MBMG 268

THE MINERALOGY OF THE BUTTE DISTRICT, MONTANA

by

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December 4, 1964
Spokane, Washington

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Prepared for Presentation to the Northwest Mining Association, Spokane, Washington

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ABSTRACT

Continuing intensive study of the geologic environments integral to the Butte ore deposits has confirmed the occurrence of over 130 minerals, many previously unreported from Butte. Grouped according to environment, the mineral suites are found to support, refine, and extend existing theories concerning chronology of the district geology and zonation of the hydrothermal mineralization. Environments mineralogically described are: the Tertiary Boulder Batholith Butte quartz monzonite host rock, including its aplite-pegmatite segregations, quartz porphyry dikes and plugs, and basic inclusions; the late-magmatic—pre-Main Stage hydrothermal phases of Early Dark Micaceous alteration-mineralization and quartz-molybdenite veinlets; the Main Stage hydrothermal mineralization and its contemporaneous wall rock alteration; post-ore rhyolite dike intrusion and ore metamorphism; and supergene alteration of ore minerals and wall rock in both pyrite-rich and pyrite-poor assemblages. The list of verified minerals at present includes 3 native metals, 19 sulfides, 14 sulfosalts, 16 oxides, 2 halides, 12 carbonates, 20 sulfates, 16 phosphate-arsenate-tungstates, and 32 silicates. A few reliably reported but unverified species are described, new occurrences and assemblages are cited, and minerals ascribed to Butte in the literature but found to be of unlikely or restricted occurrence are noted. Of particular interest to mineralogists is the reporting of the minerals aikinite, wittichenite, (?) betekhtinite, and djurleite in the Butte ores. Of general interest are preliminary descriptions of a pyrophyllite-topaz-zunyite alteration assemblage; of the pre-Main Stage, feldspar-destructive, sericite-biotite Early Dark Micaceous alteration-mineralization; and of a recently defined Deep Level Zone of Main Stage sulfide mineralization.

INTRODUCTION AND ACKNOWLEDGEMENTS

Slightly more than 50 years ago, as eminent a geologist as W. H. Weed felt justified in asserting that "the minerals in the Butte ores are neither rare nor of great variety." (1912, p. 74). A sustained and efficient geology mapping program, nurtured in The Anaconda Company's Butte Geological Department under such men as Reno H. Sales, F. A. Linforth, C. H. Steele, M. H. Gidel, E. P. Shea, and C. C. Goddard, Jr., and intensive studies of the Butte deposit over the last 25 years by the Geological Research Laboratory, inspired by R. H. Sales and successively under W. H. Swayne, Charles Meyer, and the senior author of this paper, have drastically modified the basis of that assertion. As close examination of the chronological and physical-geochemical environments which resulted in the Butte ores has developed, a valuable by-product has been the identification of 134 minerals, 61 of which comprise the hypogene mineralization. Virtually all of the minerals described below have been uniquely determined in the Geological Research Laboratory by optical procedures (transmitted and reflected illumination) and X-ray techniques (Debye-Scherrer and diffractometry) supported by the standard methods of physical and chemical determinative mineralogy. Many of these minerals have been initially identified in specimens brought from surface and mine by the members of the Geological Department, and many have been discovered in the course of both basic and applied research projects in the Laboratory. This report primarily concerns mineral distribution, time being insufficient to permit detailed individual mineral and genetic descriptions. The incisive work of Charles Meyer, now Professor of Geology at the University of California at Berkeley, has been a major contribution to the preparation of this paper. This report would have been impossible but for decades of detailed geological mapping and compilation by mining geologists, supervisors, and departmental and laboratory research geologists. Finally, the support of V. D. Perry, Vice President and Chief Geologist of The Anaconda Company, has been essential to this report.

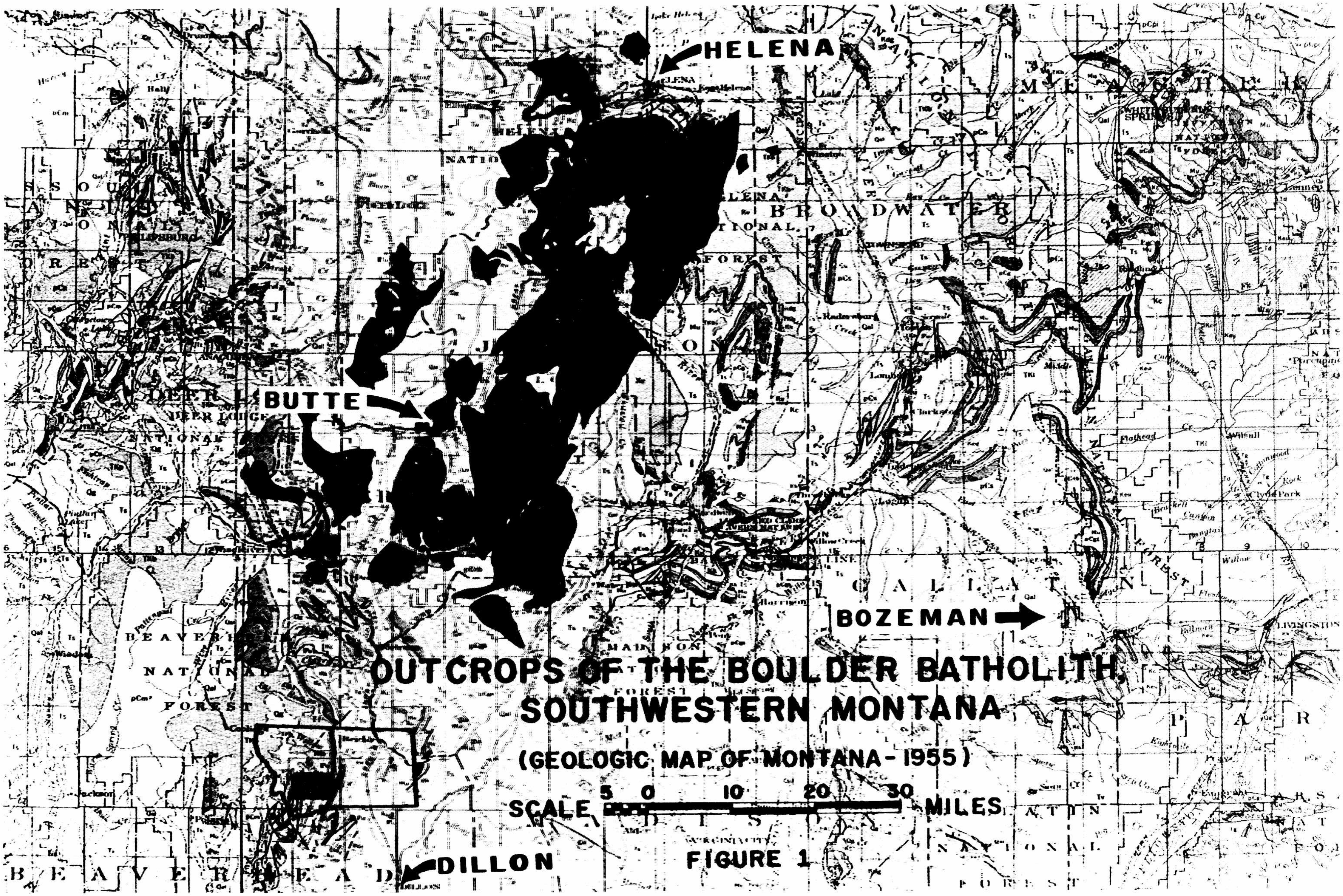
GENERAL GEOLOGY

The geology of Butte and the Boulder batholith has been described by R. H. Sales in his monumental "Ore Deposits of Butte, Montana" (1913), in a series of papers by Sales and Meyer (1948, 1949, 1950, and 1951), and by several other investigators, chief among them Billingsley and Grimes (1917), Hart (1933), Knopf (1953 and 1957), and Klepper (1962). The Laramide age Boulder batholith is a composite, shallowly-intruded calc-alkaline body with an outcrop area of over 2000 square miles. It extends 70 miles in a NNE direction and averages 25-30 miles across, the Butte district lying near the center of the southern half of the outcrop area (Fig. 1). Early potassic gabbros near the northern edge of the batholith are intruded by several younger and successively generally more acidic intrusive units (Knopf, 1953, Klepper, 1962). By far the largest, totaling 80% of the batholith outcrop area, are the cogenetic and essentially identical Clancy granodiorite to the north and the Butte quartz monzonite to the south. The quartz monzonite displays more aplite-pegmatite segregations and K-feldspar-porphyritic variants elsewhere than in the immediate Butte area, but these subtypes, along with quartz porphyry dikes and basic xenoliths, are limitedly found in the Butte mines and surface outcrops. The Butte mining district is roughly 3 miles N-S by 5 miles E-W and has been locally mined to more than a mile in depth. Fig. 2 shows general geology, vein locations, mines, and prominent physical features referred to below.

BUTTE QUARTZ MONZONITE AND RELATED ROCKS (Table 1)

Butte Quartz Monzonite

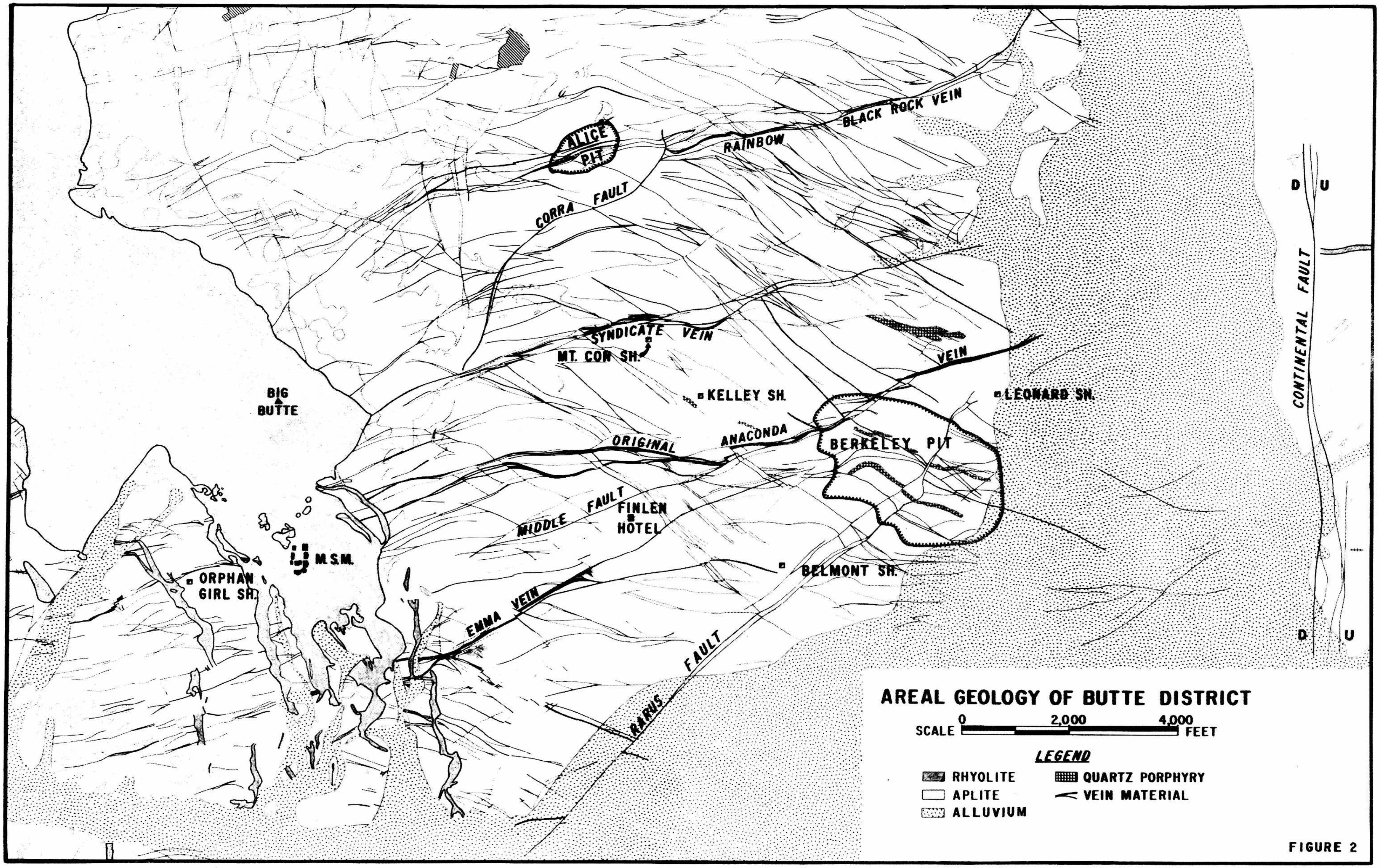
Rosiwal analyses of 57 fresh host rock specimens from the Butte district indicate averages of 36 volume per cent andesine plagioclase, 22% K-feldspar (microperthite), and 23% quartz. The feldspar is thus 62% plagioclase and 38% K-feldspar, and the rock is classified as quartz monzonite. It also contains 10% subhedral hornblende and 9% subhedral biotite. The mafics, along with anhedral quartz and anhedral to subhedral K-feldspar, are all intersititial to lath-like subhedral to euhedral plagioclase. Accessory minerals in fresh quartz monzonite normally averaging 0.2-0.3%, rarely exceeding a total of more than 1% include sphene,



OUTCROPS OF THE BOULDER BATHOLITH, SOUTHWESTERN MONTANA

(GEOLOGIC MAP OF MONTANA - 1955)

FIGURE 1



AREAL GEOLOGY OF BUTTE DISTRICT

FIGURE 2

TABLE 1. MINERALOGY OF THE BUTTE QUARTZ MONZONITE AND RELATED ROCKS

Butte Quartz Monzonite (Qm), Aplite-Pegmatite segregations (A-P), Quartz Porphyry dikes and plugs (Qp), and Basic Inclusions (BI).

Mineral	Occurrence & Abundance				Composition
	Qm	A-P	Qp	BI	
Plagioclase					
Labradorite	t	o	o	+	An_{50-55}(Qm);An_{60-65} (BI)
Andesine	+	o	+ ?	o	An_{40-50}
Albite-Oligoclase	o	m	- ?	o	An_{5-25}
Orthoclase					
Microperthite	a	a	a	m	Or_{90-100}
Microcline	-	m	-	-	Or_{90-100} ?
Quartz	a	+	a	m	SiO_2
Biotite	c	m	c	a	$K_2Mg_3Fe_3(OH)_4Si_6Al_2O_{20}$
Muscovite	o	t	o	o	$K_2Al_4(OH)_4Si_6Al_2O_{20}$
Hornblende	c	-	c	c	$Ca_2(Mg,Fe)_3Al_2(OH)_2Si_6Al_2O_{22}$
Augite	m	-	m	m	$Ca(Mg,Fe)Si_2O_6$
Magnetite	m	t	m	m	Fe_3O_4
Ilmenite	-	t	-	t	$FeTiO_3$
Sphene	m	r	m	-	$CaTiSiO_5$
Zircon	t	t	t	-	$ZrSiO_4$
Apatite	t	r	t	-	$Ca_5(F,Cl,OH)(PO_4)_3$
Pyrite	t	t	t	t	FeS_2
Chalcopyrite	t	t	t	-	$CuFeS_2$
Pyrrhotite	o	r	o	o	$Fe_{1-x}S$
Molybdenite	o	t	-	o	MoS_2
Tourmaline					
Schorlite	o	t	o	o	$NaFe_3Al_6B_3Si_6O_{27}(OH)_4$
Allanite	o	r	o	o	$Ca_2(Al,Fe)_3(OH)Si_3O_{12}$ (?)
Fluorite	-	r	-	-	CaF_2
Hematite	o	r	o	o	Fe_2O_3
Epidote	o	r	o	o	$Ca_2(Al,Fe)_3(OH)Si_3O_{12}$
Rock type	+	m	t	t	

+ = very abundant
a = abundant
c = common, some, moderate
m = minor, sparse

t = trace, infrequently encountered
r = rare, one or a few occurrences only
- = not found, but considered permissible
o = absent, considered precluded

Throughout this paper, a question mark preceding a mineral questions its identity; a question mark following a mineral (or abundance symbol) questions its distribution (or amount).

augite, magnetite, pyrite, apatite, and zircon. Locally the rock contains sparse, coarse microperthite phenocrysts in an otherwise hypautomorphic equigranular matrix, seldom in sufficient numbers to justify the term "porphyritic". The quartz monzonite is essentially homogeneous and totals well over 99% of the host rock of the immediate mining district.

Aplite-Pegmatite

Segregations of aplite, pegmatite, and composite mixtures of the two are scattered sporadically and randomly. They occur as ill-defined pods and patches varying in size from inches to feet across and rarely as diffuse, randomly-oriented sheetlike structures. Grain size and contact relationships vary. Typically, the smaller pods are sucrose granular, the larger ones commonly showing internal patches or near-core pods of pegmatitic grain size. Granoaplite and aplite porphyries are rare transitional modes. Contacts range from diffuse to sharp (trending with pod-like to dike-like occurrence), suggesting that some pegmatite constituents crystallized in place and that some components migrated for short distances along early fractures (Klepper, 1962). These composite segregations are more silicic than their host-rock, consisting predominantly of quartz and K-feldspar (nearly 40% each) and 20% plagioclase. Aplite, taken alone, averages 60% K-feldspar - 40% quartz, with traces of biotite, plagioclase (An_{45-50}), and accessories. Biotite is the most common accessory, with trace amounts of pyrite, chalcopyrite, magnetite, zircon, sphene, and apatite. The alaskitic, rarely graphic, pegmatite patches commonly carry minor pyrite and traces of molybdenite and chalcopyrite. Pyrrhotite is extremely rare, having been noted in one pegmatite with quartz, albite, orthoclase, and chalcopyrite. Tourmaline (schorlite), allanite, ilmenite, magnetite, hematite, fluorite, apatite, epidote, smoky quartz, and muscovite are rare and sporadic in the pegmatites, seldom being found in the same occurrence. Coarsely crystalline pegmatitic masses (quartz, microcline, smoky quartz, tourmaline, and cleavelandite) are common on Timber Butte, a hill 2 miles southwest of the city; sucrose aplite pods and gashes are far more abundant east of the Continental Fault and the Butte hill, and on up East Ridge, than in the mines area.

Quartz Porphyry

Typical quartz porphyry textures prevail in what appears to be a subcylindrical deep-seated plug in the Leonard mine area, in an E-W striking, near-vertical dike which appears to stem from that plug, and in a zone of several fifty-foot wide, near-surface, subparallel, E-W striking dikes in and beneath the Berkeley pit area on the east side of the Butte hill. These porphyries were predominantly emplaced in the later-pervasively-sericitized Central Zone volume, and hence their primary mineralogy is imperfectly known. They show abundant quarter-inch rounded and corroded quartz eyes and moderate euhedral plagioclase, quartz and K-feldspar, the whole probably approximating latite porphyry composition. Limited outcrops of fresh porphyry in the Continental area on the east side of the district indicate a groundmass to phenocryst ratio of 2 to 1 and a latite (quartz monzonite) porphyry composition. The quartz porphyry was fissured, altered, and mineralized during the ensuing late magmatic and hydrothermal events, but it is not known to have introduced significant copper values.

Basic Inclusions

Dispersed, partially-reacted melanocratic inclusions ranging from pebble- to boulder-size are found scattered through the quartz monzonite. They are generally sparse and small, but they have been noted in swarms constituting up to a third of the rock volume in a few mine headings. They consist predominantly of labradorite with subordinate but important amounts of hornblende, augite, and biotite. Magnetite, ilmenite, and pyrite are accessories. These dark spots are familiar phenomena in the mines, but they are of no economic significance.

LATE MAGMATIC-EARLY HYDROTHERMAL EVENTS (Table 2)

Early Dark Micaceous Alteration—Mineralization

Possibly the first distinctly fracture-controlled mineralization to have developed in the solid or quasi-solid Butte quartz monzonite is the assemblage collectively called EDM. It consists of dark greenish-gray alteration envelopes 1 to 6 inches wide which are symmetrical about 1/8- to 2-inch wide quartz-molybdenite veinlets (Table 2 and Fig. 3). The alteration and veinlet assemblages are unique in the Butte sequence, but the veinlet fillings share textural characteristics and some mineralogic common denominators with subsequent (?) quartz-molybdenite veinlets. As shown in the figure, no argillic alteration envelope separates fresh rock from the layer-lattice silicate alteration assemblage next to the veinlet. The characteristic minerals of the EDM alteration assemblage are quartz, sericite, biotite (brown and green, megascopically and in thin section), a soda-enriched K-feldspar, pyrite, anhydrite, ferromagnesian calcite, and magnetite. Appreciable chalcopyrite and minor molybdenite are introduced. The assemblage, then, contrasts sharply both chemically and mineralogically with that of the ensuing Main Stage hydrothermal event. The veinlets are dominantly sucrose quartz, generally with no evidence of a center line of solution ingress. The characteristic sulfide is molybdenite of fine-grain size and platy habit, either dispersed or in distinct bands. Chalcopyrite and pyrite are the only Cu-Fe-S minerals yet found, with minor magnetite associated. Soda-enriched K-feldspar (Or_{65-70}) is usually present in minor amounts. Sporadically occurring minerals are apatite, fluorite, scheelite, and calcite, all halide or oxy-acid salts of calcium.

EDM alteration of the quartz monzonite is extremely complex and not yet fully mineralogically described. The natures of the green and brown sucrose biotites are not well enough understood, although progress toward their definition is being made. X-ray data indicate that the green biotite is fully trioctahedral (not celadonite) and contains no significant interlayered montmorillonoid, vermiculite, or chlorite. Mg/Fe appears decreased in the green relative to the brown mica. The carbonate phase is in the magnesite-siderite system, probably with appreciable calcium. Single-phase K-feldspar appears to contain 30-35% albite molecule. Chlorite commonly occurs along basal cleavages of, and marginal to, the biotites, but whether or not it is part of an equilibrium assemblage or a later effect is as yet unknown.

Textures in EDM alteration are also complex. Much of the alteration biotite and sericite are fine-grained, sucrose, essentially randomly oriented, and tightly intergrown with Fe-Mg calcite, anhydrite, quartz, and K-feldspar. Thin rims of alteration K-feldspar between rock quartz and matted sericite-biotite intergrowths after plagioclase are common. As the figure shows, primary rock biotite is entirely recrystallized to the finer-grained, lighter-colored micas near the veinlet. Quartz is also apparently attacked and limitedly replaced by K-feldspar in the EDM environment.

TABLE 2. MINERALOGY OF THE LATE MAGMATIC-EARLY HYDROTHERMAL STAGE

Early Dark Micaceous Alteration-Mineralization (EDM), and Quartz-Molybdenite veinlets (qmb).

Mineral	Occurrence and Abundance		Composition
	EDM	qmb	
Quartz	+	+	SiO_2
Sericite (2M)	c	o	$K_2Al_4(OH)_4Si_6Al_2O_{20}$
Biotite	c	o	$KMg_3Fe_3(OH)_4Si_6Al_2O_{20}$
Orthoclase Microperthite	m	-	Or_{65-70}
Chlorite (?)	m ?	o	$(Mg,Fe,Al)_6(OH)_8(Si,Al)_4O_{10}$
Chalcopyrite	m	t ?	$CuFeS_2$
Pyrite	m	m	FeS_2
Molybdenite	t	m	MoS_2
Anhydrite	t	o	$CaSO_4$
Apatite	t	o	$Ca_5(F,Cl,OH)(PO_4)_3$
Fluorite	t	o	CaF_2
Scheelite	t	o	$Ca(W,Mo)O_4$
Calcite	t	o	$(Mg,Fe,Ca)CO_3$
Magnetite	t	r	Fe_3O_4
Hematite	t	-	Fe_2O_3
Anatase	t	o	TiO_2
Rutile	t	o	TiO_2
Rock Type	r	t	

+ = very abundant
a = abundant
c = common, some, moderate
m = minor, sparse

t = trace, infrequently encountered
r = rare, one or a few occurrences only
- = not found, but considered permissible
o = absent, considered precluded

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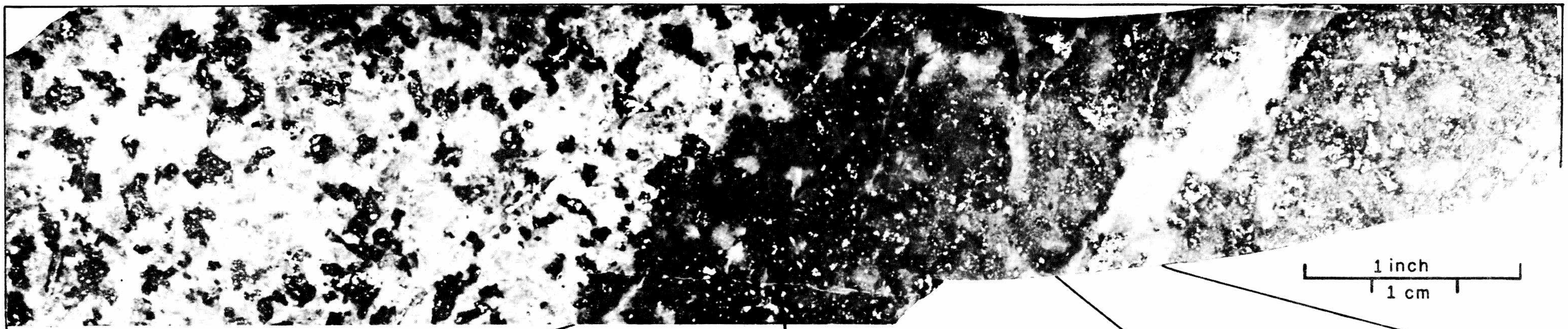

FRESH QUARTZ MONZONITE	FRINGE ZONE	MICACEOUS ZONE	VEIN
Quartz	Unchanged	Veined and replaced by K-feldspar (Or_{65-70})	Important Minerals Quartz Pyrite Chalcopyrite Molybdenite Anhydrite Common Minerals Carbonate (Fe, Mg, Ca) Apatite Hematite Magnetite Biotite Chlorite (?) Sericite (2M) K-feldspar (Or_{65-70}) Trace Minerals Fluorite Scheelite
Orthoclase (Or_{80-90} microperthite)	Unchanged	Sericite, quartz, and K-feldspar (Or_{65-70}), island texture common.	
Plagioclase (An_{45-50})	Replaced by sodic (Or_{65-70}) K-feldspar, variable from none through rimming to complete replacement.	Remaining plagioclase replaced by sericite, brown and green biotite. Anhydrite variable. Sodic K-feldspar stable.	
Hornblende (aqua green, slightly pleochroic) and Augite	Brown biotite-quartz-carbonate assemblage. Minor chlorite.	Brown biotite-quartz-carbonate assemblage.	
Biotite (dark brown to red brown pleochroic to light brown)	Bleached to light brown pleochroic to very light brown or clear. TiO_2 grid developed. Chlorite common.	Recrystallized to light brown and/or green biotite with increased Mg/Fe (?) Variable amounts of chlorite, carbonate, and anhydrite.	
Pyrite (common in biotite)	Slightly augmented	Abundant, disseminated in micas.	
Chalcopyrite (sparse in biotite)	Augmented	Markedly augmented	
Molybdenite (none)	None	Sporadic addition	
Magnetite (common in biotite)	Unchanged	Variable, augmented or pyritized	
Apatite (euhedral prisms)	Unchanged	Sporadic addition, coarse	
Sphene (euhedral wedges)	Partially leucoxenized	Rutile-Anatase and quartz	
Zircon (euhedral, sparse)	Unchanged	Unchanged	

Figure 3. Butte quartz monzonite Early Dark Micaceous alteration-mineralization mineralogy and pattern. See text for greater detail on both mineralogy and chronology

Chemically, the environment represents a relatively potassic plagioclase-destructive alteration. Studies in feldspar-mica equilibria (Hemley and Jones, 1964), bubble thermometry, and geologic and thermochemical relationships suggest temperatures below 600° C, probably nearer 400° C. Also indicated are an aK^+/aH^+ ratio near the K-mica-K-feldspar equilibrium curve at those temperatures, low relative fugacity of sulfur, and sufficiently high oxidation potential and CO_2 fugacity that anhydrite, biotite, carbonate, chalcopyrite, magnetite, and pyrite constituted an equilibrium assemblage.

Distribution of the EDM alteration-mineralization is not fully known. It was discovered 5 years ago in an area not yet extensively penetrated by mine workings deep in the Mt. Con mine near the center of the district. The type material of Fig. 3, along with related variants and subtypes, has been found in roughly the volume cut by quartz-molybdenite veinlets, especially in restricted portions of the Deep Level hypogene Zone and in parts of the upthrown Continental fault block on the east side of the district. EDM is abundantly cut by later Main Stage mineralized and altered fissures. Its recognition in hackly-surfaced crosscut walls requires great care in fresh rock; examples in subsequently-sericitized quartz monzonite have been mapped via unusually high porosity, recrystallization textures, and relict minerals.

Quartz-Molybdenite-Pyrite Veinlets

As described above, abundant quartz and moderate molybdenite occur in pegmatite segregations in the Butte quartz monzonite, commonly near the centers of composite aplite-pegmatite masses. These sulfide cores have been observed to lead directly, through decreased marginal feldspar and increased quartz content, into quartz-molybdenite-pyrite gashes against fresh quartz monzonite. However, the vast majority of the 'quartz-molly' veinlets cannot be traced directly to a pegmatitic origin and, in fact, show no first-order association with pegmatites. The filled structures, randomly-oriented and showing no discernible structural relationship to subsequent fissuring, vary in width from a millimeter to a maximum of two feet. Molybdenite, commonly subhedral to euhedral, occurs either as uniform disseminations or in distinct smoky gray to silvery black bands. Quartz forms sucrose equigranular mosaics rather than the comb patterns more typical of later vein fillings. Molybdenite content varies widely from nearly none to a maximum of 25%, with minor pyrite and rare chalcopyrite.

While molybdenite occurrences in distinctly aplitic-pegmatitic hosts are sparse but widely distributed throughout the district, the quartz-molybdenite gash fillings not demonstrably associated with pegmatites are zonal. The limits of occurrence, recently reevaluated, describe a volume nearly coextensive with that of EDM occurrence and not comformable with the distribution patterns of Main State hypogene mineralization. Both EDM and quartz-molybdenite-pyrite veinlets occupy fissures of varying thickness and orientation which bear no obvious local space relationship to Main Stage mineralization. The gross zonal pattern is also assymetric with respect to zonation of the hypogene ores, and universal cutting relationships indicate that the EDM-quartz-molybdenite event preceded Main Stage activity and was localized by distinctly different local and zonal controls.

Age relationships between EDM and quartz-molybdenite veinlets are equivocal. Many EDM veinlets contain as much molybdenite as the average quartz-molybdenite veinlet, and their origins are doubtless consanguineous. Numerous instances have been recorded of EDM alteration envelopes and controlling veinlets cut and offset by quartz-molybdenite-pyrite veinlets with no discernible alteration. No examples of typical quartz-molybdenite veinlets offset by EDM have yet been found, but further mapping may well disclose some. Both types of structures are difficult to date geologically in view of their non-persistence, their sparseness where found, and their restricted overall distribution. Simple crosscutting relationships (without offset) involving an EDM structure and a quartz-molybdenite veinlet require thin sectioning for age determination since the actual intersection is generally macroscopically quartz-healed. Quartz porphyry intrusion generally preceded quartz-molybdenite veinlet formation, although one example of a quartz-molly veinlet cut by quartz porphyry has been observed.

Both EDM and quartz-molybdenite veinlets are cut and offset by milky quartz-trace pyrite veinlets (not separated in Table 2). These veinlets are less common, show no alteration envelopes, and are not known to contain other than quartz, pyrite, and trace fluorite. All three of the sucrose, quartz-rich types described here contain similar liquid- and vapor-filled fluid inclusions, and all are considered late magmatic. The degree to which they are integral to the subsequent deposition of ore minerals is not known, but, in consideration of a crystallization model involving a descending sub-concentric magma-rock interface, the genesis of EDM, quartz-molybdenite-pyrite, and milky quartz veinlets may well be symptomatic of a continuum which ultimately produced the hydrothermal solution. It is difficult to describe classes of mineral assemblages without implying a degree of separation between them. These chronologically pre-Main Stage phenomena have only recently become the subject of intense study, and the degree to which they are integral to and in continuity with rock solidification on the one hand and later mineralization on the other is probably great. Certainly, EDM might have been generated in one volume while barren milky quartz was elsewhere cutting EDM. In short, much remains to be learned about space-time relationships obtaining during this interval.

MAIN STAGE HYDROTHERMAL MINERALIZATION-ALTERATION

Main Stage Mineralization (Table 3)

At some time after the formation of the above-described phenomena, fissure systems of district-wide proportions were developed in the Butte quartz monzonite. The genesis, timing, and structural details of the veins and faults have been set forth by Sales (1913), Billingsley and Grimes (1917), and Perry (1933). Such details need not be reviewed here, especially since mineralization-alteration effects spanned the inception and development of the two major mineralized sets such that the primary mineralization in the two is virtually identical. Local 'wrap-arounds' are commonly discernible where later Blue age veins merge with earlier Anaconda age structures but bulk mineralogy, composition of vein contents, and mineral habit are virtually indistinguishable from one vein age to the other. In the normal case, where Anaconda (East-West) age veins are cut and offset by Blue (Northwest) age structures, no mineralogic effects are detectable.

TABLE 3-1. MAIN STAGE HYDROTHERMAL VEIN MINERALOGY--Deep Level Zone (DL), Central Zone (C), Intermediate Zone (I), and Peripheral Zone (P).

Mineral	Occurrence and Abundance				Composition
	DL	C	I	P	
Quartz	+	+	+	+	SiO_2
Pyrite	+	+	+	c	FeS_2
Enargite	m	a	c	o	Cu_3AsS_4
Chalcocite	m	a	c	o	Cu_2S
Digenite	r	m	t	o	Cu_9S_5
Djurleite	-	m ?	t ?	o	$Cu_{1.96}S$
Covellite	r	m	t	o	CuS
Colusite	t	m	t	o	$Cu_3(As,Sn,V,Fe,Te)S_4$
Bornite	c	**m**	a	-	Cu_5FeS_4
Chalcopyrite	a	t	c	m	$CuFeS_2$
Tennantite	c	t	m	t	$Cu_{12}As_4S_{13}$
Wittichenite	t	t	t	-	Cu_3BiS_3
? Betekhtinite	t	t	t	-	$Cu_{10}(Fe,Pb)S_6$ (?)
Stromeyerite	r	t ?	t	t	$CuAgS$
Luzonite	-	t	-	o	Cu_3AsS_4
Dickite	-	t	-	o	$Al_4(Si_4O_{10})_3(OH)_{12}.3H_2O$
Hinsdalite	-	t	-	o	$PbAl_3(OH)_6PO_4SO_4$
Sericite	t	t	t	- ?	$K_2Al_4(OH)_4Si_6Al_2O_{20}$
Alunite	-	t	-	-	$KAl_3(OH)_6(SO_4)_2$
Wolframite	-	-	-	t	$MnWO_4$
Huebnerite	t	t	t	t	$(Fe,Mn)WO_4$
Ferberite	-	-	-	t	$FeWO_4$
Scheelite	t	t	t	t	$Ca(W,Mo)O_4$
Apatite	t	t	t	m	$Ca_5(F,Cl,OH)(PO_4)_3$
Barite	t	t	t	m	$BaSO_4$
Gypsum	r	-	r	t	$CaSO_4.2H_2O$
Fluorite	t	t	m	m	CaF_2
Sphalerite	-	t	t	a	ZnS
Galena	t	t	t	c	PbS
Rhodochrosite	t	t	t	a	$MnCO_3$
Rhodonite	o	o	o	c	$(Mn,Fe,Ca)SiO_3$
Helvite	o	o	o	r	$Mn_4SSi_3Be_3O_{12}$
? Willemite	o	o	o	r ?	Zn_2SiO_4

\+ = very abundant
a = abundant
c = common, some, moderate
m = minor, sparse

t = trace, infrequently encountered
r = rare, one or a few occurrences only
\- = not found, but considered permissible
o = absent, considered precluded

Throughout this paper, a question mark preceding a mineral questions its identity; a question mark following a mineral (or abundance symbol) questions its distribution (or amount).

MAIN STAGE HYDROTHERMAL VEIN MINERALOGY

(TABLE 3-2)

Mineral	Occurrence and Abundance				Composition
	DL	C	I	P	
Calcite	m	t	m	c	$CaCO_3$
Dolomite	m	t	m	c	$CaMg(CO_3)_2$
Ankerite	t	t	t	m	$Ca(Fe,Mg)(CO_3)_2$
Manganocalcite	-	-	t	m	$(Mn,Ca)CO_3$
Manganosiderite	-	-	r	t	$(Mn,Fe)CO_3$
Manganankerite	-	-	r	t	$Ca(Fe,Mn)(CO_3)_2$
Siderite	-	-	r	t	$FeCO_3$
Acanthite (Argentite)	-	-	r	m	Ag_2S
Tetrahedrite	o	o	- ?	r	$Cu_{12}Sb_4S_{13}$
Proustite	o	o	-	t	Ag_3AsS_3
Pyrargyrite	o	o	- ?	r	Ag_3SbS_3
Pearceite	o	o	-	t	$(Ag,Cu)_{16}As_2S_{11}$
Polybasite	o	o	- ?	r	$(Ag,Cu)_{16}Sb_2S_{11}$
Stephanite	o	o	- ?	r	Ag_5SbS_4
Andorite	o	o	r	r ?	$PbAgSb_3S_6$
Aikinite	r	-	-	r ?	$PbCuBiS_3$
Seligmannite	-	-	-	r ?	$PbCuAsS_3$
Silver	r	t	t	t	Ag
Gold	-	r	r	r	Au
Wurtzite*	-	r ?	r	r	ZnS
Greenockite	o	o	o	r	CdS
Marcasite	o	o	o	r	FeS_2
Arsenopyrite	o	o	o	r	$FeAsS$
Uraninite	r ?	r ?	r ?	r	UO_2
Hematite	o	o	o	r	Fe_2O_3
Chalcedony	o	o	-	m	SiO_2
Heulandite	o	o	-	r	$CaAl_2Si_7O_{18}\cdot 6H_2O$
Stilbite	o	o	-	r	$CaAl_2Si_7O_{18}\cdot 7H_2O$
Chabazite	o	o	-	r	$CaAl_2Si_4O_{12}\cdot 6H_2O$

+ = very abundant
a = abundant
c = common, some, moderate
m = minor, sparse

t = trace, infrequently encountered
r = rare, one or a few occurrences only
- = not found, but considered permissible
o = absent, considered precluded

Throughout this paper, a question mark preceding a mineral questions its identity; a question mark following a mineral (or abundance symbol) questions its distribution (or amount).

* Sphalerite pseudomorphs after wurtzite; wurtzite structure no longer present.

Neither is it in the province of this report to detail mechanisms of vein growth, hydrothermal chemistry, or the genesis of depositional- and post-depositional ore mineral textures and relationships, many of these subjects having been preliminarily treated by Sales and Meyer (1949). However, the direct relationship between hydrothermal zoning and mineral distribution demands a review of the zoning pattern. Four major mineral distribution zones are now recognized in the Butte ore deposit. They are the Central Zone, the Intermediate Zone, the Peripheral Zone, and the recently-recognized Deep Level Zone. Distribution of the major minerals in the first three zones is better known than is that of the trace minerals. Table 3 lists major, common, minor, trace, and rare minerals in a combined zonal-abundance arrangement in which the predominant Central Zone minerals are listed first, followed by Central Zone trace minerals, etc. Overlap is of course unavoidable, and the best appreciation of the mineralogy by zone is attained by reading downward in the appropriate column.

The Central Zone, occupying the east central portion of the Butte hill in the Berkeley pit and Leonard mine area (Fig. 4), is characterized by veins containing abundant quartz, pyrite, chalcocite, and enargite in a pervasively sericitized quartz monzonite host rock. Fissures include Anaconda and Blue age veins along with a proliferation of Anaconda age but northwest striking veins and veinlets, the renowned 'horsetail' structures described and illustrated by Sales (1913). Minor minerals in the Central Zone include digenite, djurleite, covellite, colusite, and bornite, with the trace minerals chalcopyrite, tennantite, wittichenite, (?) betekhtinite, stromeyerite, native silver, luzonite, sphalerite, galena, huebnerite, scheelite, apatite, barite, fluorite, (?) hinsdalite, rhodochrosite, calcite, ankerite, and dolomite, and the rare minerals native gold, wurtzite (now sphalerite), and (?) uraninite.

The Intermediate Zone ores lie generally outside the crude truncated dome of the Central Zone volume. They are relatively narrow on the east side, with westward protuberances of typical Intermediate Zone sulfide and alteration assemblages along the main through-going Anaconda age structures. Typically, hydrothermal alteration envelopes are developed with sericitized quartz monzonite against the vein but with fresh rock between veins. The characteristic and most abundant vein minerals are quartz, pyrite, bornite, chalcopyrite, chalcocite, and enargite. Minor amounts of tennantite, fluorite, calcite, and dolomite are accompanied by trace amounts of digenite, djurleite, (?) covellite, colusite, wittichenite, stromeyerite, (?) betekhtinite, huebnerite, scheelite, apatite, barite, sphalerite, galena, rhodochrosite, ankerite, manganocalcite, native silver, and wurtzite (now sphalerite). Rare minerals in the Intermediate Zone are manganosiderite, mangananankerite, andorite, native gold, and (?) uraninite. Recent mineral distribution studies have revealed a significant enargite sub-zone at the outer edge of the Intermediate Zone and a relatively sharp and projectable boundary between the copper ores of the Intermediate Zone and the zinc ores of the inner Peripheral Zone.

The Peripheral Zone vein mineralization is marked by a progressive drop in pyrite content. Quartz remains the dominant mineral, and sphalerite and rhodochrosite probably exceed pyrite in abundance, sphalerite mostly near the Intermediate Zone and rhodochrosite relatively farther out with common admixtures of the two. Zinc, manganese, and important amounts of lead, silver, and gold have been produced from mines in the Peripheral Zone. Only minor copper is found. Common minerals accompanying the major minerals quartz, pyrite, sphalerite, and rhodochrosite are galena, rhodonite, calcite, and dolomite. Minor minerals are chalcopyrite, barite, ankerite, manganocalcite, chalcedonic quartz, and wurtzite (now sphalerite), trace minerals are tennantite, stromeyerite, wolframite, huebnerite, ferberite, scheelite, gypsum, fluorite, manganosiderite, mangananankerite, siderite, acanthite (argentite), proustite, pearceite, native silver, and rare minerals are helvite, tetrahedrite, pyrargyrite, polybasite, stephanite, aikinite, seligmannite, native gold, greenockite, marcasite, arsenopyrite (?), uraninite, hematite, heulandite, stilbite, and chabazite. Wall rock alteration envelopes around Peripheral Zone veins are generally narrower than (but mineralogically identical to) their counterparts in the Intermediate Zone.

The Deep Level Zone is the most restricted and least well known of the four recognized zones. It has been encountered in recent years in the lowest levels of the Mt. Con and Steward mines, adjacent to one another near the geographic center of the district (See Fig. 2). Its upper limit is delineated in the Mt. Con-Steward area in four major veins, two Anaconda and two Blue age structures, but its downward and lateral extent is unknown since the Mt. Con and Steward shafts are currently the deepest in the district. It is marked by a progressive downward shift from vein fillings of typical Intermediate Zone affinity to more chalcopyritic ores, as described more fully below. The shift at any lateral point occurs over several levels, and the overall shape of the Intermediate Zone-Deep Level Zone interface appears to be that of a crude gentle dome. The highest Deep Level ores are found at the 3400 level in veins near the Mt. Con shaft, with Intermediate Zone ore types persisting as deep as the 4200 level in veins at points some thousands of feet away in any direction. The deepest levels of the Belmont and Leonard mines to the south and east are in Intermediate and Central Zone ores, and it is not known whether or not the flanks of the dome can be projected into these areas. The Deep Level ores are characterized by abundant quartz and pyrite, the common ore mineral chalcopyrite, and lesser but important amounts of bornite and tennantite. Minor amounts of enargite and chalcocite are accompanied by the trace minerals colusite, wittichenite, (?) betekhtinite, sericite, huebnerite, scheelite, apatite, barite, fluorite, and galena, and by the rare minerals digenite, covellite, stromeyerite, aikinite, native silver, and (?) uraninite. The carbonates, including minor calcite and dolomite and trace ankerite and rhodochrosite, are generally late, occurring in centerline vugs or in crosscutting fractures.

The origin of the Deep Level Zone, and its genetic integration with the long-established hypogene zonation, is under intensive investigation. It appears to reflect a lower relative fugacity of sulfur, all other variables held constant, than do the Central and Intermediate Zone ores. Whether this lower relative sulfur fugacity is a primary hydrothermal characteristic or a post-depositional phenomenon is being examined. Hypotheses of origin currently being tested are that the chalcopyrite-bornite ores are primary and reflect higher temperatures and pressures in the hydrothermal solution than those of the Intermediate or Central Zone vein fillings; that they have resulted from metamorphism by deep-seated post-mineralization intrusive masses; that differential cooling rates have resulted in expulsion of sulfur from the vein systems into wall rocks not saturated with sulfur, and that of reworking of Main Stage sulfides by later, low sulfur fugacity solutions. Whatever hypothesis of origin proves to have obtained, ore values have continued high

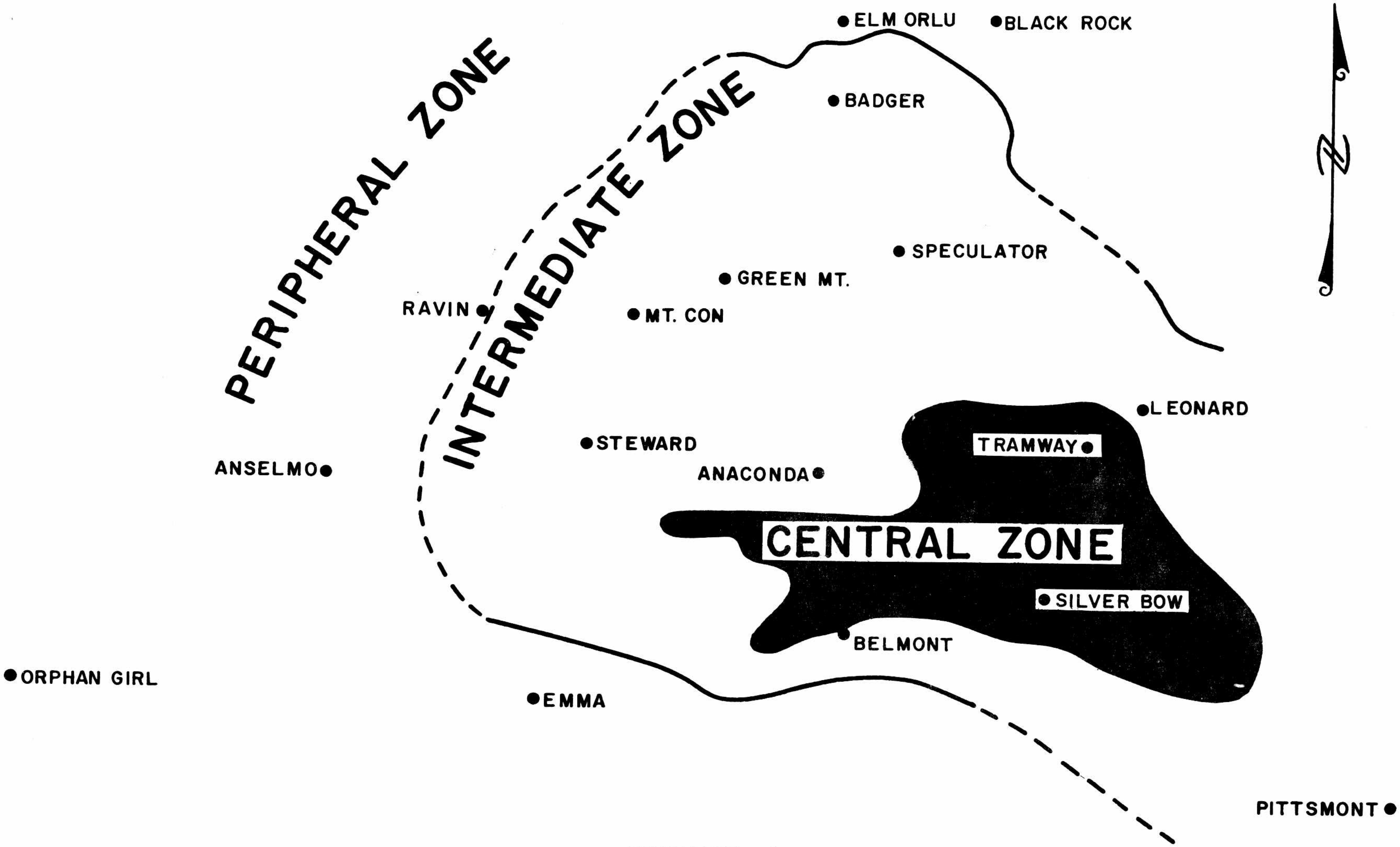

FIGURE 4

LOCATION OF ORE MINERAL ZONES
BUTTE DISTRICT

1500 LEVEL, MT. CON MINE

to the lowest levels of exploration and development in the Deep Level Zone and production has continued excellent from drifts and stopes in Deep Level Zone ores in veins that on higher levels have yielded similarly good values in typical Intermediate Zone assemblages.

Main Stage Wall Rock Alteration (Table 4)

The response of the Butte quartz monzonite to the hydrothermal solutions has been documented by Sales and Meyer in their classic papers of 1948 and 1950. That response consisted of a complex interdependent series of exchanges and reactions which produced outward expanding envelopes of alteration mineral reaction products. The alteration pattern and mineral distribution are remarkably constant throughout the district, reflecting homogeneity of wall rock composition and the generalization of the hydrothermal process itself. It is therefore possible, but of course a physical-chemical oversimplification, to construct Table 4 and Fig. 5 showing wall rock alteration mineralogy. Table 4 is designed to show only the minerals developed in the zones and subzones of the alteration envelopes, while Fig. 5 shows bulk mineralogy and the effects of the hydrothermal solution upon wall rock.

Except for the EDM alteration described above, and the absence of alteration surrounding quartz-molybdenite and milky-quartz veinlets, every fracture (those to which the hydrothermal solution had access during Main Stage ore deposition) displays the alteration assemblages of Fig. 5. Thickness ratios and net widths vary widely, but the same sequences, assemblages, and overall patterns are district-wide. Only where alteration envelopes overlap as in the pervasively sericitized Central Zone is the pattern significantly modified by elimination first of fresh quartz monzonite between veins, then of fringe alteration, and so on until sericitized wall rock extends from vein to vein. As discussed by Sales and Meyer (1948 and 1950), alunite, dickite, and a low alkali sericite are sparsely found as vein fillings and vein-adjacent wall rock alteration assemblages in the otherwise pervasively sericitized Central Zone volume. Varying intensity of silicification resulted in vein-adjacent variations in color, texture, and bulk rock hardness.

In the Intermediate and Peripheral Zones, alteration symmetry is generally maintained adjacent to joints and structurally simple fissures. Adjacent to larger minable structures, however, the pattern is likely to be assymmetrical and irregular, the former owing to multiple structural opening, the latter owing to alteration complements about smaller flanking and ramifying veinlets superimposed upon the alteration envelopes controlled by the principal fissure. Fresh rock centers in boulders defined by altered joints are common near the outer edges of alteration envelopes. Veins in the Deep Level Zone are flanked by alteration envelopes which appear to be qualitatively and quantitatively similar to those at higher levels adjacent to Intermediate and Outer Zone structures.

Main Stage alteration of earlier EDM alteration assemblages can be recognized underground by the development of coarse, angular, and abundant porosity, developed through the leaching of carbonates, anhydrite, and fluorite (?) from the EDM veinlets and altered wall rocks, coupled with the presence of a milky quartz veinlet with or without molybdenite. The mineralogic response of EDM alteration to the Main Stage hydrothermal solution results in complete sericitization of all the silicates but quartz, sulfidation of iron, and the apparent retention of chalcopyrite in the sericitized EDM. Except for leaching of the oxyacid salts, EDM assemblages appear unchanged in the argillic zone of Main Stage alteration.

A recent bulk-sample diffractometry program aimed at determining the distribution of alteration minerals in the Berkeley pit area revealed the presence of locally substantial amounts of pyrophyllite associated with the pervasive sericitization prevalent in that volume. Subsequent field and laboratory detail work have refined knowledge of the distribution and occurrence of pyrophyllite, but much remains to be learned. Pyrophyllite distribution as presently charted shows no first order relationship to any known lithogene or hypogene geometry, occurring as it does in two wide, nearly vertical belts or bands cutting across the Berkeley pit in a northwesterly direction (not obviously related to quartz porphyry). These bands are not recognizable as such in the field. Pyrophyllite seldom accounts for more than one-third of the sheet silicate in known sericitized-pyrophyllitized hand specimens, and it is as yet not known whether the two minerals are interlayered or mechanically mixed. The sericite involved may deviate slightly from the typical hypogene alteration product.

Working with x-ray diffractometer control, the search for data on pyrophyllite has been conducted by thin section and x-ray powder pattern techniques. Assemblages have thus been found of pyrophyllite-topaz, sericite-topaz, sericite-zunyite, and topaz-zunyite, these couples occurring, as does pyrophyllite-sericite, in the feldspar sites of the original quartz-monzonite. The pyrophyllite-zunyite couple has not yet been found. The combined assemblage has as yet been identified only as wall rock disseminations, not as vein fillings.

Pyrophyllite has also been discovered sparingly at intermediate depths in sericitized volumes of the Kelley mine and in association with dickite in the wall rocks as deep as the 3000-foot level of the Leonard mine. No horizontal distribution pattern has been discerned at depth. Many diffractometer traces of alteration envelopes adjacent to Intermediate, Deep Level, and Peripheral Zone veins have revealed no detectable pyrophyllite. The assemblage, therefore, appears in part coextensive with Central Zone-type pervasive sericitization and is not demonstrably surface related. It is tentatively interpreted as a Main Stage hydrothermal alteration assemblage related to the Central Zone environment. The equilibrium curves of the potash system given by Hemley and Jones (1964) indicate a pyrophyllite field in the low K+ activity, intermediate to high temperature portion of the diagram. Before the genesis of the environment can be reliably determined, however, more data must be collected on its distribution and internal and external relationships.

With decline in intensity of the hydrothermal solution, its capacity for sulfide mineralization and sericitization dwindled. The essentially post-mineral rhyolite dikes show only very limited sericitization, but it and the post-mineral Black Rock fault show extensive argillization flanking carbonate-filled fractures. Later fissures carry no discernible alteration.

POST-HYDROTHERMAL ENVIRONMENTS

Rhyolite Dikes and Vein Metamorphism (Table 5)

The Anaconda and Blue age vein systems, containing essentially all of Butte's economic hypogene mineralization, were followed successively by the Steward, Rarus, Middle, and Continental age offsetting fissures. Except that the northeast striking Steward system contains limited ore, all but the last-named show evidences of only feeble hydrothermal alteration with minor to negligible calcite-quartz-pyrite mineralization. Igneous activity at known depths in the Butte district was dormant between the pre-ore intrusion of quartz

TABLE 4. MAIN STAGE HYDROTHERMAL WALL ROCK ALTERATION AND MINERALOGY

Fringe Subzone (F), Montmorillonitized Subzone (M), Kaolinized Subzone (K), and Sericitized Zone (S). See Table 1 for Fresh Quartz Monzonite.

Mineral*	Occurrence and Abundance				Composition
	F	M	K	S	
Quartz	-	-	t	a	SiO_2
Muscovite (sericite)	r	r	t	+	$K_2Al_4(OH)_4Si_6Al_2O$
Pyrite	t	t	t	c	FeS_2
Kaolinite	-	t	+	o	$Al_4(OH)_8Si_4O_{10}$
Montmorillonite					
Montmorillonite	t	+	t	o	$(Al,Mg,Fe)_4$ ([illegible])$_m$ $(Si,Al,Fe)_8O_{20-n}(OH)_n.6H_2O$
Nontronite	t	r	-	o	$Fe_4(OH)_4Si_8O_{20}.8H_2O$ (?)
Biotite(2ndary-Eastonite?)	o	-	c	o	$K_2Mg_5Al(OH)_4Si_5Al_3O_{20}$
Chlorite	t	m	-	o	$(Mg,Fe,Al)_6(OH)_8(Si,Al)_4O_{10}$
Epidote	t	-	o	o	$Ca_2(Al,Fe)_3(OH)Si_3O_{12}$
Zoisite	t	-	o	o	$Ca_2(Al)_3(OH)Si_3O_{12}$
Calcite	m	t	o	o	$CaCO_3$
Magnetite	m	-	-	o	Fe_3O_4
Rutile	t	t	t	t	TiO_2
Anatase	t ?	t ?	t ?	t	TiO_2
Leucoxene(Rutile-Anatase)	t	t	t	o	TiO_2
Allophane-Hisingerite	t	-	o	o	$Al_2O_3.SiO_2.nH_2O$ (?) $Fe_2O_3.2SiO_2.nH_2O$ (?)
Orthoclase(?)(2ndary)	r ?	-	-	o	Or (?)
Attapulgite					
Palygorskite	r	r ?	r ?	o	$Mg_5Si_8O_{20}(OH)_2.8H_2O$
Pyrophyllite	o	o	o	m	$Al_2(OH)_2Si_4O_{10}$
Topaz	o	o	o	t	$Al_2(F,OH)_2SiO_4$
Zunyite	o	o	o	r	$Al_{13}O_4(OH,F,Cl)_{19}Si_5O_{16}$
Dickite	o	o	o	t	$Al_4(OH)_8Si_4O_{10}$
Alunite	o	o	o	t	$KAl_3(SO_4)_2(OH)_6$

+ = very abundant
a = abundant
c = common, some, moderate
m = minor, sparse
t = trace, infrequently encountered
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* Table 4 includes only minerals generated in the alteration envelopes. See Fig. 5 for bulk mineralogy of the alteration suites.

TABLE 5. MINERALOGY OF RHYOLITE PORPHYRY AND VEIN METAMORPHISM

Rhyolite Dikes (Ry) and Metamorphic Vein Minerals (MV)

Mineral	Occurrence and Abundance		Composition
	Ry	MV	
Quartz	+	a	SiO_2
Plagioclase			
Albite-Oligoclase	a	o	An_{10}
Orthoclase			
Microperthite	a	o	$(K,Na)AlSi_3O_8$
Sanidine	a	o	$(K,Na)AlSi_3O_8$
Biotite	c	o	$K_2(Fe,Mg)_6(OH)_4Si_6Al_2O_{20}$ (?)
Zircon	t	o	$ZrSiO_4$
Apatite	t	o	$Ca_5(F,Cl,OH)(PO_4)_3$
Sphene	t	o	$CaTiSiO_5$
Magnetite	t	-	Fe_3O_4
Pyrite	m	-	FeS_2
Chalcopyrite	t	c	$CuFeS_2$
Bornite	-	c	Cu_5FeS_4
Tennantite	-	m	$Cu_{12}As_4S_{13}$
Hematite	-	c	Fe_2O_3
Alabandite	o	t	MnS

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a = abundant
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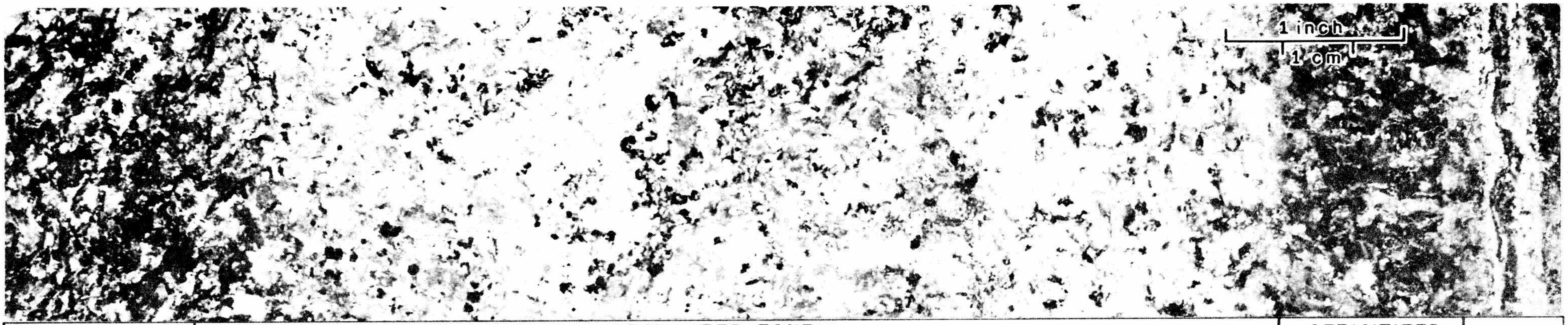

FRESH QUARTZ MONZONITE	ARGILLIZED ZONE			SERICITIZED ZONE	VEIN
	FRINGE	MONTMORILLONITIZED SUBZONE	KAOLINIZED SUBZONE		
Quartz	Unchanged	Unchanged (Argillization reaction quartz fugitive to Sericitized Zone? Vein?)	Unchanged	Augmented, reaction prod. & import	See Table 3 Central Zone Dickite Kaolinite Alunite 3T Ser.
Orthoclase (Or_{80-90} microperthite)	Unchanged	Traces of sericite, clays.	Never over 5% arg. or ser.	IM ↔ $2M_1+2M_2$ Sericite + quartz Sericite veins and replaces clays. Biotite = unit pseudomorphs. IM = hydromica ? 3T = "Low alkali sericite"?	
Plagioclase (An_{45-50})	Trace mont. & sericite wisps. Rare zoisite.	Plagioclase replaced by mechanical mixture of montmorillonite and kaolin, trace kaolinite-abundant montmorillonite at fringe yielding to trace montmorillonite-abundant kaolinite at argillized-sericitized zone boundary. Allophane-hisingerite with montmorillonite at outer edge, aluminous montmorillonite toward vein. Some mixed layers probable. Color shift green to white.			
Hornblende	Calcite, epid., chlorite; sep'n of mag or py	Aluminous nontronite yielding veinward to aluminous montmorillonite. Dark green (with minor calcite at outer edge), olive green toward kaolinized subzone.	Montmorillonite → Kaolinite, lost in alteration products of plagioclase.		
Augite	Calcite epid., mag or py				
Biotite	Separation of rutile grid, marginal chlorite.	Chloritization slowed, arrested, biotite restabilized toward kaolinized subzone (q.v.). Associated pyrite and magnetite stable.	Unattacked quartz monzonite biotite cores in halos of sucrose secondary biotite. TiO_2 excluded. Fe-Mg from chlorite and mont.		
Pyrite	Augmented	Augmented	Augmented (?)	Augmented and recrystallized	
Magnetite	Augmented	Partially pyritized	Pyritized	Pyritized	
Apatite	Unchanged	Unchanged	Unchanged	Fugitive or recrystallized	
Sphene	Unchanged	Unchanged	Unchanged	Rutile-Anatase, qz	
Zircon	Unchanged	Unchanged	Unchanged	Unchanged	

Figure 5. Butte quartz monzonite hydrothermal alteration mineralogy and pattern. See text for greater detail.
Assembled largely from descriptions by C. Meyer, PhD Thesis, Harvard University, 1949

porphyry and the near close of hydrothermal activity. Closely following Main Stage hydrothermal activity, however, porphyry intrusion began again and rhyolite porphyry dikes, some with advance upward wedges of dilation breccia (the Mountain View breccia, Sales, 1913) transected the district, cutting and occasionally displacing the veins.

At least two dike ages are recognized, an earlier east-west striking, nearly vertical set and a later north-south striking group, also steeply dipping. Potassium-argon dating indicates an 8 to 10my age difference between the Oligocene Lowland Creek volcanics west of Butte and the Big Butte surface flows, and the later north-south rhyolite dikes. A subsurface east-west dike which cuts through the main portion of the hill approaching the surface in the Anselmo area on the west and topping near the 2000 level in the Leonard area on the east, is probably of the earlier affinity.

Both ages of rhyolite porphyry consist of up to three-quarter inch euhedral albite and K-feldspar (sanidine or microperthite) phenocrysts and rounded, embayed quartz 'eyes', as in the quartz porphyry, in an aphanitic groundmass. Thin biotite flakes are common. Meyer (1949) recognized three coextensive rhyolite types, the result of variation in phenocryst ratios even along the same dike. The most abundant contains predominant plagioclase with subordinate quartz. In the second, quartz and orthoclase predominate, with quartz or biotite most abundant in the third. The plagioclase, where measurable, is albitic, and the groundmass is composed of quartz, dominant K-feldspar, and trace biotite. Accessories include those listed in Table 5: traces of zircon, apatite, sphene, and magnetite, with traces of chalcopyrite and minor pyrite. Chilled borders, flow structures, and inclusions of earlier rock types and vein material are common.

In many locations, drifts driven along veins toward rhyolite intersections have been closely mapped and mineralogical changes in the ore recorded. In the Central Zone, a typical vein containing quartz, pyrite, enargite, and chalcocite (with 2-3% of shreddy exsolved bornite) is transformed up to 5-10 feet from an east-west rhyolite dike to massively intergrown quartz, chalcopyrite, bornite, and pyrite residuals. Enargite is in part replaced by tennantite. The assemblage has been recrystallized where the hot intrusion cut through and is characterized by veinlet and reaction-rim textures farther out. The chalcopyrite to bornite ratio appears to be controlled by the distribution of primary pyrite rather than by proximity to the dike. Textural-distributional details are further covered by Sales and Meyer (1951).

Rhyolite dike intersections with Peripheral Zone veins have also been described. The principal mineralogic change is the sulfidation of rhodochrosite to the manganese sulfide alabandite, a shift accompanied by blackening of the vein contents. Sphalerite, commonly associated with the rhodochrosite, is apparently unaffected.

The mineral assemblages thus reflect removal of sulfur from Central Zone ores and addition of sulfur to Peripheral ones. Although the rhyolite porphyry contains minor pyrite as an accessory, it is not thought that sulfur fugacity in its attendant fluid phases was high. Oxidation and desulfidation of Central Zone ores is a reasonable expectation. It is probable that the metamorphism of the carbonate rhodochrosite to the sulfide alabandite was accomplished by sulfur fugitive from sulfide vein material at greater depth, either by substitution of oxygen for sulfur or by reorganization of sulfur-rich minerals to sulfur-poor ones as in the Central Zone occurrences, or by its own characteristically low (but sufficient) sulfur fugacity.

No systematic search for or study of a 'meta quartz monzonite' or 'meta quartz porphyry' has been made.

Supergene Alteration of Wall Rock and Vein Minerals (Table 6)

The success of the Berkeley pit in the southeast portion of the modern producing area (Fig. 2) is in large part the result of secondary copper sulfide enrichment. The Berkeley pit area generally is characterized by Central Zone hypogene activity--typically sulfur-rich primary ore minerals and pervasive sericitization. The remarkable southeastward fingering-out of such Anaconda age veins as the Anaconda vein itself, along with widespread and abundant veinlet and disseminated pyrite, has created eminently favorable conditions for near-surface oxidation above and sulfide enrichment below. It is the secondarily enriched volume that is referred to in the column 'Supergene plus pyrite' in Table 6. The oxidized waste environment is not treated separately in this report primarily because it has not been closely studied. It is thought to be mineralogically simple, consisting of inherited quartz and sericite (partially kaolinized?) heavily stained by hematite, goethite, lepidocrocite (?), 'limonite', jarosite, and minor jasper. Mobility of silica resulting in redposited quartz has also been suggested.

Farther east, in the Continental area on the upthrown side of the Continental fault, the quartz monzonite was not widely affected by Main Stage hydrothermal activity. The absence of extensive fissuring and the presence of only limited amounts of pyrite have restricted the depth of penetration of supergene alteration and caused the generation of secondary oxide, silicate, carbonate, and minor sulfate and phosphate minerals. The Berkeley ores are typically dark bluish black to black owing to secondary copper sulfide pyrite coatings and sulfide replacements, while the Continental materials are dominantly greens, reds, and black. The Continental area type materials are included in the 'Supergene minus Pyrite' column of Table 6.

Supergene plus Pyrite

Berkeley pit sulfide-enrichment mineralogy is complicated by the superposition of a complex supergene history upon an equally complex hypogene environment and by the existence of 80-year old near surface underground workings. These collapsed workings, now visible in the pit walls, are haloed by zones of oxidation extending tens of feet into their walls. This old backfill oxidation, partially the result of mine fires of decades ago, has introduced few post-mine minerals not reasonably to be expected in the unaffected ores. It has, however, markedly increased the abundance of iron oxides and mixed iron-copper sulfates in the pit ores.

A discussion of supergene effects upon host rock silicate mineralogy in the enriched portion of the pit can be largely reduced to consideration of sericite and quartz in the supergene environment. The low-temperature, acid supergene solutions have limitedly decomposed sericite and generated abundant poorly-ordered kaolinite, minor (?) halloysite, and probably minor allophane

TABLE 6-1. SUPERGENE ALTERATION MINERALOGY

Supergene Alteration of Wall Rock and Ore Minerals in Pyrite-Rich (S+P) and Pyrite-Poor (S-P) assemblages.

Mineral	Occurrence and Abundance		Composition
	S+P	S-P	
Kaolinite	a	m ?	$Al_4(OH)_8Si_4O_{10}$
Halloysite	m ?	m	$Al_4(OH)_8Si_4O_{10}.nH_2O$
Allophane	t ?	t ?	$Al_2SiO_5.nH_2O$ (?)
Quartz	-	t	SiO_2
Chalcocite	m	t	Cu_2S
Covellite	t	-	CuS
? Digenite	r	-	$Cu_{1.96}S$
Goethite	t	t	FeO(OH)
Hematite	r	r	Fe_2O_3
Limonite (Goethite+Hematite)	t	t	$Fe_2O_3.nH_2O$
Brochantite	t	-	$Cu_4(OH)_6SO_4$
Antlerite	t	-	$Cu_3(OH)_4SO_4$
Alunite	t	-	$KAl_3(OH)_6(SO_4)_2$
Jarosite	t	-	$KFe_3(OH)_6(SO_4)_2$
?Natrojarosite	r	-	$NaFe_3(SO_4)_2(OH)_6$
? Plumbojarosite	-	r	$PbFe_6(SO_4)_4(OH)_{12}$
Nontronite	r ?	r ?	$Fe_4(OH)_4Si_8O_{20}.8H_2O$
Chlorite	r ?	r ?	$(Mg,Fe,Al)_6(OH)_8(Al,Si)_4O_{10}$
Boehmite	-	r ?	AlO(OH)
Sepiolite	t	-	$Mg_3Si_4O_{11}\cdot nH_2O$ (?)
Beraunite	t	-	$Fe''Fe'''_4(PO_4)_3(OH)_5.3H_2O$
Wavellite	t	r	$Al_3(OH)_3(PO_4)_2.5H_2O$
Copper	r	t	Cu
Cuprite	-	m	Cu_2O
Tenorite	-	m	CuO
Chrysocolla	-	c	$CuSiO_3.2H_2O$
Malachite	-	t	$Cu_2CO_3(OH)_2$
Azurite	-	r	$Cu_3(CO_3)_2(OH)_2$
Chalcosiderite	-	r	$CuFe_6(PO_4)_4(OH)_8.4H_2O$
Turquoise	-	t	$CuAl_6(PO_4)_4(OH)_8.4H_2O$
Libethenite	-	r	$Cu_2(PO_4)OH$
Wulfenite	-	r	$PbMoO_4$
Vivianite	r	r	$Fe_3(PO_4)_2.8H_2O$
Autunite	-	r	$Ca(UO_2)_2(PO_4)_2\cdot 10\text{-}12H_2O$

+ = very abundant
a = abundant
c = common, some, moderate
m = minor, sparse
t = trace, infrequently encountered
r = rare, one or a few occurrences only
- = not found, but considered permissible
o = absent, considered precluded

Throughout this paper, a question mark preceding a mineral questions its identity; a question mark following a mineral (or abundance symbol) questions its distribution (or amount).

Continued, Table 6-2

SUPERGENE ALTERATION MINERALOGY

(TABLE 6-2)

Mineral	Occurrence and Abundance		Composition
	S+P	S-P	
Cornwallite	-	r	$Cu_5(AsO_4)_2(OH)_4.H_2O$
Pseudomalachite	-	r	$Cu_5(PO_4)_2(OH)_4.H_2O$ (?)
Cryptomelane	-	c	$K_2Mn_8O_{16}$
Psilomelane	-	c	$(Ba,H_2O)_2Mn_5O_{10}$
Pyrolusite	-	c	MnO_2
Ramsdellite	-	m	MnO_2
Amorphous MnO_2	-	t	MnO_2
Cerussite	-	t	$PbCO_3$
Smithsonite	-	t	$ZnCO_3$
Chlorargyrite (Cerargyrite)	-	t	AgCl
Silver	-	t	Ag
Gold	-	t	Au
Arsenolite	-	t	As_2O_3
Chalcanthite*	m	-	$CuSO_4.5H_2O$
Pisanite*	r	-	$(Fe,Cu)SO_4.7H_2O$
Szomolnokite*	r	-	$FeSO_4.H_2O$
Roemerite*	r	-	$Fe''Fe'''_2(SO_4)_4.14H_2O$
Gypsum*	t	-	$CaSO_4.2H_2O$
Goslarite*	t	-	$ZnSO_4.7H_2O$
Epsomite*	t	-	$MgSO_4.7H_2O$
Pickingerite*	t	-	$MgAl_2(SO_4)_4.22H_2O$
Coquimbite*	t	-	$Fe_2(SO_4)_3.9H_2O$
Copiapite*	t	-	$(Fe,Mg)Fe'''_4(SO_4)_6(OH)_2.20H_2O$
Voltaite*	t	-	$(K,Fe'')_3Fe'''(SO_4)_3.4H_2O$

\+ = very abundant
a = abundant
c = common, some, moderate
m = minor, sparse

t = trace, infrequently encountered
r = rare, one or a few occurrences only
\- = not found, but considered permissible
o = absent, considered precluded

Throughout this paper, a question mark preceding a mineral questions its identity; a question mark following a mineral (or abundance symbol) questions its distribution (or amount).

* Also as post-mine efflorescences.

type mineraloid. The generation of illite-type stripped micas or of a less well-ordered sericite has not been observed. Pyrophyllite as a supergene mineral cannot yet be denied, but geologic and physical-chemical considerations deem it unlikely. Kaolinite and related products are also limitedly developed in less hydrothermally altered quartz monzonite islands within the pit and on its fringes, where a crumbly, gruss-like wall rock is observed. Quartz is apparently stable. The supergene development of an aluminous chlorite as rare veinlet fillings is suspected but not demonstrated.

The secondary ore minerals are predominant chalcocite (both 'sooty' and steely), covellite, and a subcrystalline material of the approximate bulk composition of digenite. These minerals occur principally as thin films coating and marginally replacing pyrite or as thicker rims more extensively replacing other primary sulfides. Secondary sulfide coats both disseminated and vein pyrite; some vein sulfides and sulfosalts (especially hypogene chalcocite and enargite) are resistant to replacement by secondary sulfides. Other trace minerals in the environment are limonite, goethite, and rare hematite (probably principally as downward contaminants from the suprajacent leached oxidizing capping, subordinately as stable phases), the copper sulfates brochantite, antlerite, and chalcanthite as vug linings and veinlet fillings, the sulfates alunite and jarosite, the phosphates beraunite and wavellite as veinlet centerline fillings and drusy crystals on secondary chalcocite respectively, and native copper toward the fringes of the heavily enriched zones. Rare occurrences of sepiolite, vivianite, and (?) natrojarosite, have been recorded. Several mixed sulfates have been identified as both rare minerals,chiefly as drusy to massive coatings of sulfides and in cavities,and as more abundant post-mine oxidation products. They are chalcanthite, pisanite, szomolnokite, pickingerite, roemerite, coquimbite, copiapite, voltaite, gypsum, goslarite, and epsomite. It is appropriate, however, to stress again the fact that these are but minor minerals associated sparsely with the far more typical sulfidic ore. A zone of mixed sulfate-sulfide ores, more common in arid climates, is not found in Butte, there existing an irregular but relatively sharp interface between the secondarily enriched sericitized-mineralized quartz monzonite below and the barren, leached, oxidized veins and sericitized wall rock above.

Supergene minus Pyrite

The mineralogy of the oxidized deposits of the Continental area, and of the low pyrite out-croppings of veins in the Peripheral Zone, is well known qualitatively but inadequately known quantitatively. In the Continental area, relatively sparse, thin, and weakly-mineralized early and Main Stage fissures cut the crumbly quartz monzonite. Oxidation has left residuals of original quartz-chalcopyrite-bornite-pyrite-sphalerite-galena-marcasite, but these species are largely converted to colorful aggregates of chrysocolla, cuprite, tenorite, traces of malachite, native copper, 'limonite', and goethite, and rare occurrences of azurite, chalcosiderite, turquoise, libethenite, wulfenite, wavellite, vivianite, cornwallite, and pseudomalachite. Wall rock susceptibility to the weakly-acid low-temperature supergene solutions is measured in terms more of bleaching, staining, and incipient alteration than of pervasive replacement. Crumbly quartz monzonite now consists of whitened to greenish partially kaolinized and (?) boehmitized feldspars, nontronitized-chloritized mafic silicates, and unaffected quartz, the whole commonly laced with iron-oxide stained veinlets.

Oxidation mineralogy in Peripheral Zone vein outcroppings is, of course, largely controlled by local primary Main Stage vein contents. Many veins on the western and northern periphery of the district contain dominant quartz, rhodochrosite, and rhodonite with minor calcio-magnesian carbonates at depth which near the surface have been abundantly oxidized to the black manganese oxides cryptomelane and psilomelane with lesser amounts of ramsdellite and traces of amorphous MnO_2. Traces of native silver and gold are also found, probably through oxidation-decomposition of precious metal-bearing sulfantimonides. Quartz-sphalerite-galena veins commonly contain silver in solid solution, rarely in sulfantmonides or as the primary element. These veins oxidize to cerussite and smithsonite with trace amounts of chlorargyrite (cerargyrite), native silver, native gold, and arsenolite. Wall rock alteration is similar in these peripheral areas to that in the Continental area--crumbly bleached and stained gruss from which blackened quartz-rich vein outcrops stand in relief.

CONCLUSIONS

The mineralogy of the Butte district is both responsive to and descriptive of a complicated and extensive magmatic, hypogene, and supergene system. In view of the brevity of this report many generalizations have of necessity been drawn. The outlining of Butte geological relationships as a framework for discussion of mineral distribution precludes rigorous genetic discussion. We have instead stressed those hypotheses which appear consistent with the broad scale field facts of the Butte district. Neither are the compositional-structural variations of Butte minerals adequately covered in this preliminary report, although abundant information has been accumulated and analyzed.

Conclusions of this paper are that:

1. The mineralogy of Butte is far more varied and complex than has generally been recognized;
2. Butte mineralogy permits examination of the genesis of the district's ore deposits and host rocks through both qualitative and quantitative variations. These variations are further amenable to study through a recently-completed set of level maps of mineral distribution which for the first time subject Butte hypogene mineralogy to thorough and detailed local and zonal evaluation;
3. The geologic-mineralogic research program has revealed, described, and at least preliminarily integrated three important new geologic environments, the Early Dark Micaceous alteration-mineralization, the hypogene Deep Level Zone, and the pyrophyllite-topaz-zunyite alteration assemblage;
4. Mineralogic studies have supported, refined, and extended existing genetic models of the Butte deposit developed largely through the keen observations of R. H. Sales fifty years ago and found through subsequent decades to be notably accurate and adequate; and
5. Continued mineralogic description and quantification is yielding information valuable to The Anaconda Company and the geological profession and is contributing tangibly toward the development of an acceptable physical-geochemical and geological integration of genetically-related systems.

MINERALOGICAL SUMMARY

(Table 7-1)*

Occurrence and Abundance

	Rock, Etc.				Early		Hypo. Vein				Hypo. Altn.				Rhy.		Superg.	
	Qm	A-P	Qp	BI	**EDM**	qmb	DL	C	I	P	F	M	K	S	Ry	MV	S+P	S-P
Native Elements																		
Copper																	r	t
Gold							–	r	r	r							–	t
Silver							r	t	t	t							–	t
Sulfides																		
Acanthite							–	–	r	m								
(Argentite)																		
Alabandite																t		
Arsenopyrite										r								
? Betekhtinite							t	t	t	–								
Bornite							c	t	a	–					–	c		
Chalcocite							m	a	c								m	t
Chalcopyrite	t	t	t	–	m	t?	a	t	c	m					t	c		
Covellite							r	m	t								t	–
Digenite							r	m	t								?r	
Djurleite							–	m?	t?									
Galena							t	t	t	c								
Greenockite										r								
Marcasite										r								
Molybdenite		t	–		t	m												
Pyrite	t	t	t	t	m	m	+	+	+	c	t	t	t	c	m	–		
Pyrrhotite		r																
Sphalerite							–	t	t	a								
Stromeyerite							r	t?	t	t								
Wurtzite							–	r?	r	r								
Sulfosalts																		
Aikinite							r	–	–	r?								
Andorite									r	r?								
Colusite							t	m	t									
Enargite							m	a	c									
Luzonite							–	t	–									
Pearceite									–	t								
Polybasite									–?	r								
Proustite									–	t								
Pyrargyrite									–?	r								
Seligmannite							–	–	–	r?								
Stephanite									–?	r								
Tennantite							c	t	m	t					–	m		
Tetrahedrite									–?	r								
Wittichenite							t	t	t	–								
Oxides																		
Amorphous MnO_2																	–	t
Anatase					t						t?	t?	t?	t				
Leucoxene											t?	t?	t?					
Arsenolite																	–	t
Boehmite																	–	r?
	Table 1				Table 2		Table 3				Table 4				Table 5		Table 6	

* Open squares in Table 7 = 'absent, considered precluded'. Other symbols as in T's. 1-6.

Continued, Table 7-2

MINERALOGICAL SUMMARY

(Table 7-2)

Occurrence and Abundance

	Rock, Etc.				Early		Hypo. Vein				Hypo. Altn.				Rhy.		Superg.	
	Qm	A-P	Qp	BI	EDM	qmb	DL	C	I	P	F	M	K	S	Ry	MV	S+P	S-P
Cuprite																	-	m
Cryptomelane																	-	c
Goethite																	t	t
Hematite		r			t	-				r					-	c	r	r
Ilmenite	-	t	-	t														
Magnetite	m	t	m	m	t	r					m	-	-		t	-		
Psilomelane																	-	c
Pyrolusite																	-	c
Ramsdellite																	-	m
Rutile					t						t	t	t	t				
Leucoxene											t?	t	t				-	m
Tenorite																	-	m
? Uraninite							r?	r?	r?	r								
Halides																		
Chlorargyrite																	-	t
(Cerargyrite)																		
Fluorite	-	r	-	-	t		t	t	m	m								
Carbonates																		
Ankerite							t	t	t	m								
Azurite																	-	r
Calcite					t		m	t	m	c	m	t	-	-				
Cerussite																	-	t
Dolomite							m	t	m	c								
Malachite																	-	t
Mangananankerite							-	-	r	t								
Manganocalcite							-	-	t	m								
Manganosiderite							-	-	r	t								
Rhodochrosite							t	t	t	a								
Siderite							-	-	r	t								
Smithsonite																	-	t
Sulfates																		
Alunite							-	t	-	-				t			t	-
Anglesite																	r	r
Anhydrite					t													
Antlerite																	t	-
Barite							t	t	t	m								
Brochantite																	t	-
Chalcanthite																	m	-
Copiapite																	t	-
Coquimbite																	t	-
Epsomite																	t	-
Goslarite																	t	-
Gypsum							r	-	r	t							t	-
Selenite																	t	t?
Jarosite																	t	-
?Natrojarosite																	r	-
	Table 1				Table 2		Table 3				Table 4				Table 5		Table 6	

Continued, Table 7-3

MINERALOGICAL SUMMARY

(Table 7-3)

Occurrence and Abundance

	Rock, Etc.				Early		Hypo. Vein				Hypo. Altn.				Rhy.		Superg.	
	Qm	A-P	Qp	BI	EDM	qmb	DL	C	I	P	F	M	K	S	Ry	MV	S+P	S-P
? Plumbojarosite																	r	–
Pickingerite																	t	–
Pisanite																	r	–
Roemerite																	r	–
Szomolnokite																	r	–
Voltaite																	t	–
Phosphates, Arsenates, and Tungstates																		
Apatite																		
Apatite	t	r	t	–	t		t	t	t	m					t			
Lewistonite								r?										
Autunite																	–	r
Beraunite																	t	–
Chalcosiderite																	–	r
Cornwallite																	–	r
Ferberite							–	–	–	t								
Hinsdalite							–	t	–									
Huebnerite							t	t	t	t								
Libethenite																	–	r
Pseudomalachite																	–	r
Scheelite					t		t	t	t	t								
±Powellite																		
Turquoise																	–	t
Vivianite																	r	r
Wavellite																	t	r
Wolframite							–	–	–	t								
Wulfenite																	–	r
Silicates																		
Allophane-																		
Hisingerite											t	–					t?	t?
Allanite		r																
Attapulgite																		
Palygorskite											r	r?	r?					
Augite	m	–	m	m														
Biotite	c	m	c	a	c							–	c		c			
(?)Phlog.-Annite																		
Chabazite									–	r								
Chlorite					m?						t	m	–				r?	t ?
Chrysocolla																	–	c
Dickite							–	t	–					t				
Epidote		r									t	–						
Halloysite																	m?	m
Helvite										r								
Heulandite									–	r								
Hornblende	c	–	c	c														
Kaolinite											–	t	+				a	m?
Montmorillonite																		
Montmorillonite											t	+	t					
Nontronite											t	r	–				r?	r?
	Table 1				Table 2		Table 3				Table 4				Table 5		Table 6	

Continued, Table 7-4

MINERALOGICAL SUMMARY

(Table 7-4)

Occurrence and Abundance

	Rock, Etc.				Early		Hypo. Vein				Hypo. Altn.				Rhy.		Superg.	
	Qm	A-P	Qp	BI	EDM	qmb	DL	C	I	P	F	M	K	S	Ry	MV	S+P	S-P
Muscovite		t																
Sericite					c		t	t	t	-?	r	r	t	+				
Orthoclase																		
Microperthite	a	a	a	m	m	-					r?	-	-		a			
Microcline	a	m	-	-														
Sanidine															a			
Plagioclase																		
Albite-Oligoclase		m	-?												a			
Andesine	+		+?															
Labradorite	t			+														
Pyrophyllite														m				
Quartz	a	+	a	m	+	+	+	+	+	+	-	-	t	a	+	a	-	t
Chalcedony									-	m								
Rhodonite										c								
Sepiolite																	t	-
Sphene	m	r	m	-											t			
Stilbite									-	r								
Topaz														t				
Tourmaline		t																
Schorlite																		
?Willemite										r?								-
Zircon	t	t	t	-											t			
Zoisite											t	-						
Zunyite														r				
	Table 1				Table 2		Table 3				Table 4				Table 5		Table 6	

References Cited

Billingsley, P., and Grimes, J. A. (1918) Ore deposits of the Boulder Batholith of Montana: Trans. AIME, Vol. 58, pp 284-361.

Hart, L. H. (1933) The Butte district, Montana: from "Copper Resources of the World", XVI Internat. Geol. Cong., Washington, D. C.

Hemley, J. J., and Jones, W. R. (1964) Chemical aspects of hydrothermal alteration with emphasis on hydrogen metasomatism: Econ. Geol., Vol. 59, pp 538-569.

Klepper, M. R. (1962) Emplacement of the Boulder Batholith: Address to Rocky Mountain Minerals Conference, AIME, Butte. Copies available from M.R.K., USGS, Wash., D. C.

Knopf, A. (1953) Geology of the northern portion of the Boulder bathylith, Montana (Abs.): GSA Bull., Vol. 64, p. 1547.

________ (1957) The Boulder bathylith of Montana: Amer. Journ. Sci., Vol. 255, pp 81-103.

Perry, E. S. (1933) The Butte Mining District, Montana, XVI Internat. Geol. Cong., 25 pp.

Meyer, C. (1949) Hydrothermal wall rock alteration at Butte, Montana: Doctoral thesis, Harvard Univ., 270 pp.

Sales, R. H. (1914) Ore deposits at Butte, Montana: Trans. AIME, Vol. 46, pp 3-106.

Sales, R. H., and Meyer, C. (1948) Wall rock alteration at Butte, Montana: TP 2400, Min. Tech. AIME, 25 pp.

____________________ (1949) Results from preliminary studies of vein formation at Butte, Montana: Econ. Geol., Vol. 44, pp 465-484.

____________________ (1950) Interpretation of wall rock alteration at Butte, Montana: Quart. Colo. Sch. Mines, Vol. 45, pp 261-273.

____________________ (1951) Effect of post-ore dike intrusion on Butte ore minerals: Econ. Geol., Vol. 46, pp 813-820.

Weed, W. H. (1912) Geology and ore deposits of the Butte District, Montana: USGS P.P. 74, 262 pp.

Error: References in text to "Sales (1913)" and to "Billingsley and Grimes (1917)" should read respectively "Sales (1914)" and "Billingsley and Grimes (1918)".