterns for high-salinity fluid inclusions, biotitic alteration assemblages, and disseminated Cu-Mo sulfides in intensely fractured rocks of the Bingham stock suggests a genetic connection. Similar relations have been noted at many other porphyry deposits, most recently those in the Brenda and Babine Lake areas of British Columbia (Soregaroli, 1974; Carson and
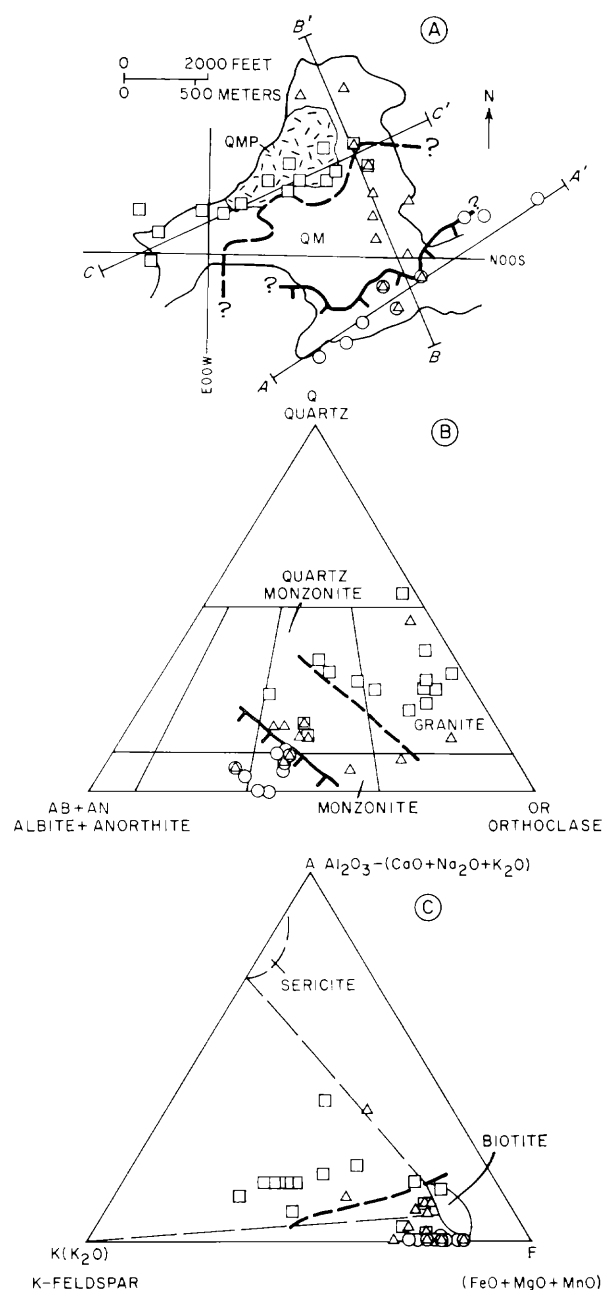
Jambor, 1974), Copper Canyon, Nevada (Nash and Theodore, 1971; Theodore and Blake, 1975), and El Salvador, Chile (Gustafson and Hunt, 1975).

Pervasive sericitic alteration (Fig. 2C), in contrast to the concentric or coaxial distribution of sulfides, hydrothermal biotite, and high-salinity fluids, occurs in a northeast-trending zone that transects the Cu orebody. Plagioclase in the sericite zone is replaced by fine-grained aggregates of sericite + quartz ± kaolinite ± montmorillonite; hydrothermal biotite was apparently stable during this alteration. The northern and southern boundaries of the sericite zone were, in part, structurally controlled by the same set of northeast-striking faults and fractures (Fig. 2C, rose diagram) that previously guided emplacement of the quartz monzonite porphyry and latite porphyry dikes (cf. Atkinson and Einaudi, 1978).

Chemical Data

Chemical variations of rocks from the Bingham stock are related to biotitic and sericitic alteration. Three profiles, each about 2 km long, are used to characterize these variations: the first (Fig. 3A, section A-A') includes relatively unaltered quartz monzonite from the southern margin of the stock; the second (section B-B') is oriented approximately at 90° to the long axis of the orebody and passes from unaltered to biotitized, to biotitized *and* sericitized quartz monzonite in the eastern part of the stock; the third profile (section C-C') follows the long axis of the orebody and is used to compare sericitized and unsericitized quartz monzonite porphyry. The vertical interval represented is in excess of 500 m, but the analytical data retain primarily two-dimensional significance relative to the total column of altered rock. Variations related to the inverted, cuplike shells of mineralization discussed by James (1971) and John (1975) are not apparent.

The profiles incorporate 31 representative samples, some of which were collected by Bronson Stringham in the mid 1940s and represent an average level about 400 ft above the current level of mining activity, although most were collected by the author on short visits to the mine between 1966 and 1974. The material submitted for analysis was sawed from fracture blocks to minimize the effect of alteration envelopes enclosing megascopic veinlets. Some locations are projected more than 150 m to the plane of the profiles; thus there is ample opportunity for scatter in the chemical trends. However, coherent chemical patterns can be directly related to the distribution of alteration mineral zones and reflect the large-scale

Fɪɢ. 3. A. Locations of analyzed samples and lines of section used in plotting chemical profiles (samples located by large open circles projected to section A-A' indicated by small, filled circles, etc); QM, quartz monzonite; QMP, quartz monzonite porphyry; southern boundary of pervasive sericitic alteration (heavy dashed line) and biotitic alteration (heavy solid line) from Figures 2B, 2C.

B. CIPW normative salic mineral plot for samples listed in Table 1; P_2O_5 set equal to zero and total iron recalculated as FeO before normalizing analyses to 100 percent.

C. AKF plot for samples listed in Table 1 with total iron calculated as FeO; excess quartz is assumed; mineral phases are those commonly observed in alteration assemblages at Bingham, but equilibrium is not implied.

TABLE 1. Analyses of Quartz Monzonite and Quartz Monzonite Porphyry from the Bingham Stock

Sample no.	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	57.1	58.0	60.5	59.5	57.2	61.0	62.5	61.6	57.6	58.4	63.6	60.9
Al_2O_3	15.6	15.7	15.0	15.5	16.4	15.3	15.4	15.1	15.0	14.3	15.2	15.2
Fe_2O_3	3.0	3.3	2.9	3.4	3.5	2.8	2.5	2.3	2.3	3.2	1.5	2.3
FeO	3.8	3.6	3.4	3.9	4.1	3.7	2.7	2.8	4.9	3.6	3.2	4.2
MgO	4.2	3.6	3.9	3.7	4.6	3.6	2.8	3.1	4.9	6.0	3.7	4.6
CaO	5.4	4.0	3.3	3.1	4.0	2.9	3.5	4.0	6.4	0.92	1.4	1.5
Na_2O	3.6	3.8	3.5	3.0	3.2	3.0	3.4	3.6	3.2	1.6	3.8	3.1
K_2O	4.5	5.1	5.1	5.1	3.6	5.2	4.6	4.9	3.8	7.9	4.5	4.9
H_2O (total)	1.18	1.51	1.62	2.41	2.28	1.76	1.4	1.3	0.84	1.46	2.3	2.53
TiO_2	0.93	0.95	0.78	0.94	0.92	0.85	0.72	0.70	0.94	1.0	0.81	0.94
CO_2	0.30	<0.05	0.02	0.02	0.02	0.04	0.30	0.50	0.06	0.02	0.02	0.02
P_2O_5	0.52	0.57	0.50	0.64	0.75	0.56	0.39	0.37	0.46	0.58	0.60	0.67
MnO	0.12	0.10	0.00	0.00	0.00	0.00	0.07	0.07	0.12	0.00	0.00	0.00
S	0.09	<0.04	0.19	0.04	0.49	0.35	0.06	0.08	0.00	1.80	0.65	0.66
Subtotal	100.3	100.2	100.7	101.3	101.1	101.1	100.3	100.4	100.5	100.2	101.3	100.5
Less O=S	0.1	0.0	0.3	0.1	0.7	0.5	0.1	0.1	0.0	2.7	1.0	1.0
Total	100	100	100	100	100	101	100	100	100	98	100	100
Bulk specific gravity	2.75	2.66	2.66	2.60	2.68	2.68	2.64	2.69	2.80	2.64	2.62	2.62

Sample no.	13	14	15	16	17	18	19	20	21	22	23	24
SiO_2	62.0	60.9	61.1	60.3	61.9	60.9	60.0	62.8	62.2	68.9	68.3	68.5
Al_2O_3	15.0	15.2	14.9	14.1	16.1	18.0	14.1	14.4	15.3	15.8	15.4	15.0
Fe_2O_3	2.2	1.3	3.0	1.4	1.5	2.7	4.4	4.3	3.7	3.7	0.56	0.44
FeO	3.6	2.9	3.9	3.6	2.7	2.2	3.7	1.8	1.1	0.50	0.84	0.76
MgO	4.0	4.9	4.1	4.9	4.5	3.2	6.0	3.7	3.8	1.1	2.2	2.3
CaO	1.3	1.9	1.4	2.8	0.30	0.32	1.4	1.6	0.08	0.13	0.29	0.62
Na_2O	3.4	2.4	2.9	2.8	0.80	0.17	1.4	1.7	0.13	0.24	0.86	1.9
K_2O	4.4	7.4	4.7	5.1	9.6	5.5	4.1	4.2	8.1	5.9	9.2	7.4
H_2O (total)	2.15	2.23	1.6	3.3	1.40	5.05	3.6	4.4	1.62	2.14	1.47	1.70
TiO_2	0.86	0.94	0.82	0.87	1.0	0.82	0.87	0.63	0.60	0.75	0.67	0.47
CO_2	<0.05	0.04	0.09	0.88	<0.05	<0.05	0.02	0.02	<0.05	<0.05	0.02	<0.05
P_2O_5	0.57	0.61	0.72	0.57	0.34	0.48	0.52	0.44	0.17	0.27	0.33	0.22
MnO	0.04	0.00	0.00	0.00	0.05	0.05	0.03	0.00	0.04	0.04	0.00	0.00
S	0.19	0.37	0.11	0.25	0.78	1.08	1.54	2.11	2.38	2.69	0.54	0.27
Subtotal	99.7	101.1	99.3	100.9	101.0	100.5	101.7	102.1	99.2	102.2	100.7	99.6
Less O=S	0.3	0.6	0.2	0.4	1.2	1.6	2.3	3.1	3.5	4.0	0.8	0.4
Total	99	100	99	100	100	99	99	99	96	98	100	99
Bulk specific gravity	2.64	2.67	2.63	2.62	2.55	2.55	2.65	2.66	2.68	2.58	2.56	2.54

Sample no.	25	26	27	28	29	30	31
SiO_2	66.9	66.8	67.5	68.2	68.6	73.7	65.6
Al_2O_3	15.1	15.6	14.6	14.7	14.5	12.8	15.0
Fe_2O_3	0.00	0.76	0.61	0.55	0.79	0.58	1.1
FeO	2.3	0.84	0.72	0.75	1.01	0.53	1.9
MgO	2.2	2.0	2.7	1.9	2.2	1.3	2.5
CaO	0.74	0.13	0.47	0.23	0.30	0.16	2.8
Na_2O	2.1	1.1	1.5	0.62	0.73	0.56	3.2
K_2O	6.4	9.4	9.0	9.5	8.8	8.9	3.8
H_2O (total)	2.8	1.00	1.20	0.87	1.31	0.84	2.2
TiO_2	0.51	0.59	0.53	0.79	0.67	0.52	0.55
CO_2	<0.05	<0.05	0.06	<0.05	<0.05	0.02	0.28
P_2O_5	0.23	0.07	0.38	0.22	0.15	0.22	0.19
MnO	0.02	0.05	0.02	0.03	0.04	0.03	0.08
S	0.44	1.00	0.56	0.73	0.84	0.61	0.00
Subtotal	99.7	99.3	99.9	99.1	99.9	100.8	99.2
Less O=S	0.7	1.5	0.8	1.1	1.3	0.9	0.0
Total	99	98	99	98	99	100	99
Bulk specific gravity	2.52	2.54	2.53	2.54	2.51	2.51	2.63

Samples 1–9. Quartz monzonite reference samples.
Samples 10–16, 31. Biotitized quartz monzonite or quartz monzonite porphyry.
Samples 17–20. Biotitized and sericitized quartz monzonite.
Samples 21–30. Biotitized and sericitized monzonite porphyry.
Sample locations. Refer to Figures 4–6.
Analyses: By rapid methods by U.S. Geological Survey Analytical Laboratories under the direction of Leonard Shapiro.
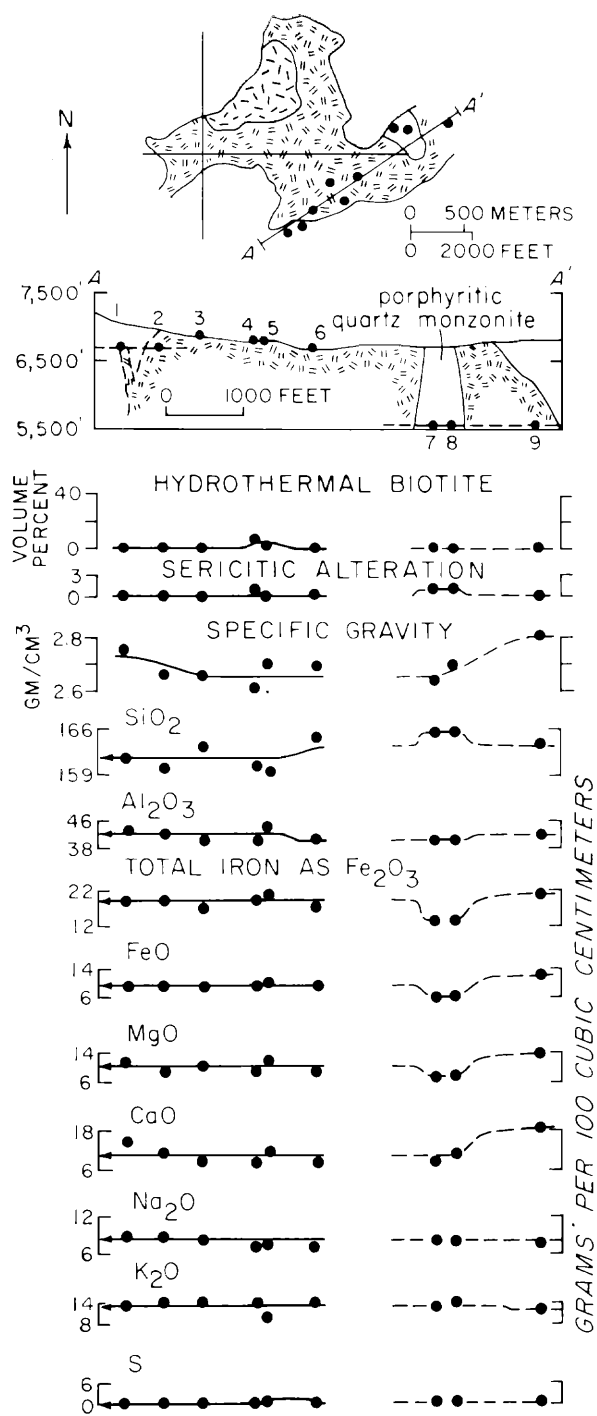
minerals in Figure 3B was derived from data in
Table 1 and illustrates the direction and nature of
chemical change resulting from hydrothermal altera-
tion. Subgroups of samples separated by solid and
dashed lines correspond to those indicated in Figure
3A. Rocks peripheral to the zone of biotitic altera-
tion plot generally in the normative monzonite field;
biotitized (but weakly sericitized) rocks plot as
quartz monzonites. Both quartz monzonite and
quartz monzonite porphyry from the zone of sericitic
alteration plot in the granite field. The trend toward
more granitic compositions—a result of cumulative
alteration as suggested previously by Peters et al.
(1966)—helps to explain the former lack of agree-
ment in names applied to these rocks (e.g., String-
ham, 1953; Lanier et al., 1975).

Similarly, the AKF diagram shown in Figure 3C
illustrates trends in terms of common (idealized)
alteration minerals; this usage follows Creasey
(1966) and Meyer and Hemley (1967). Unaltered
and biotitized rocks plot near the biotite field whereas
sericitized rocks plot nearer the muscovite-orthoclase
side. The observation that no sample plots appreci-
ably above the sericite-biotite "join" is compatible
with the apparent stability of orthoclase throughout
the ore zone. These features are common to many
porphyry copper deposits (Creasey, 1959, 1966;
Burnham, 1962).

Profile A-A' through the southern margin of the
Bingham stock (Fig. 4) illustrates the chemical
nature of the least altered equivalents of the metal-
lized host rocks (Moore, 1973). All samples along
profile A-A' are outside the copper ore zone (>0.4%
copper) and were not exposed at the time of String-
ham's (1953) study. Pyrite veinlets and propylitic
(chlorite $\pm$ epidote $\pm$ calcite) alteration assemblages
replacing mafic minerals occur locally but have been
avoided, as far as possible, in sample selection. This
profile is used to establish chemical reference levels
for evaluating changes resulting principally from
biotitic or sericitic alteration. Quantities for plotting
were obtained by recalculation of chemical analyses
from Table 1 into grams of oxide per 100 cm³ of
rock assuming constant total volume. Modal abun-
dance of hydrothermal biotite and the sericitic alter-
ation index (a petrographic estimate of the fraction
of plagioclase replaced by sericite or clay minerals)
are taken from unpublished petrographic data sum-
marized diagrammatically by Moore and Nash
(1974).

Samples of a pyroxene-rich border phase and a
porphyritic quartz monzonite dike (collected in
underground workings near the eastern edge of
the stock) have been included in profile A-A' to
illustrate the limited extent of primary variation in

homogeneity of alteration at Bingham, which is in
itself a characteristic feature of the deposit.

Before individual profiles are discussed, composi-
tional relationships among the entire group of sam-
ples are considered. The triangular plot of salic

this series of calc-alkaline rocks. However, only the six samples of hypidiomorphic-granular amphibole-augite quartz monzonite (nos. 1–6) were used to

FIG. 5. Chemical characteristics of successively biotitized and sericitized quartz monzonite along B-B′; dashed reference lines are estimates from Figure 4.

establish a base line for chemical comparison by projecting estimated average values to the ordinates for each element.

Section B-B′ (Fig. 5) shows progressive chemical changes in the Bingham quartz monzonite. The profile of the upper pit shown beneath the sketch map indicates the extent of mine development in 1947 and was constructed from Stringham's field sheets; the lower pit profile shows more recent mine topography adapted from Smith (1969). The dashed and solid boundary lines in plan and section are used in Figure 3A to mark the southeastern limits of pervasive sericitic alteration and biotitic alteration. The horizontal (dashed) base line are average values from Figure 4.

In passing from unaltered to biotitized quartz monzonite, the most pronounced chemical change is a loss of CaO. (Note that all trend lines have been sketched freehand; inflection points or changes in slope at major alteration boundaries are exaggerated to emphasize chemical differences.) Although biotite content of the altered quartz monzonite is about twice that of the unaltered rock, there is no regular increase in K_2O. Quartz monzonite affected by both biotitic and sericitic alteration shows additional loss of CaO (as well as Na_2O), together with some addition of potassium; minor and erratic gains of potassium in three samples from profile B-B′ may be a result of greater sericitization of plagioclase in alteration envelopes of fractures bounding the large blocks collected at each sample site. A measure of the chemical uniformity of the biotitized rock is provided by comparison of the most southerly of Stringham's samples (upper profile) with a sample of virtually identical bulk composition collected about 400 ft lower in 1971.

All rocks incorporated in profile C-C′ have been biotitized and most have been pervasively sericitized. However, the chemical trend lines cannot be evaluated as with those of profile B-B′ for several reasons. First, the major inflections occur across intrusive contacts; thus the chemical changes related to the decrease in hydrothermal biotite, for example, simply reflect the original leucocratic nature of the quartz monzonite porphyry. A second complication, which also impeded Stringham's (1953) evaluation, is that no unaltered sample of prophyry has been recovered and analyzed for comparative purposes. In this study a single deep core sample (Table 1, no. 31) of thoroughly biotitized but unsericitized porphyry (Moore, 1975, fig. 14) serves as a basis for dashed reference lines indicated in Figure 6. The core was provided by Mercer Thompson of the Anaconda Company. The location of the analyzed interval projected vertically about 850 m to the surface was
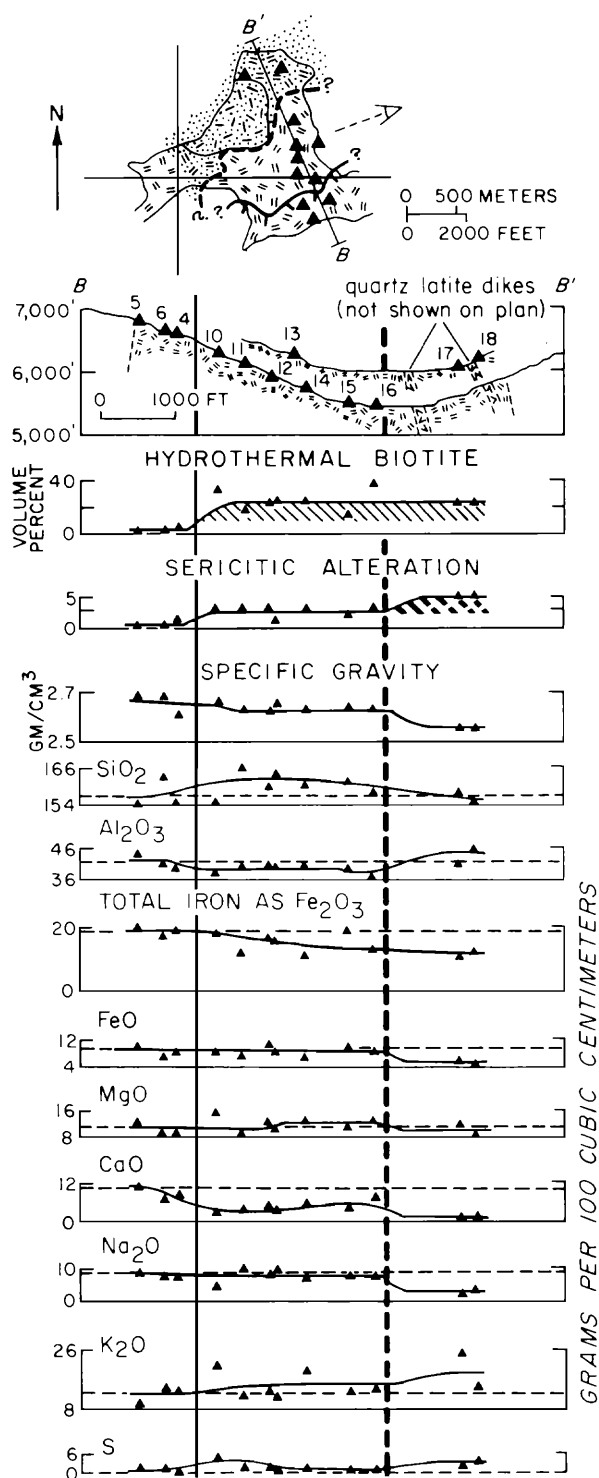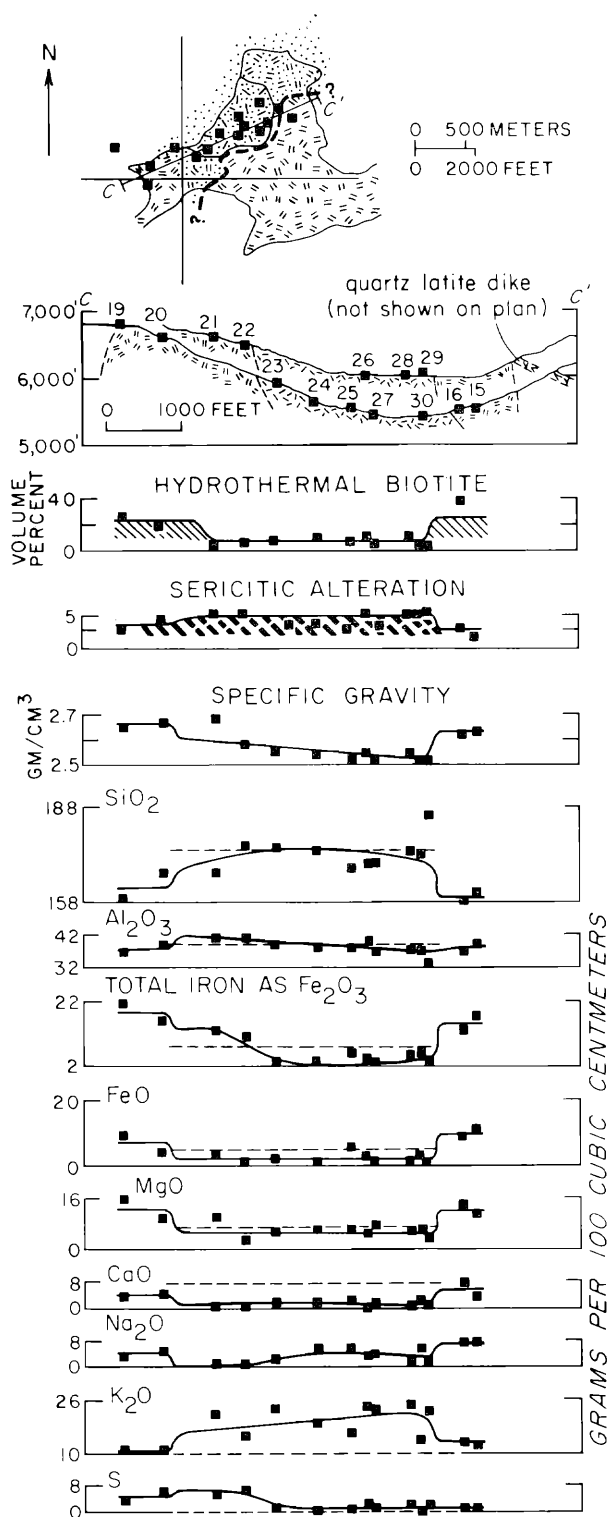
FIG. 6. Chemical characteristics of sericitized and biotitized quartz monzonite and aplitic quartz monzonite porphyry along C-C'; dashed reference lines are for biotitized porphyry from drill core.

supplied by M. T. Einaudi (written commun., 1975) and is indicated in the sketch map by a filled square northwest of the present porphyry-sediment contact.

Assuming that chemical changes resulting from biotitic alteration of the porphyry were comparable to those in the quartz monzonite (i.e., relatively slight except for removal of CaO), then the dashed lines are a base for evaluating additional changes resulting from sericitic alteration. Not surprisingly, the major changes are a twofold increase in K_2O and almost total loss of CaO; Na_2O is depleted less than CaO, in keeping with the presence of hydrothermal albite reported by Lanier et al. (1975); decreases in FeO and MgO are modest. Again, note the chemical similarity between samples from different levels along the profile.

Discussion

The close correspondence of compositional variations with distribution patterns of hydrothermal mineral assemblages in rocks of the Bingham stock provides the empirical justification for a generalized chemical characterization of the alteration. The analytical data support previous studies (Bray, 1969; Rose, 1970; Moore and Nash, 1974) indicating a coextensive distribution of biotitic alteration assemblages, disseminated copper ores, and high-salinity fluids; these are treated as broadly contemporaneous elements of a protracted hydrothermal episode that began after crystallization and shattering of the quartz monzonite and quartz monzonite porphyry. The chemically distinct zone of sericitic alteration that transects the orebody is apparently superimposed upon the biotitic assemblages and disseminated copper ores. Patchy propylitic alteration (that was, perhaps, contemporaneous with biotitic alteration) and a pyritic zone occur peripherally, but the mass of intensively altered rock and hypogene orebody are coincident. Mineralization was apparently the cumulative result of an overlapping sequence of discrete hydrothermal events; the hydrothermal episode was marked by repeated boiling of hydrothermal fluids (Moore and Nash, 1974) within the zone of shattering.

Characterization of the chemical environment of alteration at Bingham should be coordinated with studies aimed at establishing precisely which vein networks controlled fluid circulation and resultant rock-fluid interactions at any given stage of hydrothermal activity (cf. Soregaroli, 1974; Gustafson and Hunt, 1975). In the absence of this detailed paragenetic information, a fundamental connection between copper metallization and hydrothermal alteration can be only assumed. Nevertheless, the data clarify certain mineral-chemical relationships and

TABLE 2. A Summary of Analytical Data for Quartz Monzonite and Quartz Monzonite Porphyry from the Bingham Stock

	Quartz monzonite			Quartz monzonite porphyry	
	Unaltered	Biotitized	Biotitized and sericitized	Biotitized	Biotitized and sericitized
	A	B	C	D	E
	Weight percent				
SiO_2	58.9	61.1	61.4	65.6	68.0
A_2O_3	15.6	14.9	15.6	15.0	14.9
Fe_2O_3	3.2	2.2	3.2	1.1	1.2
FeO	3.8	3.6	2.6	1.9	1.6
MgO	3.9	4.6	4.4	2.5	2.2
CaO	3.8	1.6	0.90	2.8	0.32
Na_2O	3.4	2.0	1.0	3.2	1.0
K_2O	4.8	5.5	5.8	3.8	8.3
H_2O (total)	1.79	2.2	3.6	2.2	1.50
TiO_2	0.90	0.90	0.83	0.55	0.61
CO_2	0.07	0.15	0.01	0.28	0.01
P_2O_5	0.59	0.62	0.44	0.19	0.23
MnO	0.04	0.01	0.03	0.08	0.03
S	0.19	0.58	1.38		1.00
Specific gravity	2.67	2.63	2.60	2.63	2.55
	Grams per 100 cubic centimeters				
SiO_2	157.3	160.7	159.6	172.5	173.4
Al_2O_3	41.7	39.2	40.6	39.4	38.0
Fe_2O_3	8.5	5.8	8.3	2.9	3.1
FeO	10.1	9.5	6.8	5.0	4.1
MgO	10.4	12.1	11.4	6.6	5.6
CaO	10.1	4.2	2.3	7.4	0.8
Na_2O	9.1	5.3	2.6	8.4	2.6
K_2O	12.8	14.5	15.1	10.0	21.2
H_2O (total)	4.8	5.8	9.4	5.8	3.8
TiO_2	2.4	2.4	2.2	1.4	1.6
CO_2	0.2	0.4		0.7	
P_2O_5	1.6	1.6	1.1	0.5	0.6
MnO	0.1		0.1	0.2	0.1
S	0.5	1.5	3.6		2.6

A. Average of samples 1–6.
B. Average of samples 10–16.
C. Average of samples 17–20.
D. Sample 31.
E. Average of samples 21–30.

permit a number of chemical generalizations, some applicable to many porphyry copper deposits and others specific to Bingham or at least not well documented in the literature.

A relationship commonly noted in porphyry copper deposits and documented at Bingham by Burnham (1962, fig. 6), is the exchange of K for (Ca + Na) in rocks of the sericite zone (Fig. 6). This alteration does not obliterate rock textures (cf. John, 1975) but is confined primarily to discrete alteration envelopes around quartz-sericite veinlets (Lanier et al., 1975) or to replacement of plagioclase, particularly phenocrysts in the quartz monzonite porphyry. The limited extent of hydrolytic exchange at Bingham is indicated by relatively small values for the ratio gm equiv. H^+/gm equiv. ($Mg^{2+} + Ca^{2+} + Na^+ + K^+$), averaging 0.4 to 0.7 for sericite zone

rocks of profiles B-B′ and C-C′ as compared to an average value of 1.4 for mica-clay mineral associations in altered rocks summarized by Hemley and Jones (1964, table 1). Stable persistence of K-feldspar throughout the sericite zone suggests that hydrolysis and base exchange reactions occurred under conditions near the stability boundary between sericite and K-feldspar but on the mica side of the sericite-plagioclase boundary (cf. Hemley, 1959, Hemley et al., 1971). A similar conclusion was reached by Meyer and Hemley (1967, fig. 15) for early K-silicate alteration at Butte and by Guilbert and Lowell (1974) for the coarse orthoclase-sericite alteration in the Valley Copper orebody of the Highland Valley district, British Columbia.

Biotite (or biotite-orthoclase) alteration is the type most closely associated with hypogene copper ores

at Bingham and many other deposits (cf. Rose, 1970). For example, the recent work of Roberts (1973) indicates that primary Cu-Mo metallization and pervasive biotitic alteration at Butte have approximately the same limits, and in the Babine Lake area of British Columbia (Carson and Jambor, 1974) the size and grade of individual copper zones can be correlated directly with the areal extent, petrographic character, and composition of hydrothermal biotite. Moore and Nash (1974) have attributed this alteration and initial copper metallization to fluids concentrated during final crystallization of the monzonitic parent magma. The replacement of clinopyroxene and amphibole by hydrothermal biotite may represent a high-temperature hydrolytic exchange capable of exerting an effect on fluid-wall-rock equilibria and sulfide deposition similar to the sericitization of feldspars; i.e., hydrogen ions would be consumed and base ions liberated as in the various types of hydrolysis equilibria discussed by Meyer and Hemley (1967).

Magnesium and potassium were generally redistributed within the biotite zone in Mg-rich hydrothermal biotite (Moore and Czamanske, 1973), whereas ferrous iron was incorporated in various sulfide phases derived, in part, from sulfidization of original magnetite (Bray, 1969). Retention of Mg, anticipated by Meyer and Hemley (1967, p. 210), is consistent with petrographic evidence for limited base leaching. Additions of K_2O in the biotite zone are less than expected based on previous reviews of chemical changes resulting from "potassic" alteration of intermediate igneous rocks (Creasey, 1959, 1966; Hemley and Jones, 1964; Meyer and Hemley, 1967). Comparable analytical results obtained by Lanier et al. (1975) suggest that the present data are representative of the biotitized quartz monzonite. The approximate K_2O balance for equal volumes of unaltered and biotitized rock may be largely a result of recombination of potassium derived from original amphibole (~ 0.5 wt % K_2O; G. K. Czamanske, unpub. data) and incipient replacement of K-feldspar by quartz. The present results indicate that "potassic" mineral assemblages can develop in monzonitic rocks without appreciable addition of K; in such cases, terms emphasizing the characterizing minerals, e.g., biotitic or biotite-orthoclase alteration (Rose, 1970), are preferable to those emphasizing bulk chemical attributes.

Average compositions for major rock types of the Bingham porphyry copper deposit, summarized in Table 2, show the cumulative effects of successive biotitic and sericitic alterations. Apart from the retention of FeO and MgO and limited additions of K_2O during biotitization of the quartz monzonite,

most of the trends (e.g., slight loss of Al_2O_3, substantial loss of $CaO + Na_2O$, increase in Na : Ca ratios) are characteristic of porphyry coppers in general. The data suggest that Ti and P may also have been conserved rather than transported out of the system. Moderate losses in total iron as Fe_2O_3 may be balanced relative to the total volume of altered rock by pyrite or iron oxides added to peripheral sediments (James et al., 1961).

The average compositions of Table 2 and the triangular plots (Fig. 3) provide a useful measure of interzonal bulk chemistry but variations within alteration zones are more readily evaluated by reference to the profiles of Figures 4, 5, and 6. With the apparent exception of K_2O plots in Figures 5 and 6, the intrazonal major-element trends are reasonably coherent: chemical differences between a given sample and its nearest neighbors are generally small; hence the averages of Table 2 are not seriously distorted by extreme values. The profiles demonstrate the correspondence of chemical trends to abundance or distribution of alteration minerals, a necessary condition if the chemical evolution of the Bingham hydrothermal system is to be understood in terms of specific alteration mineral reactions.

Acknowledgments

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