Geology and Porphyry Copper Mineralization of the Fawn Peak Intrusive Complex, Methow Valley, Washington

by

Karl Brock Riedell

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Date 7 June 1979

Master's Thesis

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Abstract

GEOLOGY AND PORPHYRY COPPER MINERALIZATION
OF THE FAWN PEAK INTRUSIVE COMPLEX,
METHOW VALLEY, WASHINGTON

By Karl Brock Riedell

Chairman of the Supervisory Committee: Professor Eric S. Cheney
Department of Geological Sciences

The 88-m.y.-old Fawn Peak complex intrudes steeply dipping late Cretaceous arkose, red beds, and intermediate volcanic rocks east of Mazama, Washington. Minor quartz diorite predates the main phases of fine- to coarse-grained dioritic intrusions. Younger, quartz-bearing phases are equigranular to porphyritic. Disseminated and veinlet-controlled chalcopyrite-pyrite-molybdenite mineralization occurs primarily in the western half of the complex, centered about and genetically related to the later intrusive phases. A substantial tonnage of $\geq$0.2% copper has been delineated. Eastward-dipping intrusive contacts and a northeast-plunging breccia pipe suggest that the deposit has been tilted 45° west-southwest.

Early alteration of magmatic hornblende and augite to actinolite occurs throughout most of the complex. Secondary biotite overprints actinolite and accompanies most copper mineralization. Propylitic alteration and pyritic mineralization overprint and are peripheral to biotitic alteration. Late sericitic alteration and redistribution of copper are limited to veinlets, shears, and two breccia pipes, primarily within the zone of biotitic alteration. Oxidation of the deposit is

weak, and supergene enrichment is negligible.

The relatively mafic intrusive rocks, low molybdenum values, rarity of K-feldspathic, sericitic, and argillic alterations, and abundance of hydrothermal amphibole all suggest that the Mazama deposit bears more similarities to porphyry deposits in island arcs than to those of the southwestern U.S. The generally equigranular rocks and restricted sericitic alteration imply affinities with batholithic deposits.

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(in rear pocket)

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INTRODUCTION

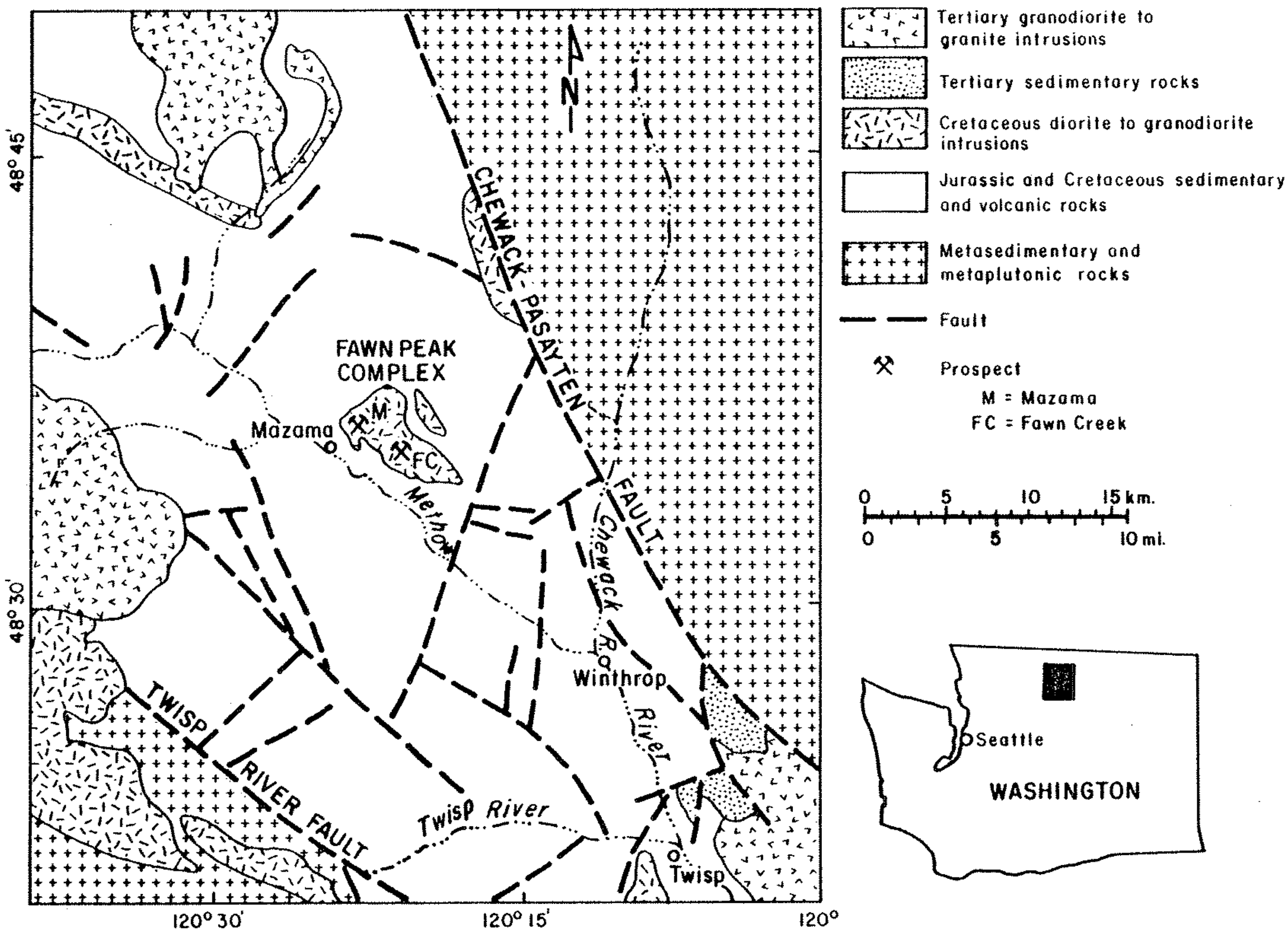
The Fawn Peak intrusive complex (the Fawn Peak stock of Barksdale, 1975) is in north-central Washington, 185 km northeast of Seattle (Figure 1). A medium-sized, low-grade porphyry copper system occurs in and around the younger intrusive phases of the western portion of the complex, between Goat Peak and Flagg Mountain.

The area has been prospected since the turn of the century (Appendix 1; Huntting, 1956; Livingstone and Wolfhard, 1976). Since the early 1960's, Bear Creek Mining Company, Brenda Mines, Ltd., Inspiration Development Company, and Quintana Minerals Corporation have explored and drilled the western half of the complex for porphyry copper-molybdenum mineralization. Exxon Minerals Company has evaluated similar mineralization farther east in the complex. Hereafter, the eastern (Exxon) and western (Quintana) properties will be referred to as the Fawn Creek and Mazama prospects, respectively (Figure 1, Plate I-A). The latter has also been termed Lesley, Lesley-Den, Goat Creek, and Flagg Mountain.

Pitard (1958) and Barksdale (1975) mapped the generalized outline of the pluton. Quintana geologists Livingstone and Wolfhard (1976) mapped separate intrusive phases in the Mazama prospect, and described the salient features of the mineralization and hydrothermal alteration.

The purpose of the present study was to build on the work of Livingstone and Wolfhard by completing detailed mapping of the complex, adjacent country rocks, and mineralization and alteration. In addition, core from 28 drill holes in the Mazama prospect was selectively relogged. The study shows that: (1) The pluton consists of several dioritic to quartz dioritic phases; more leucocratic and potassic rocks

FIGURE 1. Generalized geologic map of the Methow Valley, showing location of the Fawn Peak complex and the two porphyry copper prospects. Geology from Barksdale (1975).



Tertiary granodiorite to granite intrusions
Tertiary sedimentary rocks
Cretaceous diorite to granodiorite intrusions
Jurassic and Cretaceous sedimentary and volcanic rocks
Metasedimentary and metaplutonic rocks
Fault
Prospect
M = Mazama
FC = Fawn Creek
0 5 10 15 km.
0 5 10 mi.
Seattle
WASHINGTON
N
CHEWACK - PASAYTEN FAULT
TWISP RIVER FAULT
FAWN PEAK COMPLEX
M
FC
Mazama
Methow
Chewack R.
Winthrop
River
Twisp River
Twisp
48° 45'
48° 30'
120° 30'
120° 15'
120°

are absent, and porphyritic phases are volumetrically insignificant. (2) The rarity of sericitic, and abundance of early (pre-biotitic) actinolitic alteration contrast markedly with most porphyry deposits of the southwestern United States. (3) Mineralization is related spatially to biotitic alteration, and genetically to several of the later intrusive phases. (4) Oxidation is shallow, greatly facilitating study of the deposit from the surface; supergene enrichment is poor to non-existent. (5) The deposit bears many similarities to porphyry deposits of island arcs (Kesler and others, 1975, 1977; Titley, 1975; Gustafson, 1978, p. 602-603), and shows affinities toward batholithic deposits (Cheney and Trammell, 1975; Cheney and others, in preparation).

GENERAL GEOLOGY

ROCK TYPES

The complex intrudes the non-marine Winthrop and Midnight Peak Formations of late Cretaceous age (Barksdale, 1975). Massive arkose with subordinate siltstone and graywacke make up the Winthrop. The Midnight Peak Formation consists of a lower member of nonresistant red beds (Ventura member), and an upper member of andesitic and minor dacitic breccias, tuffs, and flows. Appendix 2 describes the units in more detail.

Seven intrusive phases are present (Table 1 and Appendix 2). Early phases are primarily equigranular diorites. Younger, quartz-bearing phases range from equigranular to porphyritic, the latter being volumetrically minor. All lack magmatic potassium feldspar. Chemically, the intrusive rocks exhibit the "quartz diorite trend" (Figure 2) characteristic of mineralized intrusions in island arcs, defined by Kesler and others (1975). K-Ar determinations (Table 2) give ages of 85-88 m.y. The consistent late Cretaceous ages and similar range of compositions of the pluton and the Midnight Peak volcanic rocks suggest that the two may be comagmatic. Medium-grained quartz diorite yields a discordant age of 70 m.y.; possibly the fine-grained biotites in this sample (Table 2) lost argon during Tertiary intrusive events, as Miller and Engels (1975) and Pearson and Obradovich (1977) have documented farther east in Washington.

Contact metamorphism of the Midnight Peak volcanic rocks formed a well jointed hornfels in an ill-defined aureole less than 100 m wide. The weakness of thermal effects may indicate that the volcanic rocks were still cooling at the time of intrusion.

TABLE 1. Characteristics of the intrusive rock units. "Minor" signifies less than 5 volume percent.

	UNIT	FORM OF INTRUSION	PHENOCRYSTS	GROUNDMASS	DISTINGUISHING FIELD CHARACTERISTIC(S)	RELATIVE AGE AND EVIDENCE
	ANDESITE PORPHYRY (ap)	Northeast- to east-northeast-trending dikes. Probably regional feature, unrelated to complex	5-20% labradorite 2-8mm Rarely, hornblende 1-3 mm (Some are strongly aphanitic)	Aphanitic to fine-grained; plagioclase, amphibole, biotite, and locally quartz	Dark gray to green-gray Coarse plagioclase laths	Cut cd; Locally cut qdp on Fawn Peak
FAWN PEAK COMPLEX	DACITE PORPHYRY (dp): QUARTZ-FELDSPAR PORPHYRY subphase	East-west-trending dikes	20-40% andesine, 3-10 mm 3-10% rounded quartz 5-10% hornblende minor biotite	Aphanitic; 25-35% quartz, 15-30% andesine lesser biotite, hornblende, magnetite	Light to medium gray; strongly porphyritic with 50-60% groundmass	Cut all units of complex except fqd. Feldspar porphyry contains xenoliths of quartz-feldspar porphyry Intermineral to late mineral
FAWN PEAK COMPLEX	DACITE PORPHYRY (dp): FELDSPAR PORPHYRY subphase	Matrix of Molly breccia	20-40% altered plagioclase 5-10% hornblende			
FAWN PEAK COMPLEX	QUARTZ DIORITE PORPHYRY (qdp)	Small plug, sill, small stock	50-65% andesine, 1-4 mm minor hornblende, biotite; locally, anhedral quartz	Fine-grained; 15-35% quartz; lesser andesine, hornblende, biotite, magnetite	Light gray; "crowded" porphyritic texture, 25-50% quartzose groundmass	Map patterns and lower Cu grades suggest post-mqd. Xenoliths of fmd and cd. Intermineral
FAWN PEAK COMPLEX	MEDIUM-GRAINED QUARTZ DIORITE (mqd)	Stock with concordant and discordant lobes	Minor andesine phenocrysts at southeast end	50-70% andesine, 1-5 mm; 8-25% quartz, 1-3 mm; 5-15% each biotite and hornblende, 1-5 mm; minor magnetite, zircon	Light gray, generally equigranular. ≥8% quartz (locally not conspicuous)	Dikes cut fmd and cd Predates most mineralization
FAWN PEAK COMPLEX	COARSE-GRAINED DIORITE (cd)	Stock	--	60-65% andesine, 2-8 mm, aligned laths; 25-30% hornblende, 4-6 mm; Minor augite, biotite, quartz, magnetite, apatite	Moderately dark gray Coarse plagioclase laths Relative lack of quartz, biotite	Map patterns suggest post-fmd Premineral
FAWN PEAK COMPLEX	FINE- TO MEDIUM-GRAINED DIORITE (fmd)	Semi-concordant body, with peripheral sills and dikes	Chilled margin is seriate porphyritic; Hornblende, subordinate andesine phenocrysts, both 2-5 mm	60-70% andesine, ≤ 2-5 mm; 30-35% hornblende, 2-5 mm; Minor augite, biotite, quartz, magnetite, sphene; Chilled margin has aphanitic to fine-grained groundmass	Moderately dark gray Relative lack of quartz, biotite Midnight Peak volcanic rocks generally lack hornblende phenycrysts	Xenoliths of fqd Premineral
FAWN PEAK COMPLEX	FINE-GRAINED QUARTZ DIORITE (fqd)	Remnants of stock, largely destroyed by intrusion of fmd	Locally, minor andesine, 1-3 mm	35-50% andesine, 0.5-1 mm; 15-30% hornblende, 0.5-1mm; 10-15 % quartz, 0.3-0.6 mm; 5-10% biotite, 0.3-1 mm; Minor augite, sphene, magnetite	Moderately dark gray Commonly abundant euhedral biotite (Quartz not conspicuous)	Premineral

TABLE 2. K-Ar age determinations on rocks of the Fawn Peak complex. All determinations by Krueger Laboratories, Cambridge, Massachusetts.

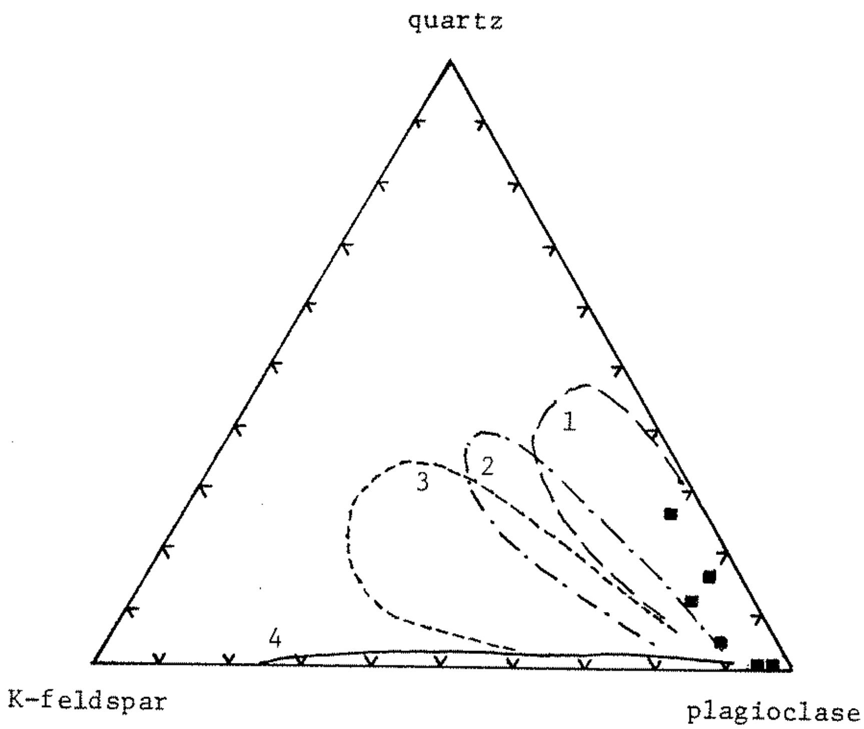
SAMPLE NO. (drill hole/ depth in ft.)	ROCK UNITS	ALTERATION ZONE (see Table 3)	MATERIAL DATED	AVERAGE GRAIN SIZE OF BIOTITE BEFORE SAMPLE PREPARATION (mm)	AGE (m.y.)
18/650-685[1]	Fine- to medium-grained diorite	Actinolite zone	Magmatic biotite, with chlorite and other impurities	0.5 - 1	87.9 ± 3.5
23/86-110[1]	Fine- to medium-grained diorite (some Midnight Peak andesite?)	Biotite-chlorite zone	Veinlet-controlled secondary biotite, partially concentrated	0.01 - 0.05	85.1 ± 3.5
23/510-560[1]	Medium-grained quartz diorite	Biotite-chlorite zone	Secondary biotite replacing primary mafic minerals, with chlorite and other impurities	0.01 - 0.05	69.7 ± 2.9
29/118-180[2]	Dacite porphyry (quartz-feldspar porphyry subphase)	Biotite-chlorite zone (intrusion of dacite postdates most secondary biotite)	Magmatic biotite, fairly pure concentrate	0.5 - 2	87.6 ± 3.3

[1]Livingstone and Wolfhard, 1976; M. R. Wolfhard, written commun.

[2]This study

FIGURE 2. Normative quartz-K feldspar-plagioclase plot of rocks of the Fawn Peak complex. Because fresh rocks are rare, samples from the actinolite and actinolite-chlorite zones of alteration (Table 3) have been included; the data of Orazulike (1979) suggest that only minor chemical changes resulted from such alteration. Fields of intrusive rocks associated with porphyry mineralization elsewhere are shown for comparison:

FIELD	Kesler and others, 1975, 1977	Sutherland Brown, ed., 1976	Hollister, 1978
1	Quartz diorite trend, island arcs	Calc-alkaline suite of the Canadian Cordillera	Lowell and Guilbert model
2	Granodiorite trend, island arcs		
3	Mineralized intrusions of the southwestern U.S.	----	
4	Shoshonite trend, island arcs	Alkaline suite of the Canadian Cordillera	Diorite model


quartz
1
2
3
4
K-feldspar
plagioclase

BRECCIAS

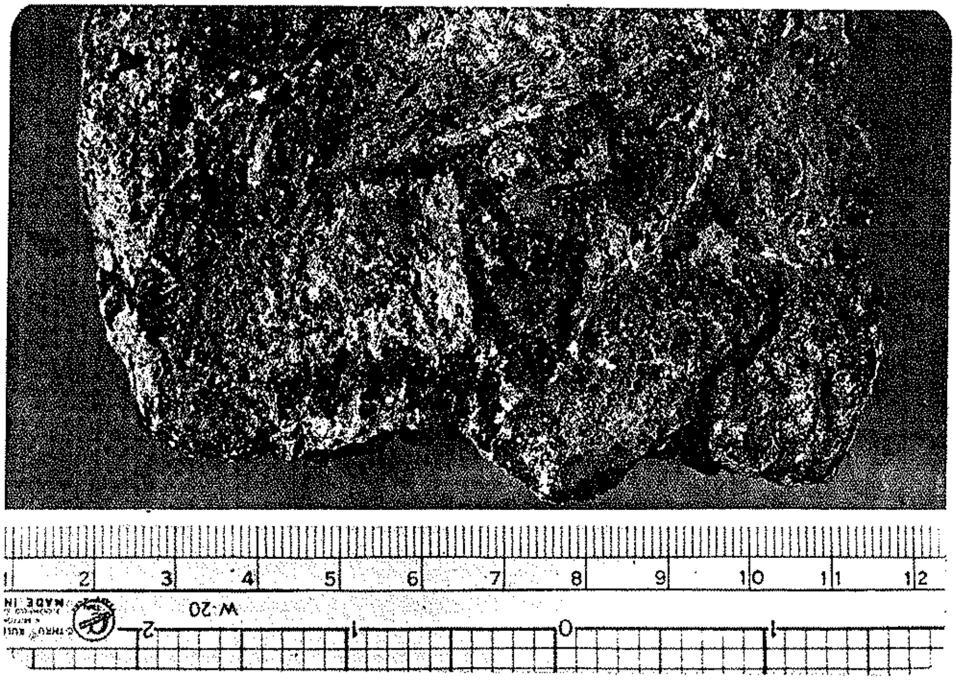
Two breccias occur on the north and south sides of Flagg Mountain (Plate 1). At the American Flag breccia, sericitized, well fractured quartz diorite crops out in an area 15 m in diameter. Samples on the dumps suggest that the rock at depth is strongly brecciated (Figure 3) with partially rotated fragments of quartz diorite up to 3 cm long in a matrix of quartz, tourmaline (schorl), calcite, pyrite, and chalcopyrite. The matrix lacks clastic material. The subsurface extent and geometry of this breccia are unknown. It cuts, and must therefore post-date, medium-grained quartz diorite.

The American Flag breccia is similar to the Chilean examples described by Sillitoe and Sawkins (1971). These authors envision dissolution of rock by corrosive hydrothermal fluids, creating a void that leads to brecciation and collapse. Alternatively, Norton and Cathles (1973) advocate accumulation of a vapor bubble beneath the margin of an intrusion to create the void necessary for collapse.

The Molly breccia is a pipelike body approximately 125 m in diameter, plunging easterly or northeasterly (Figure 5). On the surface it is southwest of the near-vertical Union fault (Plate II), but because of its plunge, the breccia probably lies northeast of the fault below the 2500-foot elevation (Figure 14). A matrix of feldspar porphyry encloses well mixed, subrounded xenoliths, up to 25 cm long, of Midnight Peak andesite, fine- and coarse-grained diorites, medium-grained quartz diorite, quartz diorite porphyry, quartz-feldspar porphyry, and andesite porphyry, and fragments of barren quartz veinlets. Local

FIGURE 3. Specimen of the American Flag breccia. Tourmaline-rich matrix (black) surrounds sericitized, partially rotated fragments of medium-grained quartz diorite. Upper scale is in centimeters.

FIGURE 4. Specimens of the Molly breccia from DDH-32. Note the matrix of feldspar porphyry, the irregular sulfide-rich lenses, and the fragment of a quartz veinlet in the sample at right (circled). Relatively coarse green sericite, with calcite and kaolinite, replaces plagioclase in both the fragments and matrix.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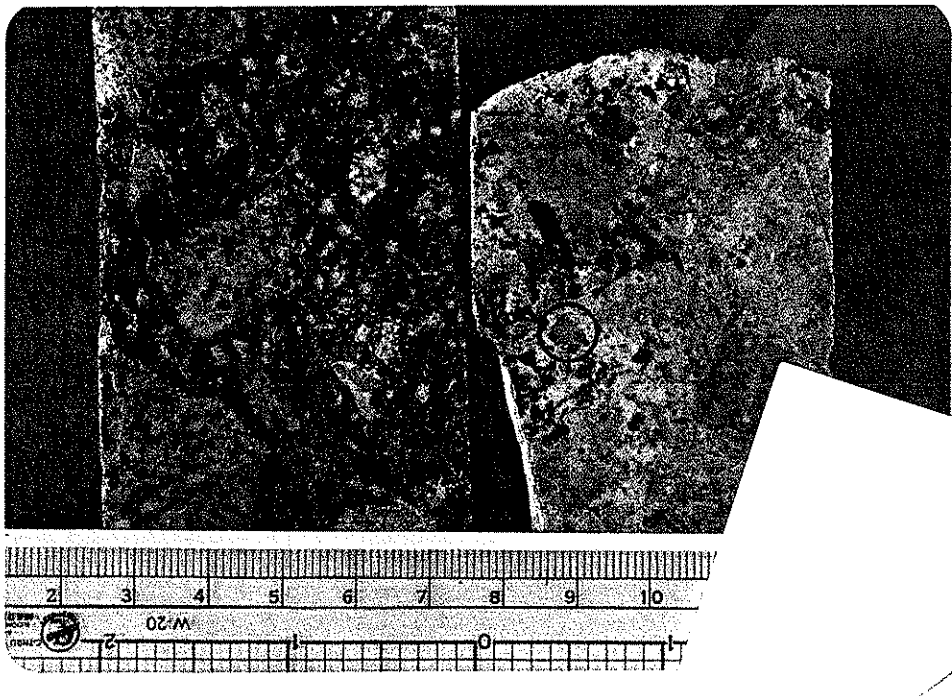
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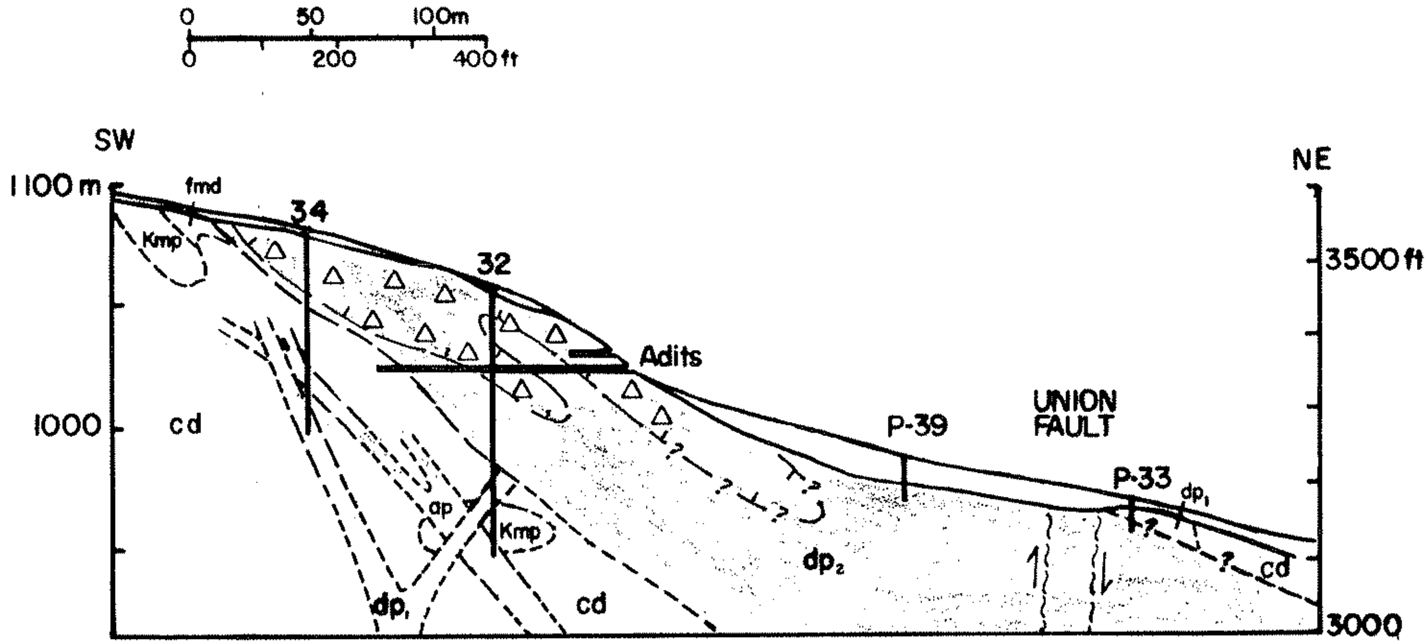
FIGURE 5. Cross section through the Molly breccia, looking northwest. Location shown on Plate II. P, percussion drill hole.



(blank box)	Quaternary, undifferentiated
△△	Quartz-calcite-sulfide matrix
dp_2	Feldspar porphyry with abundant xenoliths
dp_1	Quartz-feldspar porphyry
ap	Andesite porphyry
cd	Coarse-grained diorite
fmd	Fine- to medium-grained diorite
Kmp	Midnight Peak volcanic rocks
~~	Fault or shear
(dashed outline)	Zone of 0.2% copper

flow banding parallels the walls of the pipe. Sericitic alteration of fragments and feldspar porphyry is intense throughout the pipe, but decreases abruptly in the surrounding rocks. The breccia locally includes discontinuous pods and lenses of quartz, calcite, and sulfides (Figure 4), which contain rare fragments of feldspar porphyry. The quartz-calcite-sulfide matrix occurs in a zone that may cap the breccia, or it may extend eastwardly as the core of the body (Figure 5). The Molly pipe is a hydrothermal intrusion breccia in the terminology of Bryner (1968).

The matrix of feldspar porphyry suggests an origin different from that proposed for the American Flagg breccia. Flow banding and mixing of fragments imply movement along the axis of the pipe during intrusion of the feldspar porphyry. Given these constraints, two mechanisms may have formed the Molly breccia:

(1) Xenolith-rich magma of feldspar porphyry may have formed a pipe-shaped mass. Shatter brecciation (i.e., formation of quartz- and sulfide-filled cavities *in situ*, without rotation of fragments) and sericitic alteration then occurred within the pipe of feldspar porphyry. This two-stage model best explains the age relationships between the feldspar porphyry and the quartz-calcite-sulfide matrix.

(2) A one-stage model involving fluidization (Reynolds, 1954), the upward entrainment of fragments in a gaseous or liquid phase, might have formed both the intrusion breccia and the quartz-calcite-sulfide matrix. Briskey and Bellamy (1976) suggested that this would result from sudden escape of vapor from a shallow intrusion once a fracture propagates to the surface. Upward flow of volatiles might have entrained xenoliths

and magma into a column localized by the fracture. This model best accounts for the flow banding and mixing of different types of fragments, but does not explain the strong sericitic alteration. Moreover, fluidization without comminution of the feldspar porphyry into fine clastic material may be unlikely. Hydrothermal intrusion breccias with igneous matrices occur at Redwell Basin, Colorado (Sharp, 1978), the New World district, Montana (Eyrich, 1969), and Bethlehem, British Columbia (Briskey and Bellamy, 1976); for all these examples, an origin by fluidization has been proposed. J.R. Delaney (pers. commun., 1979) states that intrusion breccias commonly grade upwards into breccias cemented by quartz and sulfides, as is likely for the Molly pipe.

Both models suggest that the Molly breccia is nearly coeval with intrusion of the feldspar porphyry. In the two-stage model, shatter brecciation would postdate crystallization of the porphyry in the upper portion of the pipe.

STRUCTURE

Structural analysis is hindered by the massive nature of the stratified rocks, particularly the Midnight Peak andesites. The Winthrop Sandstone dips 50° northeasterly to 70° southwesterly. Crossbedding is common, and shows that the northeasterly dipping strata are overturned. Barksdale (1975) mapped the Goat Peak syncline, of late Cretaceous age, trending northwesterly through the summit of Flagg Mountain (Plate I), but this cannot be verified within the map area.

High angle faults are longitudinal, transverse, and, in one case, oblique to the syncline. Insufficient outcrop precludes determination of the geometry and displacement of most faults. Transverse structures are well exposed southwest of Flagg Mountain (Plate I). Slickensides show that the most recent movement was dip-slip. Because the attitude of the offset contact between quartz diorite and Midnight Peak is uncertain, the sense of movement on these faults is unknown.

The near-linear trace of the longitudinal Union fault implies the fault plane dips steeply. Apparent displacement of the east-dipping contact between diorite and quartz diorite (Plate II) suggests that the northeast side moved relatively down, antithetic to the late Cretaceous folding, but the evidence is not conclusive. In the Fawn Creek drainage, this fault presumably downdropped the inlier of Winthrop Sandstone. Shearing along the trend of the Union fault cuts dacite porphyry 200 m northeast of the Molly workings (Plate II); this suggests some relatively late movement.

The bedding and transverse structures apparently influenced the shapes of intrusive bodies. For example, peripheral dikes and sills of fine- to medium-grained diorite most commonly strike northwesterly. Lobes of the body of medium-grained quartz diorite show northeast and northwest alignment. However, the dikes of dacite porphyry consistently trend east-west, oblique to beds and transverse faults. The Fawn Peak complex does not deform the country rocks; therefore, intrusion was dominantly passive.

The bodies of coarse-grained diorite, medium-grained quartz diorite, quartz diorite porphyry, and the Molly breccia all dip or plunge about 45° easterly to northeasterly (Plate III; Figures 5 and 14). Where breccia pipes are known to be untilted, they are consistently within twenty degrees of vertical (Sillitoe and Sawkins, 1971; F. J. Sawkins, pers. commun., 1979). Thus the entire deposit has apparently been tilted 45° west-southwest.

The age and mechanism of this tilting are unclear. Intrusion of the complex prior to (or during) late Cretaceous folding would have produced a southwestward tilt. However, because the medium-grained quartz diorite is unfoliated, such deformation seems unlikely; this model would require folding of the quartz diorite around the axis of the Goat Peak syncline (Plate I). Alternatively, the complex could postdate the folding. Late Cretaceous reverse (west side up) movement on the Chewack-Pasayten fault (Figure 1) suggested by Lawrence (1978) could have caused westward tilting of the block west of the fault. Cheney (1977) documented mid-Tertiary north-south folding of the Kettle dome and synclinal Republic graben 130-150 km to the east; however, no independent evidence supports such folding as far west as the Methow Valley.

ECONOMIC GEOLOGY

Disseminated and veinlet-controlled copper-molybdenum sulfide mineralizations, most with associated hydrothermal alterations (Table 3), occur predominantly in the western portion of the complex (the Mazama prospect) and adjacent country rocks (Figures 6 and 7). Although all intrusive phases are mineralized, later phases postdate some mineralization. Dikes of medium-grained quartz diorite locally cut mineralization (Figure 8). Dacite porphyry cuts sulfide veinlets (Figure 9) and commonly averages 0.1-0.2% less copper than adjacent rocks. Quartz diorite porphyry appears to cut off the zone of 0.2% copper (Plate III, Section B-B'; Figure 14). Petrographic and x-ray studies delineate the succession of spatially overlapping alteration-mineralization events described below. Figures 6 and 7 show the extent of the composite zones listed in Table 3.

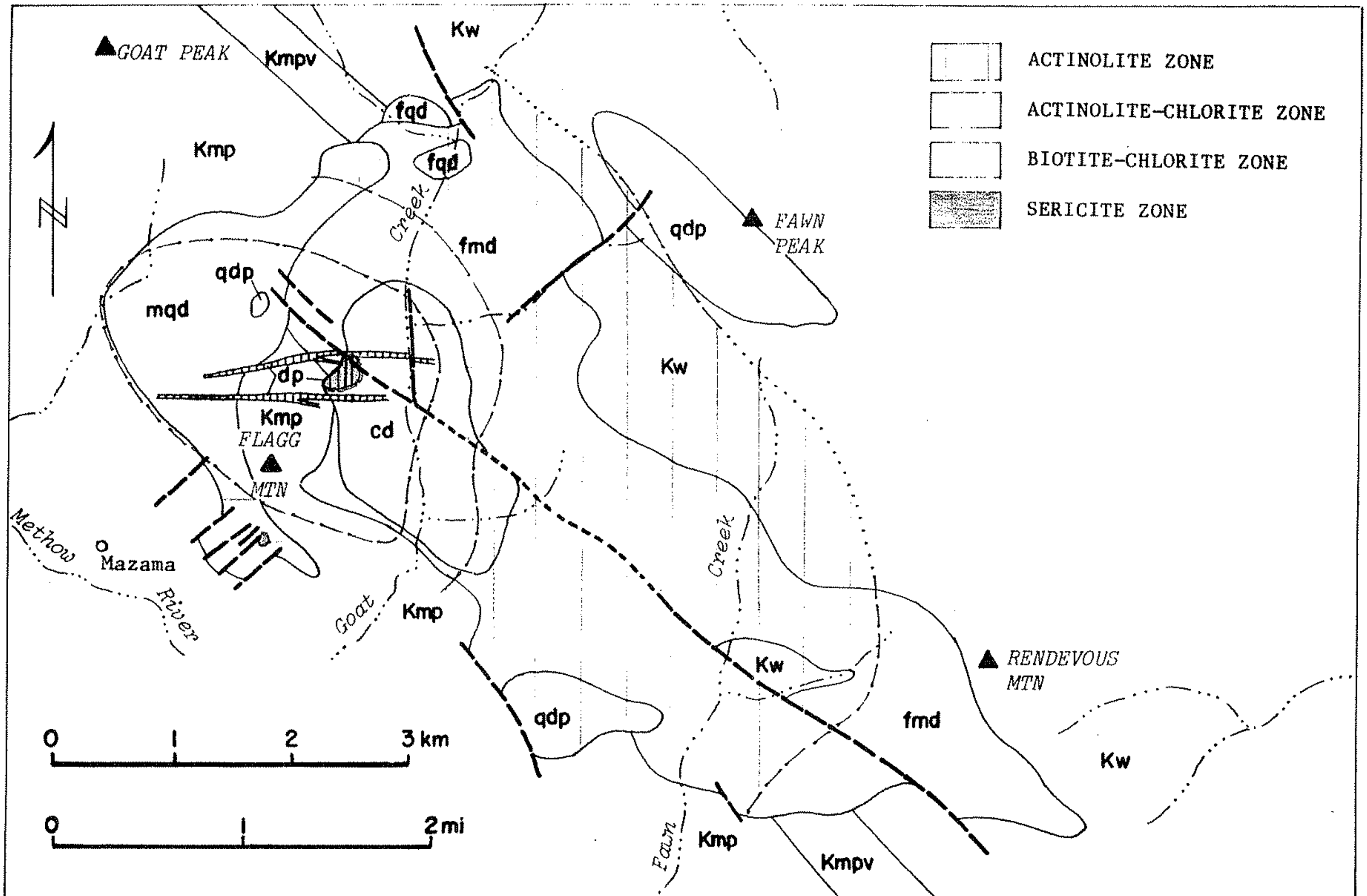
EARLY PYRITE-CHALCOPYRITE MINERALIZATION

Minor early mineralization predates the intrusion of the medium-grained quartz diorite. Thin veinlets of quartz, pyrite, and chalcopyrite occur primarily along the western contact of, and possibly are related to, the coarse-grained diorite (Plate III, Section A-A'). The proximity of the coarse diorite, and the lack of later intrusive phases at the surface (and probably at depth; Orazulike, 1979) suggest that mineralization of the Fawn Creek prospect may predate the medium-grained quartz diorite. This early mineralization lacks distinct associated hydrothermal alteration, possibly due to overprinting by later assemblages. However, the bulge of the actinolite zone southeast of the Fawn Creek area (Figure 6) suggests that an actinolitic alter-

TABLE 3. Mineralogy of the zones of hydrothermal alteration in Figure 6. Each arrow represents a single stage of replacement; multiple arrows in a single box signify successive stages of replacement of a particular magmatic mineral. The term "sericite" is used to designate any fine-grained highly birefringent white phyllosilicate, and probably includes kaolinite and montmorillonite.

		ACTINOLITE ZONE	ACTINOLITE-CHLORITE ZONE	BIOTITE-CHLORITE ZONE	SERICITE ZONE
PERVASIVE ALTERATION OF MAGMATIC SILICATES	Plagioclase	fresh	→ sericite (weak to strong)	→ sericite local K-feldspar rims	→ sericite > calcite
	Biotite	→ chlorite intergrowths	→ chlorite	fresh, weakly recrystallized, or → chlorite	→ sericite > chlorite, calcite
	Hornblende, augite	→ actinolite (>50% replaced)	→ actinolite → chlorite ± epidote	→ actinolite → biotite → chlorite (weak)	→ sericite > chlorite, calcite
ENVELOPES ABOUT VEINLETS AND FRACTURES		chlorite + epidote	not observed	biotite + sericite ± K-feldspar sericite ± chlorite, K-feldspar, calcite, epidote	not observed
ASSOCIATED OPAQUE MINERALS		magnetite restricted veins of pyrite, chalcopyrite, arsenopyrite	pyrite, magnetite	pyrite, chalcopyrite, magnetite, molybdenite	pyrite, chalcopyrite, magnetite, molybdenite
ALTERATION EVENTS AFFECTING ROCK IN GIVEN ZONE ( ) signifies restricted occurrence		ACTINOLITIC (& PROPYLITIC)	ACTINOLITIC & PROPYLITIC	(ACTINOLITIC) & BIOTITIC & PROPYLITIC (& SERICITIC)	ACTINOLITIC ? (& BIOTITIC ?) & PROPYLITIC & SERICITIC

FIGURE 6. Map of the complex showing zones of hydrothermal alteration described in Table 3. Rock units as on Plate I.



ACTINOLITE ZONE
ACTINOLITE-CHLORITE ZONE
BIOTITE-CHLORITE ZONE
SERICITE ZONE
GOAT PEAK
Kmpv
Kw
fqd
fqd
Kmp
Creek
fmd
qdp
FAWN PEAK
qdp
mqd
dp
Kmp
FLAGG MTN
cd
Kw
Methow River
Mazama
Goat
Kmp
Creek
Kw
RENDEVOUS MTN
qdp
fmd
Kw
0 1 2 3 km
0 1 2 mi
Fawn
Kmp
Kmpv

FIGURE 7. Map of the complex showing zones of sulfide mineralization. Rock units as on Plate I.

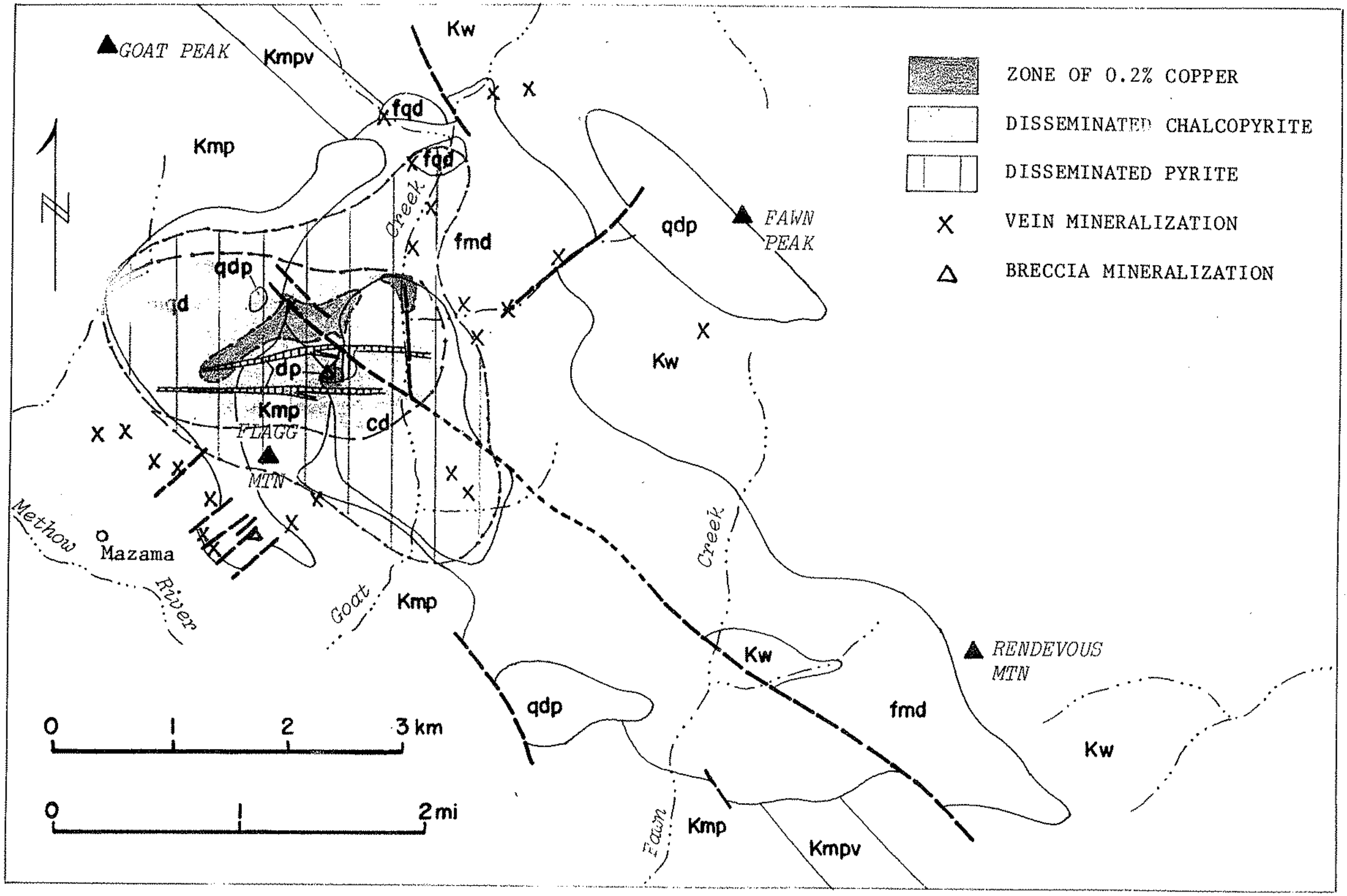
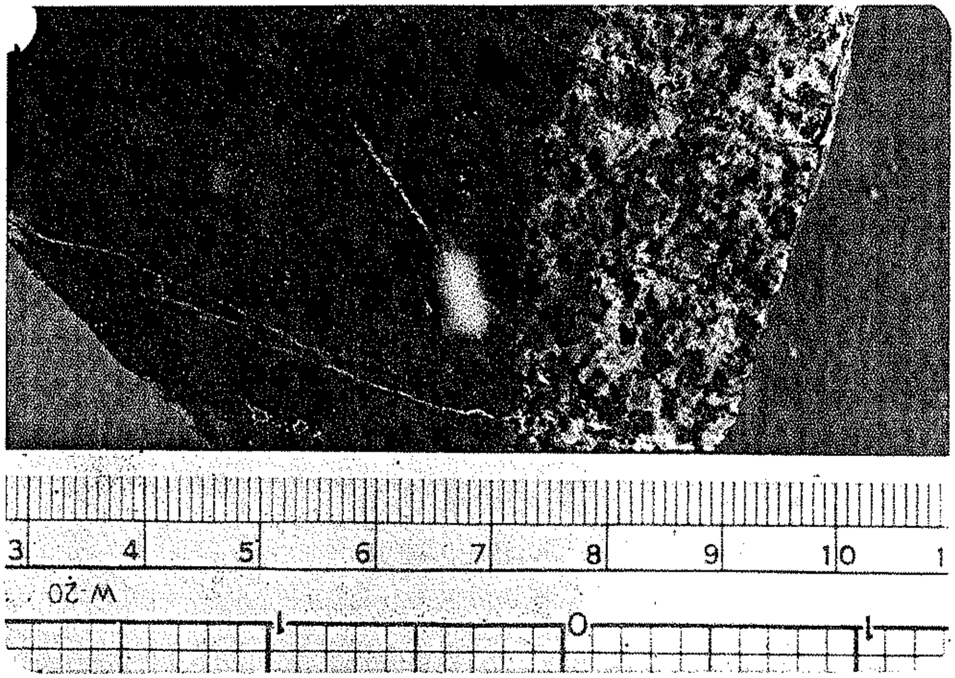

ZONE OF 0.2% COPPER
DISSEMINATED CHALCOPYRITE
DISSEMINATED PYRITE
VEIN MINERALIZATION
BRECCIA MINERALIZATION
GOAT PEAK
FAWN PEAK
FLAGG MTN
RENDEVOUS MTN
Mazama
Methow River
Goat Creek
Fawn Creek
Kw
Kmpv
Kmp
fqd
fmd
qdp
dp
cd
0 1 2 3 km
0 1 2 mi

FIGURE 8. Medium-grained quartz diorite cutting a sulfide veinlet in a xenolith of Midnight Peak andesite, DDH-31.

FIGURE 9. Dacite porphyry cutting a quartz-sulfide veinlet in medium-grained quartz diorite; DDH-33.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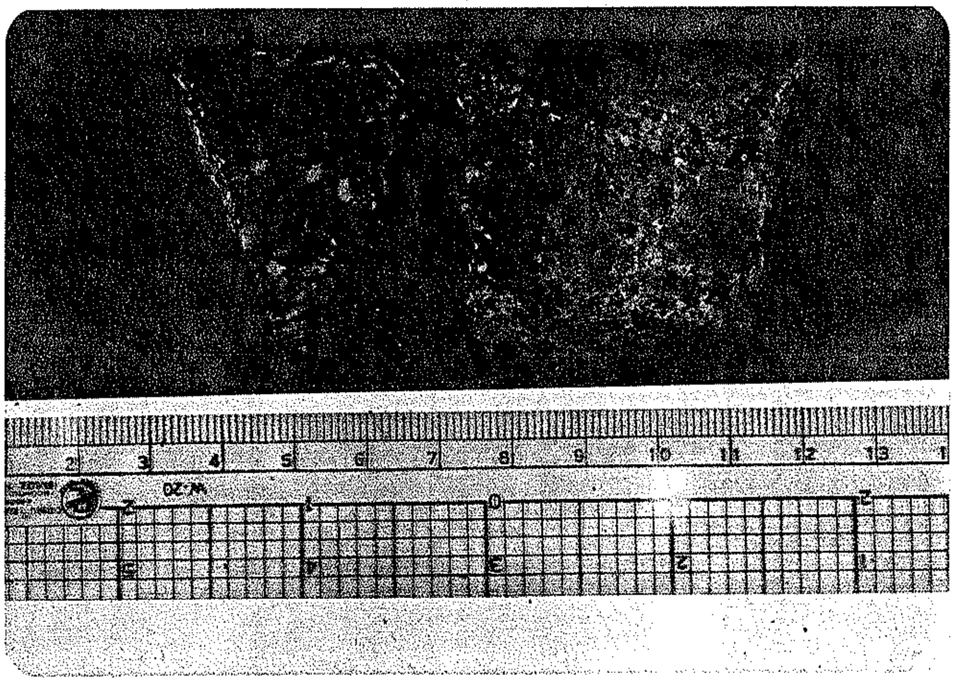

W-20

ation, indistinguishable from the assemblage that follows, might accompany this early mineralization.

BARREN ACTINOLITIC ALTERATION

Early alteration consists of pale actinolite rimming or replacing magmatic hornblende and augite. Both pseudomorphs, and aggregates of fibrous grains of actinolite 0.05 to 0.5 mm, are common. Actinolite does not replace primary biotite. Veinlets of magnetite without sulfides are coextensive, and probably temporally associated with actinolitization. Actinolitic alteration predates the intrusion of dacite porphyry, but affects all older rock types. It is the most extensive alteration assemblage (Figure 6); relatively fresh hornblende occurs only in the extreme northeastern and southeastern parts of the complex. Where not obliterated by later alteration, actinolite persists into the core of the deposit, where it generally is present only in the earlier, dioritic phases. Evidently biotitic alteration occurred in the later intrusive phases before actinolite could form.

Hydrothermal amphibole occurs in a few American deposits (Bingham and Ray). In the more mafic porphyry systems of the southwest Pacific islands, Puerto Rico, and British Columbia, it commonly replaces augite and hornblende (Table 4). The rarity of hydrothermal amphibole in American deposits is probably due to the lack of magmatic augite and hornblende in the relatively felsic intrusions.

BIOTITIC ALTERATION AND CHALCOPYRITE-PYRITE MINERALIZATION

Pervasive and veinlet-controlled biotitic alteration accompanies the earliest prominent chalcopyrite mineralization. Random to parallel

TABLE 4. Occurrences of hydrothermal amphibole in porphyry copper deposits.

Abbreviations:

act -- actinolite
aug -- augite
bio -- biotite, biotitic alteration
chl -- chlorite, propylitic alteration
cpx -- clinopyroxene
hb -- hornblende
px -- pyroxene
ser -- sericite, sericitic alteration
trm -- tremolite

Name	Properties	Host Rock	Mineralization	Developments	Production (metric tons)
AMERICAN FLAG	3 claims 2 patented	mqd	Breccia pipe; qz, ca, py, asp, cpy, sph	450 m: 2 adits, raise winze, sublevel	Several hundred tons before 1910; minor 1940.
CROWN POINT (IMPERIAL)	3 claims	Kw	Silicified zone: qz, cpy, py, asp, po	250 m: 3 adits, 3 crosscuts, 2 drifts	---
DJ	---	fmd	Shear zone; qz, py, cpy	1 adit	---
GOLD KEY	within Mazama Pride block(?)	Kmp	Qz stringer; py, asp, cpy	40 m: adit and winze	35 tons, 1931
JAN	---	fmd	Intersection of shear and qz stringer; py	1 shaft	---
LOST LODE	---	fmd	Shear zone; py, cpy	1 adit	---
MAZAMA PRIDE	9 claims	Kmp	Qz veins; py, asp, cpy	200 m: shaft, drifts, crosscut	Minor, 1931 and 1939(?)
MOLLY	5 claims	dp	Breccia pipe; py, mo, cpy, bn	60 m: 3 adits, trenches and cabin	---
MONTANA	1 claim	fmd, mqd	Qz veins; cpy, asp, po	≤200 m: 3 adits. Mill and cabins	Minor, 1915.
ORE BUCKET	---	Kw	Shear zone; cpy	1 adit	---
ROSALIND (CHINAMAN)	2 claims	fgd	2 shear zones; py, asp, po, cpy	175 m: 2 adits, drifts and crosscuts	---
ROSS	---	fmd	Shear zone; qz, py	1 adit	---
SILVER KING	7 claims	fmd, Kmp	Shear zone; qz, ca, py, cpy, gal	65 m: 2 adits, cuts. Cabin	---
SOONER	2 claims	fqd, fmd	Shear zone; qz, ca, py, cpy	2 adits, cuts	---
SURE DEAL	---	dp	Shear zones; qz, py, cpy	1 adit, 1 shaft	---
unnamed adit, near DDH-9	---	fmd	Union fault zone; cpy, py, mo	1 adit	---
unnamed adit, 0.7 km southwest of Montana	---	fmd	Intersection of shear zone and fault; qz, py, asp, cpy	1 adit, 1 pit	---

aggregates of black biotite, consisting of grains generally less than 0.05 mm across, replace primary mafic minerals and actinolite. Where replacement is incomplete, secondary biotite rims actinolite (Figure 10). Primary biotite is stable or very weakly recrystallized. Secondary biotite is commonly difficult to discern megascopically because of overprinting by chlorite. The relatively dark color and strong pleochroism suggest that the secondary biotite is magnesium-poor. Rare rimming of magmatic plagioclase by K-feldspar probably occurred at this time. Disseminated pyrite and chalcopyrite 0.1 to 2 mm across occur in biotitized mafic minerals. Biotite-rich envelopes up to 5 mm wide, locally with K-feldspar, surround discontinuous quartz-pyrite-chalcopyrite veinlets. These early veinlets, 1-3 mm thick, locally contain magnetite, calcite, and anhydrite. In a narrow zone surrounding many of the biotitic envelopes, sericite (not verified by x-ray diffraction) intensely replaces plagioclase, but not mafic minerals.

Biotitic alteration and chalcopyrite mineralization only weakly affect, and in part predate dacite porphyry. Biotitic alteration occurs primarily in the biotite-chlorite zone (Figure 6), although Orazulike (1979) reported hydrothermal K-feldspar at depth in the Fawn Creek prospect.

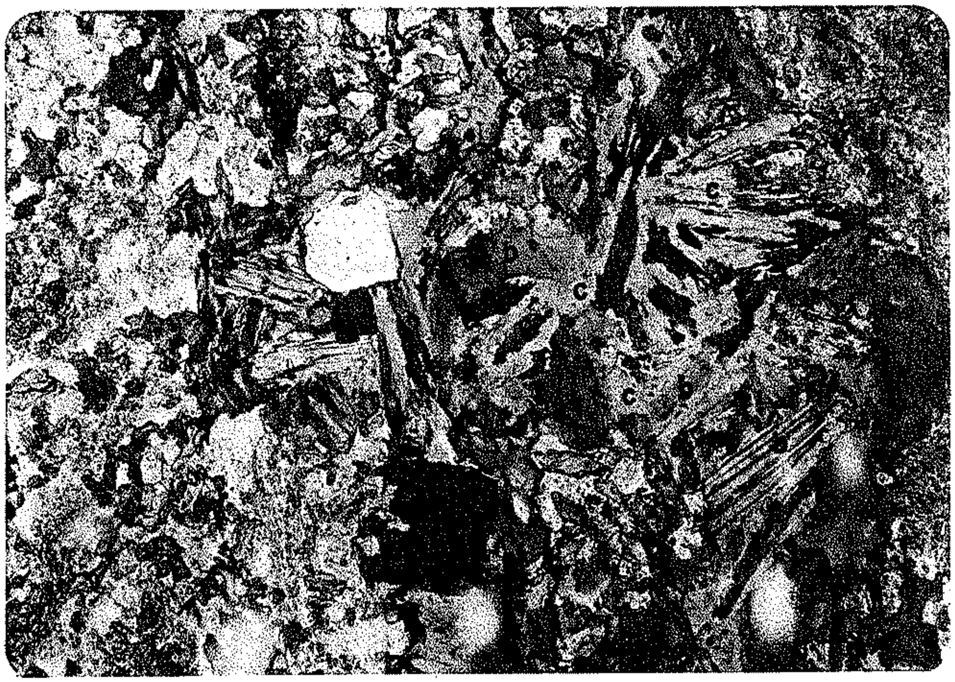
PROPYLITIC ALTERATION AND PYRITIC MINERALIZATION

Chlorite pervasively replaces magmatic and hydrothermal amphiboles and biotites in the biotite-chlorite and actinolite-chlorite zones (Figure 6). Chlorite does not replace pyroxene except where the latter was first altered to actinolite. Rarely chlorite rims secondary biotite

FIGURE 10. Aggregate of fine-grained actinolite (a) in a primary mafic site, rimmed by secondary biotite (b). Fine- to medium-grained diorite, DDH-14, crossed polars.

FIGURE 11. Chlorite (c) rimming and replacing individual grains of secondary biotite (b) in a mafic site. Coarse-grained diorite, DDH-32, uncrossed polars.

1 mm



0.1 mm

(Figure 11), but more commonly the two minerals are intergrown. Epidote occurs with chlorite in the mafic sites, and locally rims plagioclase. More commonly, grains of sericite and montmorillonite less than 0.01 mm across dust the plagioclase. Atkinson and Einaudi (1978, p. 1335) described a similar replacement of plagioclase by sericite-montmorillonite at Bingham, Utah.

Pervasive propylitic alteration is spatially associated with disseminated pyrite in the mafic sites. The greater areal extent of this entire assemblage relative to biotitic alteration and chalcopyrite mineralization produces a pyritic-propylitic halo about the Mazama center of mineralization. Intensity of chloritization appears to decrease somewhat with depth in the biotite-chlorite zone (e.g., DDH-28).

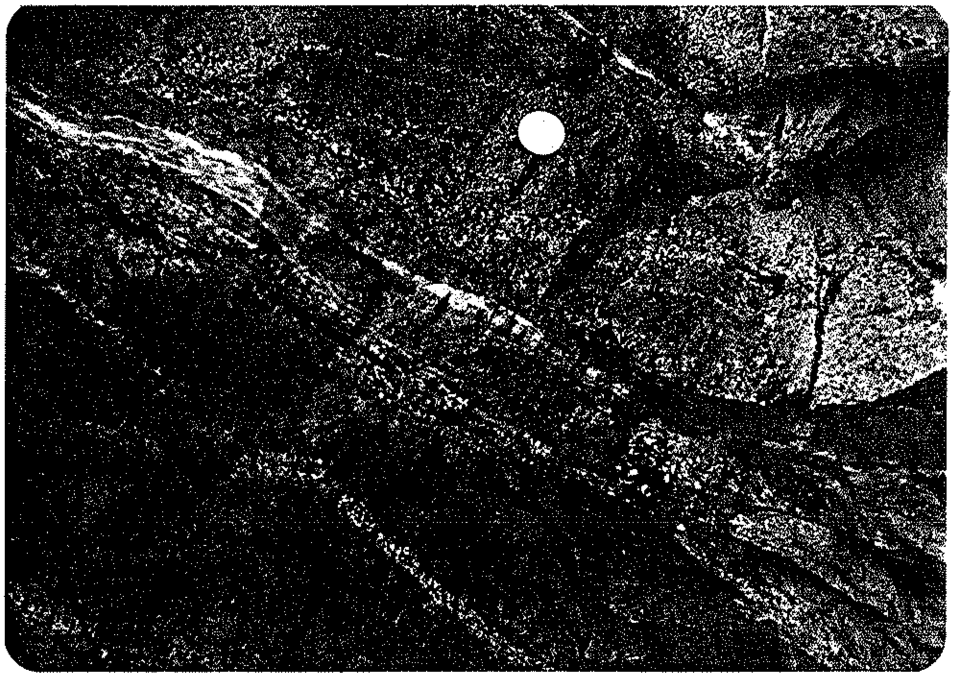
Fracture-controlled propylitic alteration extends outward into the actinolite zone, especially to the north. Chlorite replaces actinolite; epidote and albite bleach calcic plagioclase in envelopes extending up to 10 cm from fractures (Figure 12). Monomineralllic epidote veinlets 1-3 mm thick occur throughout the Mazama prospect.

SERICITIC ALTERATION AND PYRITE-CHALCOPYRITE-MOLYBDENITE MINERALIZATION

Strong sericitic alteration is generally limited to shear zones, envelopes about late veinlets, and the breccia pipes. Structurally controlled sericitic alteration cuts biotitized and propylitized rock, a relationship evident in a prospect pit 150 m south-southwest of DDH-30. In thin section, sericite commonly rims both hydrothermal biotite and chlorite. Associated mineralization is primarily fracture-controlled, rarely disseminated.

FIGURE 12. Epidote-chlorite envelopes along fractures cutting actinolitized fine- to medium-grained diorite, south of Whiteface Creek.

FIGURE 13. Sericitic envelope replacing plagioclase and mafic minerals adjacent to sulfide veinlet. Fine- to medium-grained diorite, DDH-25, crossed polars.



1 mm

Aggregates of sericite and kaolinite, the individual grains rarely more than 0.01 mm across, replace plagioclase and most mafic minerals adjacent to quartz-pyrite-chalcopyrite veinlets (Figure 13). Molybdenite, calcite, K-feldspar, chlorite, anhydrite, and zeolites are also common in this assemblage. These discrete, continuous veinlets contain generally coarser sulfides (1-10 mm) than the earlier, discontinuous veinlets with biotitic envelopes. Sericitic veinlets are most common below the present surface in the biotite-chlorite zone.

In and adjacent to the two breccia pipes, coarser sericite, up to 0.05 mm, with associated kaolinite, calcite, and chlorite, pervasively replaces plagioclase and mafic minerals. Associated pyrite and chalcopyrite occur as blebs in the quartz-calcite matrix, and as rare disseminations in the fragments.

This sericite differs from that associated with pervasive propylitic alteration because it: (1) is of limited areal extent; (2) is strongly controlled by veinlets, faults and breccia pipes; (3) postdates hydrothermal biotite and chlorite; (4) replaces mafic minerals, not just plagioclase; and (5) is associated with kaolinite instead of montmorillonite. The coexistence of sericite and K-feldspar is unusual; such assemblages occur in the pre-Main Stage alteration at Butte, Montana (Brimhall, 1977) and at El Teniente, Chile (Camus, 1975).

PERIPHERAL VEINS

Outside the disseminated pyrite zone, surface mineralization occurs primarily in discrete veins, lodes, and shear zones, of uncertain age. Mineralized structures commonly trend N 10 E to N 40 E and N 70 W to N 85 W. Pyrite, chalcopyrite, lesser arsenopyrite, and other sulfides occur as grains 1 to 10 mm across in a gangue of quartz and calcite. Envelopes of sericite (with secondary biotite at the Montana workings) surround most veins. Comb structure and veinlets with discrete walls suggest that the mineralization filled open fractures. Early prospectors worked many of the peripheral veins for the minor gold and silver present (Figure 7, Plate I-A, and Appendix 1).

LATE BARREN VEINLETS

Veinlets of anhydrite, calcite, and calcite-heulandite postdate all sulfide mineralization and silicate alteration. These distinct, continuous veinlets lack alteration envelopes. They are relatively common in the subsurface throughout the better mineralized portions of the Mazama prospect.

OXIDATION AND SUPERGENE ALTERATION-MINERALIZATION

Weakly oxidized rock, containing limonite, malachite, and hypogene sulfides, caps the deposit to depths up to 50 m. Oxidation along faults locally extends to several hundred meters depth. Exotic limonite (Blanchard, 1968, p. 12) occurs with better grade mineralization in sericitic alteration, such as at the Molly breccia.

Supergene enrichment is negligible, although rare films of chalcocite rim chalcopyrite in the oxidized zone, as in DDH-33. Lack of enrichment is due to three factors: (1) The low total sulfide content hindered the generation of highly acidic solutions during weathering, hence little copper could be transported. (2) The feldspathic rocks tended to neutralize acidic solutions, causing precipitation of copper prior to significant concentration (Blanchard, 1968, p. 65-66, 84-85).

(3) Late Pleistocene continental ice overrode even the summit of Goat Peak (Waitt, 1972; Barksdale, 1975, p. 53-56) and probably eroded any supergene enriched ore.

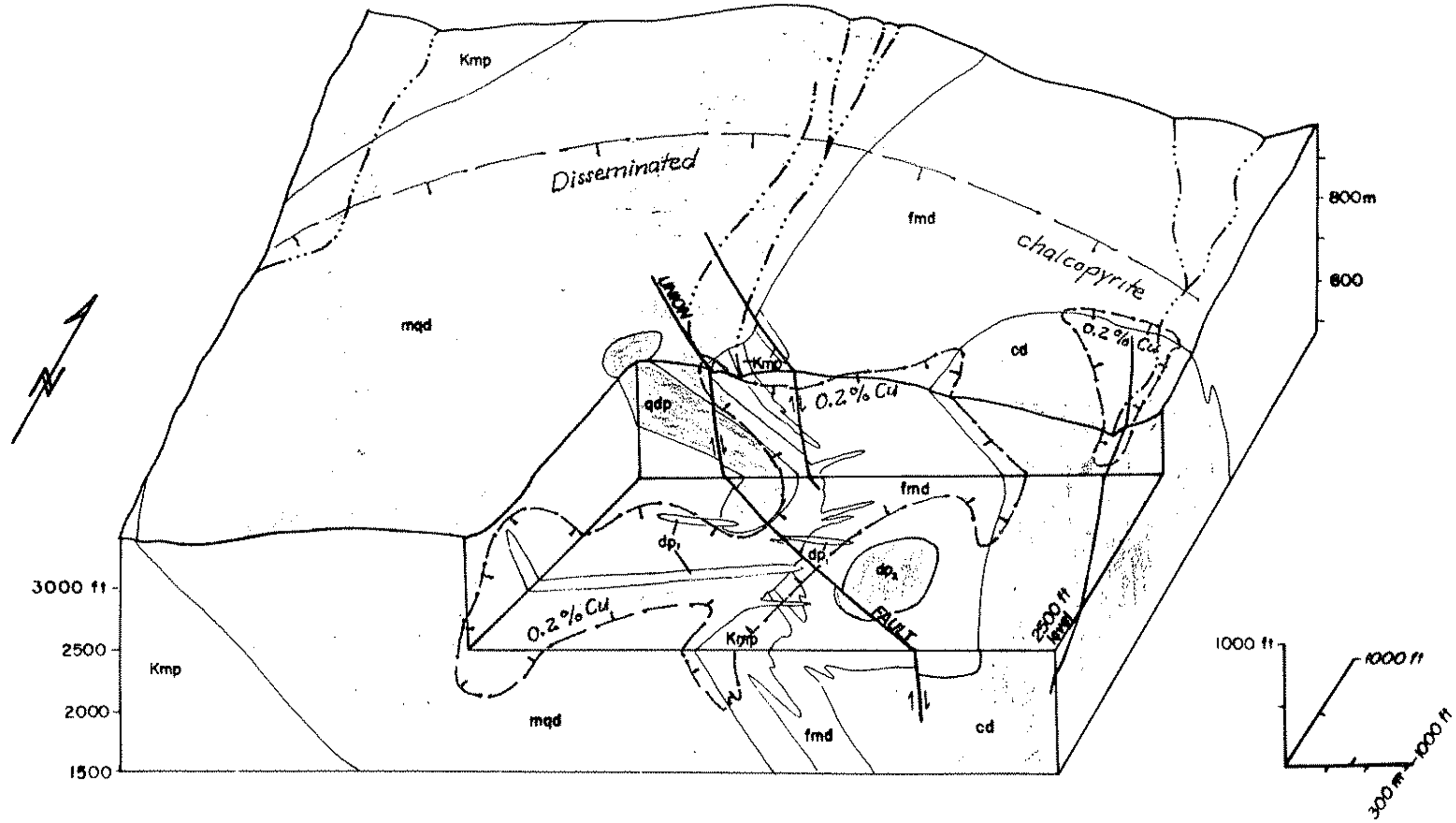
Supergene alteration is insignificant below the oxidized zone. Petrographic and x-ray analyses of samples from the Molly breccia show no systematic change in relative abundances of phyllosilicates with depth; the abundant sericite and clay, therefore, are hypogene, not supergene. Weathering does control the present distribution of sulfate minerals. Anhydrite rarely occurs within 200 m of the surface. Gypsum extends a maximum of 100 m, but more commonly 20-30 m above the anhydrite zone. The upper, sulfate-free zone ranges from 0 to 180 m thick. Hydration and leaching of hypogene anhydrite by ground water probably accounts for the sulfate zoning.

CONTROLS OF MINERALIZATION

Grades better than 0.2% copper occur in an east-dipping zone that is 1300 by 250 m at the surface and widens at depth (Plates II and III; Figures 14 and 15). Although strongly controlled by intrusive contacts, higher grade mineralization is not spatially related to any single intrusive phase. Ore controls are clearly complex.

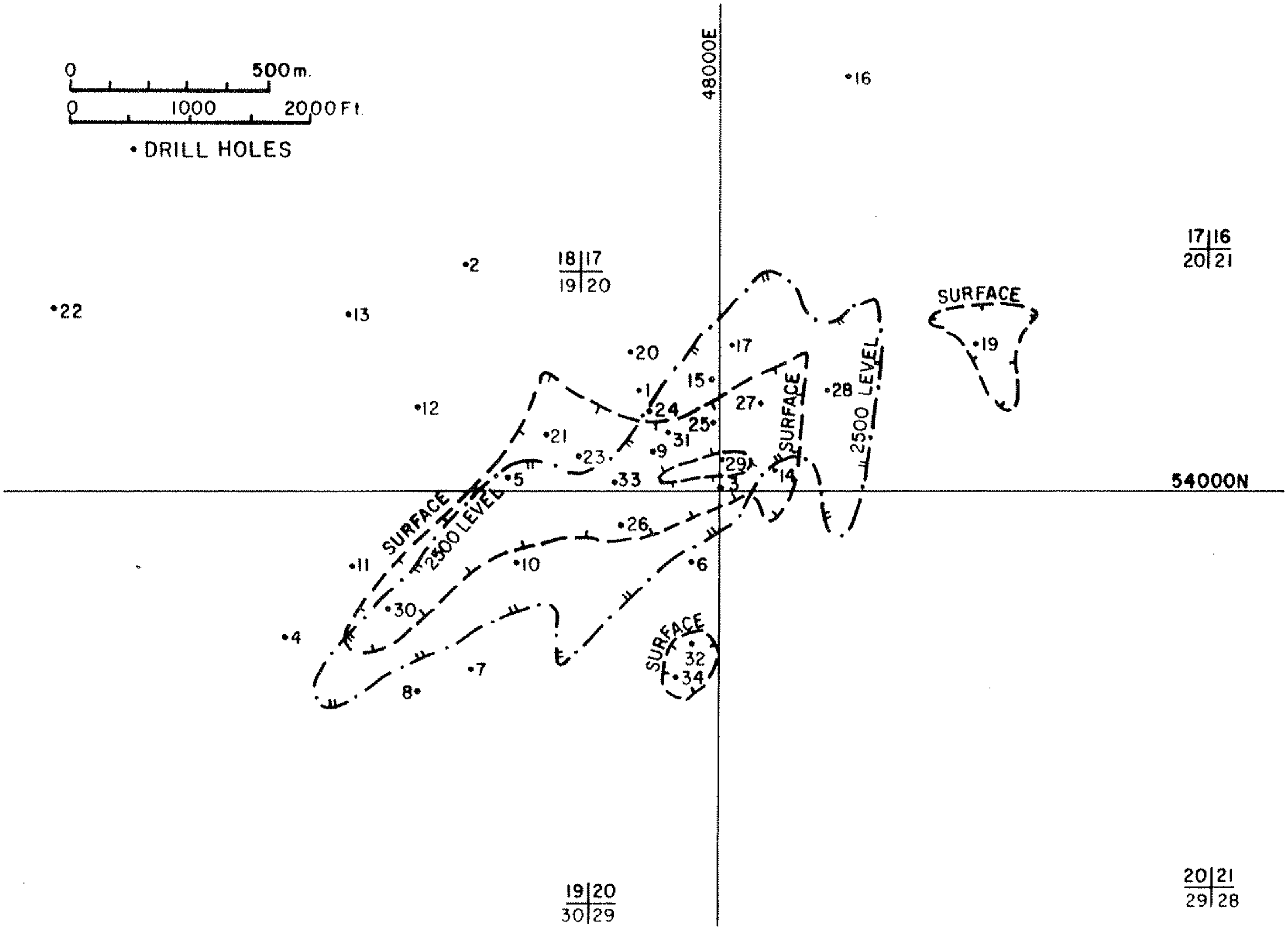
Much mineralization is fracture controlled. Earlier, finer grained rock types, especially hornfels, have the most numerous joints, and therefore host much of the better grade mineralization. Faults and shears guided mineralization, especially in the periphery of the deposit. For example, the transverse fault just west of the summit of Fawn Peak probably localizes several vein deposits (Figure 7). Abundant quartz-

FIGURE 14. Isometric diagram of the Mazama deposit. Location shown on Plate II.



dp_2	Feldspar porphyry with abundant xenoliths	cd	Coarse-grained diorite
dp_1	Quartz-feldspar porphyry	fmd	Fine- to medium-grained diorite
qdp	Quartz diorite porphyry	Kmp	Midnight Peak volcanic rocks
mqd	Medium-grained quartz diorite		

FIGURE 15. Plan of the zone of 0.2% copper at the surface and at the 2500 ft (762 m) elevation.



0 500 m.
0 1000 2000 Ft.
• DRILL HOLES
48000E
54000N
SURFACE
2500 LEVEL
18|17
19|20
17|16
20|21
19|20
30|29
20|21
29|28
•1
•2
•4
•5
•6
•7
8•
•9
•10
•11
•12
•13
•14
15•
•16
•17
•19
•20
•21
•22
•23
•24
25•
•26
27•
•28
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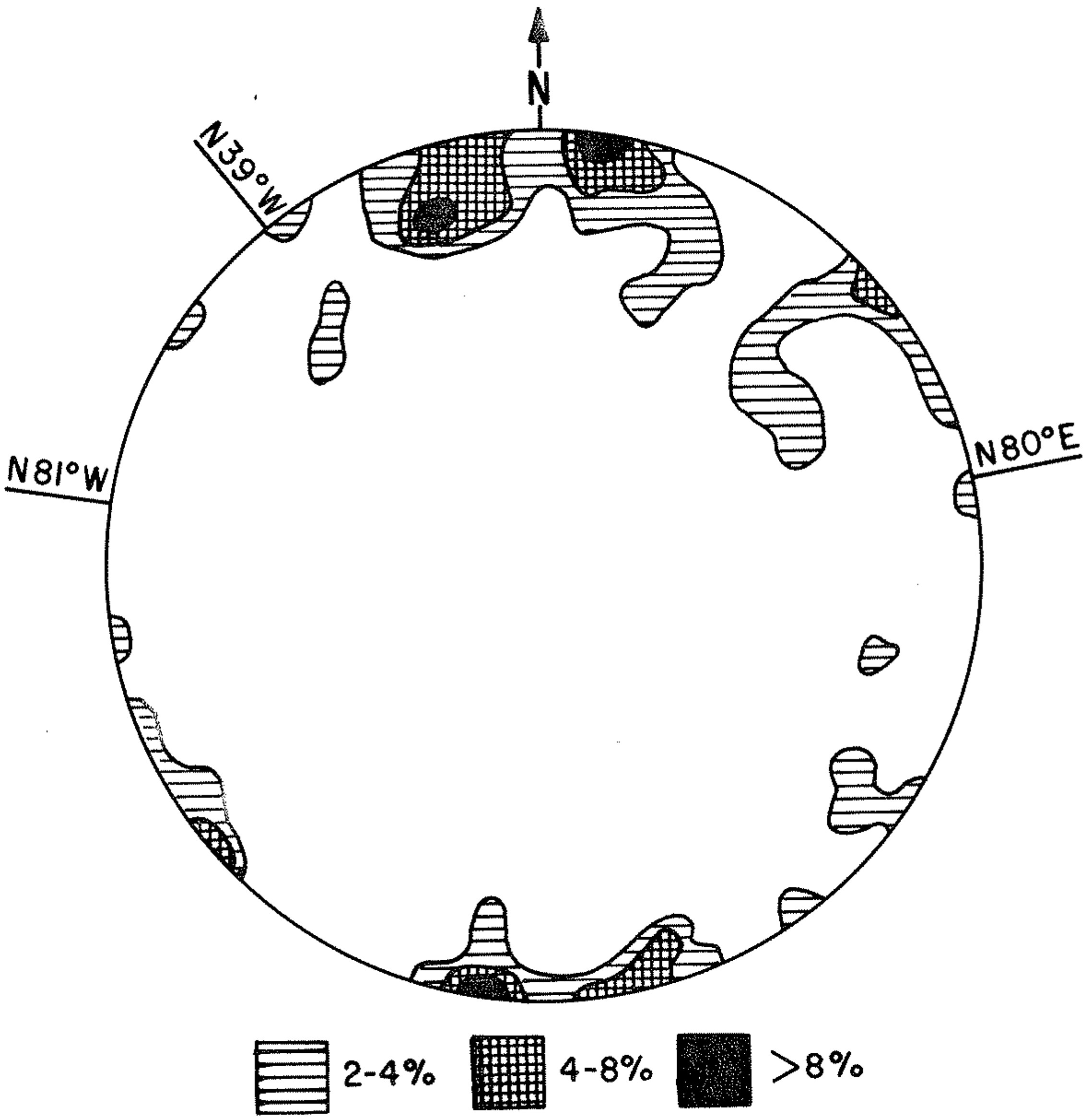
•34

FIGURE 16. Equal-area (lower hemisphere) contour diagram of poles to mineralized fractures in the Mazama deposit. (P. G. Dunn, pers. commun., 1978).



N
N39°W
N81°W
N80°E
2-4%
4-8%
>8%

sulfide veinlets occur in outcrops adjacent to the northwestern end of the Union fault.

Mineralized fractures show a strong preferred east-west orientation, with a subordinate northwest trend (Figure 16). These are comparable to the trend of the dikes of dacite porphyry, and the regional structural grain, respectively. Because earlier intrusive phases are not elongated east-west, much of the later, veinlet-controlled mineralization and the dacite porphyry may be temporally related.

The distribution of biotitic alteration (Figure 6) is probably related to the east-dipping body of medium-grained quartz diorite. The surface extent of disseminated pyrite (Figure 7) most nearly mimics the map pattern of coarse-grained diorite and medium-grained quartz diorite. The zones of 0.2% copper are spatially associated with segments of the contacts of both these phases (Plate III), although the lobe of mineralization along the coarse-grained diorite is also parallel to the contact of, and might in large part be genetically related to, the quartz diorite. Thus, these patterns suggest the relationship of early mineralization with medium-grained quartz diorite and possibly coarse-grained diorite.

Alternatively, an intrusive body at depth may control the better grade mineralization. The northeast-plunging body of feldspar porphyry is a possible source (Figures 5 and 14), although it is largely barren through much of its known extent, and probably postdates much of the mineralization.

In summary, in neither a spatial nor temporal sense is mineralization related to a single intrusive phase. The earliest mineralization predated intrusion of medium-grained quartz diorite, and is probably associated with coarse-grained diorite. Much of the better grade copper, like the biotitic alteration, is spatially, and probably genetically related to medium-grained quartz diorite. Quartz diorite porphyry and dacite porphyry are weakly biotitized, carry low copper values, and post-date considerable mineralization in the rocks explored to date. Parallel trends of dacite dikes and mineralized fractures, however, may suggest a temporal relationship between dacite porphyry and the later, veinlet-controlled mineralization associated with sericitic alteration. The present distribution of higher grade copper, therefore, might be explained by (1) spatial overlapping of pulses of low-grade mineralization associated with specific intrusive phases; and (2) the presence of favorable, well fractured rock units.

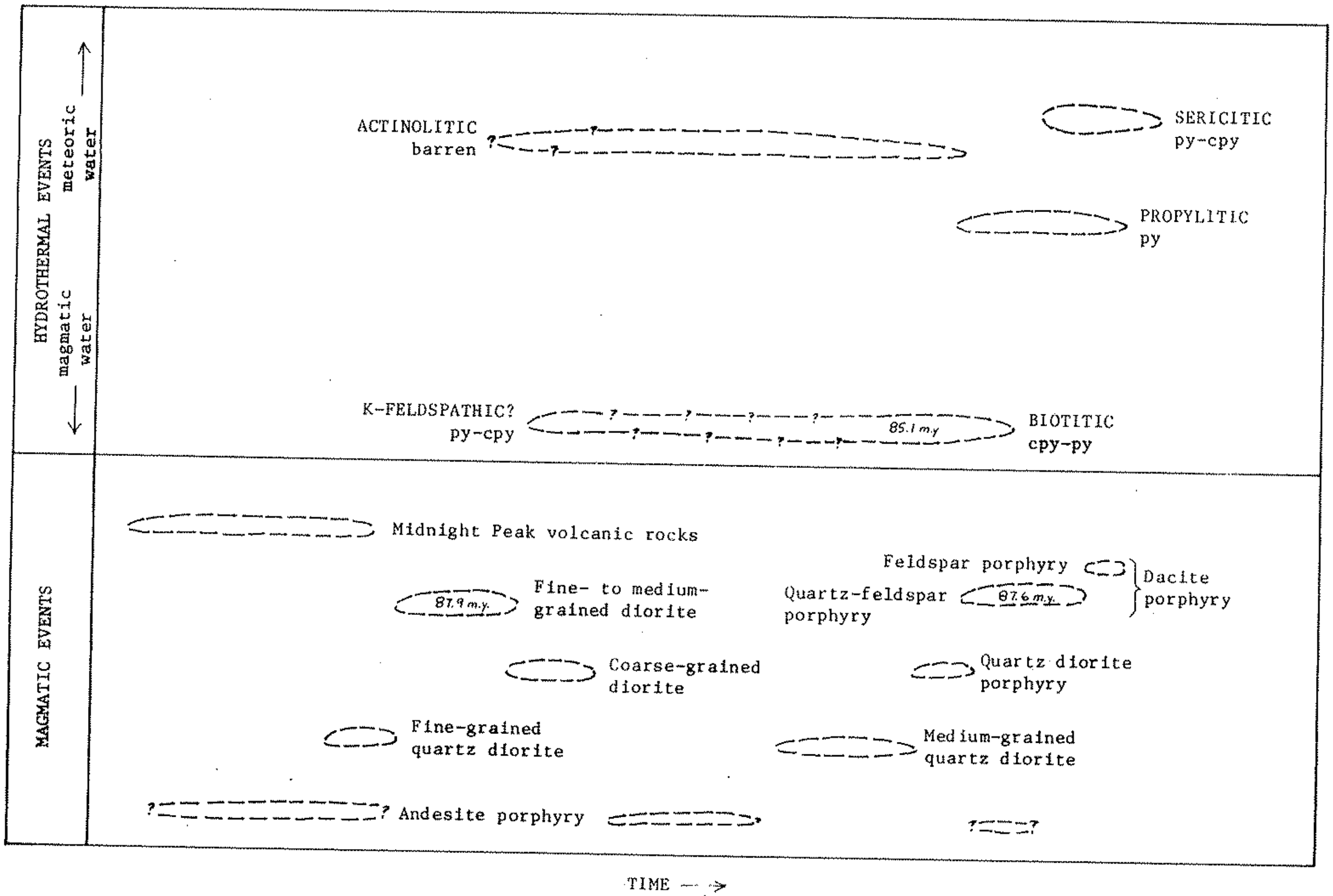
DISCUSSION

Oxygen and hydrogen isotopic studies of other porphyry deposits (Taylor, 1974; Sheppard and Gustafson, 1976) suggest that magmatic hydrothermal solutions cause biotitic alteration and the initial deposition of copper; whereas, sericitic and propylitic alterations involve exchange with meteoric water. Isotopic data are not available at Mazama, but a similar pattern is likely. Because actinolitic alteration appears to predate biotitic alteration and most copper mineralization, perhaps the actinolite resulted from convection of meteoric water during emplacement of the earlier intrusive phases.

As discussed above, biotitic alteration is spatially associated with medium-grained quartz diorite. Actinolite is generally absent from biotitized quartz diorite, although it commonly predates biotitization in older intrusive phases. Thus, significant magmatic-hydrothermal mineralization and biotitic alteration appear to be nearly coeval with the intrusion of medium-grained quartz diorite. This surge of magmatic fluid probably limited meteoric water and actinolitic alteration to the periphery of the system, where actinolitization affects phases as young as quartz diorite porphyry. Finally, the magmatic source waned, culminating in intrusion of minor dikes of dacite porphyry. Subsequently, meteoric water infiltrated the system, superimposing propylitic and sericitic alterations over the biotitic assemblages, and redepositing early copper (cf. Gustafson and Hunt, 1975; Henley and McNabb, 1978). Figure 17 summarizes the hypothesized temporal relationships.

The Mazama deposit differs somewhat from the porphyry deposits of the southwestern United States. At Mazama, the associated intrusive rocks are relatively mafic, potassium-poor, and primarily equigranular.

FIGURE 17. Paragenetic diagram showing hypothesized relationships between intrusive and alteration-mineralization events. Ages are K-Ar determinations considered reliable; see Table 2.



HYDROTHERMAL EVENTS
magmatic water
meteoric water
ACTINOLITIC
barren
SERICITIC
py-cpy
PROPYLITIC
py
K-FELDSPATHIC?
py-cpy
85.1 m.y
BIOTITIC
cpy-py
MAGMATIC EVENTS
Midnight Peak volcanic rocks
Feldspar porphyry
Quartz-feldspar porphyry
87.6 m.y.
Dacite porphyry
87.9 m.y.
Fine- to medium-grained diorite
Coarse-grained diorite
Quartz diorite porphyry
Fine-grained quartz diorite
Medium-grained quartz diorite
Andesite porphyry
TIME

Magnetite is abundant in the deposit, and molybdenite is sparse. Actinolite is abundant as an early alteration mineral, whereas K-feldspathic, sericitic, and argillic alterations are rare. Supergene enrichment is essentially nil. The Fawn Peak complex is mineralogically and chemically similar to intrusive rocks associated with porphyry mineralization in island arcs. Tennyson (1974) suggested that, at the time of eruption of the Midnight Peak, the area was on the landward side of a volcanic arc along the present site of the Cascade Range. The abundance of secondary biotite, rarity of K-feldspathic alteration, and low molybdenum values typical of porphyry deposits in island arcs (Gustafson, 1978, p. 602-603) also characterize the Mazama hydrothermal system. Guilbert and Lowell (1974, p. 101-102) implied that biotite, rather than K-feldspar, is the principal product of potassic alteration in more mafic host rocks.

The rarity of porphyritic intrusive rocks and the restricted sericitic alteration at Mazama suggest affinities with batholithic copper-molybdenum deposits such as Brenda, British Columbia, Butte, Montana, and Quartz Creek, Washington (Cheney and Trammell, 1975). The Mazama deposit differs from the batholithic model, however, in the presence of disseminated mineralization and a pyritic-propylitic halo. Clearly, Mazama has some characteristics of both end member porphyry and batholithic deposits.

SUGGESTIONS FOR EXPLORATION

Controls of mineralization and the proposed evolutionary model for the Mazama deposit suggest several exploration guides in searching for and evaluating similar deposits:

(1) Because mineralization may be related to several intrusive phases in a given complex, areas where such phases (and any associated mineralization) overlap have favorable exploration potential.

(2) At Mazama, significant mineralization might be genetically related to equigranular intrusive rocks. Whitney (1975, 1977) suggested that epizonal intrusions can release fluids gradually, without quenching of the remaining melt; therefore, exploration of porphyry systems should not concentrate solely in the vicinity of porphyritic intrusive phases.

(3) K-feldspathic alteration is commonly minor in quartz dioritic porphyry systems, and the more abundant secondary biotite is a more suitable guide to ore. However, its recognition in hand specimen may be difficult due to overprinting by chlorite.

(4) Mazama exemplifies an important variant of batholithic copper-molybdenum deposits (Cheney and others, in preparation). Sericitic alteration occurs in structural zones inside of biotitic alteration, whereas propylitic alteration forms a halo, with associated pyritic mineralization, typical of true porphyry deposits. Because sericitic overprinting and reworking of early copper are minor in batholithic deposits, biotitic alteration should be more closely associated with ore than in porphyry deposits.

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APPENDIX 1. Workings in and adjacent to the complex. Data compiled from this study; Huntting, 1956; Ross and Reed, 1972.

Abbreviations: Rock units as in Plate I
asp -- arsenopyrite
bn -- bornite
ca -- calcite
cpy -- chalcopyrite
gal -- galena
po -- pyrrhotite
py -- pyrite
sph -- sphalerite

LOCALITY AND REFERENCE	REPLACES	DESCRIPTION	EXTENT AND ASSOCIATED ALTERATION MINERALS	AGE RELATIVE TO OTHER ALTERATION MINERALS
BINGHAM, UT Lanier and others (1978)	Aug in quartz monzonite	Act - rims, pseudomorphs, or frayed laths, 0.4-0.6 mm	Peripheral; with chl	Pre-bio, pre-chl
ESIS, PAPUA NEW GUINEA Hine and others (1978)	Hb in granitic rocks; cpx, hb in andesite and basalt	Act, hb	Widespread; with bio, chl	?
HIGHMONT, B.C. Reed and Jambor (1976)	In quartz diorite and quartz porphyry	Act - veinlets, rosettes, patches	Primarily between bio and chl zones	?
KOLOULA 'A' SYSTEM, GUADALCANAL Chivas (1978)	Px in porphyritic tonalite	Act - rims, veinlets	Core; with quartz, alkali feldspar, cpx, magnetite	Coeval ?
MAMUT, SABAH, MALAYSIA Kósaka and Wakita (1978)	Hb in quartz monzonite porphyry	Trm, act, hastingsite	Core (but peripheral to fresh rock); with chl	Pre-ser, coeval with bio?
MORRISON, B.C. Carson and Jambor (1976)	Hb in dacite porphyry	Trm, act - pseudomorphs, aggregates, veinlets	Core, with bio	Pre-bio
PANGUNA, PAPUA NEW GUINEA Ford (1978)	Px in andesite	Act, hb - pseudomorphs, veinlets	Between bio and chl zones, with magnetite	Pre-bio, pre-ser
PLEYSUMI, PAPUA NEW GUINEA Titley (1978)	Hb in quartz diorite, granodiorite, and dacite porphyry	Act	Core, with bio	
RAY, AZ Phillips and others (1974)	Px in diabase	Composition not given -- aggregate?	?	Pre-bio ?
SCHAFT CREEK, B.C. Fox and others (1976)	Px in andesite	Act - pseudomorphs	Peripheral, with chl	?
N. TANAMA, PUERTO RICO Cox and others (1973, 1975)	Hb in quartz diorite porphyry	Hb - veinlets Trm - fibrous pseudomorphs	Core	Hb early (pre-quartz + magnetite); Trm latest

APPENDIX 2. DESCRIPTIONS OF ROCK UNITS

SEDIMENTARY AND VOLCANIC ROCKS

Descriptions of the stratified rocks that follow are from the author's mapping and limited petrographic study, augmented by the regional work of Barksdale (1975).

Winthrop Sandstone. Up to 4000 m of mottled light gray to buff arkose, with subordinate thin-bedded gray siltstone, make up the Winthrop. Interbeds of feldspathic and lithic graywacke are common, especially high in the section. The sandstones are medium-grained, massive to well bedded, and commonly cross-laminated. The well indurated rocks consist of subrounded quartz, plagioclase, and lithic fragments in a matrix of chlorite, epidote, quartz, biotite, and zeolites. By x-ray diffraction, Cole (1973, p. 57-60) verified the presence of laumontite and prehnite, indicating zeolite-facies metamorphism. Contact metamorphic biotite occurs up to 1 km from the complex, but is too fine-grained to be evident in hand specimen. The Winthrop contains fossil leaves of late Cretaceous age (Barksdale, 1975, p. 44).

Midnight Peak Formation. The Midnight Peak conformably overlies the Winthrop Sandstone, and is intruded by the 88-m.y.-old Fawn Peak complex. The lower, or Ventura member consists of approximately 600 m of well bedded orange to maroon siltstone, sandstone, and conglomerate, with minor volcanic breccia. Except for several exposures of the basal volcanic lithic graywacke southeast of the Fawn Peak complex, it rarely crops out in the map area.

Up to 3500 m of andesitic and subordinate dacitic breccias, tuffs, and flows comprise the upper member. Highly resistant, massive green-gray breccia, with epidotized clasts up to several centimeters across, predominates. Epidote-coated joints are common. Phenocrysts of saussuritized andesine or labradorite 0.5 to 2 mm long constitute 10 to 35 percent of the rock. Hornblende and pyroxene are subordinate and megascopically inconspicuous. In the andesites, the groundmass consists of plagioclase, amphibole, and magnetite; the dacites contain abundant quartz. Where contact metamorphosed, the volcanic rocks are dark gray, containing fresh plagioclase and lacking the epidotized fractures. A chemical analysis of one andesite is in Table 5.

INTRUSIVE ROCKS

The Fawn Peak complex consists of the first six phases described below and in Table 1. Dikes of andesite porphyry are probably more regional in extent. Figure 18 illustrates the intrusive phases. Table 5 gives major element analyses for selected samples; note, however, that most of the rocks are altered.

Fine-grained quartz diorite. Dark-gray, fine-grained quartz diorite crops out in the northwestern part of the complex. Most of the unit is equigranular, with 0.5 to 1 mm grains of andesine, hornblende, biotite, quartz, and minor augite, sphene, and magnetite. Rarely, plagioclase forms phenocrysts several millimeters long. Euhedral books of biotite are characteristic, although their abundance is highly variable.

Fine- to medium-grained diorite. The main phase diorite is a semi-concordant body with numerous dikes and sills at its northwestern and southeastern ends. It contains rare xenoliths of fine-grained quartz diorite near the contact. Fresh, dark gray diorite averages 65 percent subhedral calcic andesine, 30 percent subhedral hornblende, with minor augite, biotite, magnetite, sphene, and less than 5 percent quartz. Equigranular rock (1 to 4 mm) comprises the core of the body. Toward its periphery, the unit grades into seriate porphyritic rock, with phenocrysts of hornblende and plagioclase 1 to 3 mm long in a finer grained groundmass. Chilled diorite differs from Midnight Peak andesite in the abundance of mafic phenocrysts in the diorite.

Coarse-grained diorite. Coarse-grained diorite is mineralogically nearly identical to the fine- to medium-grained diorite. A distinct contact between the two units occurs in DDH-28; in map pattern, coarse-grained diorite cuts the finer diorites south of the Molly breccia (Plate II). The coarse-grained diorite contains subhedral grains of andesine 2 to 8 mm long which show a preferred orientation of c axes. Hornblende, augite, biotite, quartz, magnetite, and apatite are subordinate to, and form slightly smaller grains than plagioclase.

The cores of plagioclase grains in diorites and Midnight Peak andesites are locally clouded by numerous inclusions of magnetite less than 0.05 mm across. Rims of such grains are free of inclusions, as is plagioclase in all younger intrusive phases. This effect occurs irregularly within one-half km of the medium-grained quartz diorite; and is probably the result of contact metamorphism by the quartz

FIGURE 18. Samples of the intrusive rocks

1: Fine-grained quartz diorite, near the junction of Goat and Whiteface Creeks

2: Fine- to medium-grained diorite, 2 km north-northeast of Flagg Mountain

3: Chilled fine- to medium-grained diorite, 1.8 km southwest of Rendevous Mountain

4: Coarse-grained diorite, 2 km east of Flagg Mountain

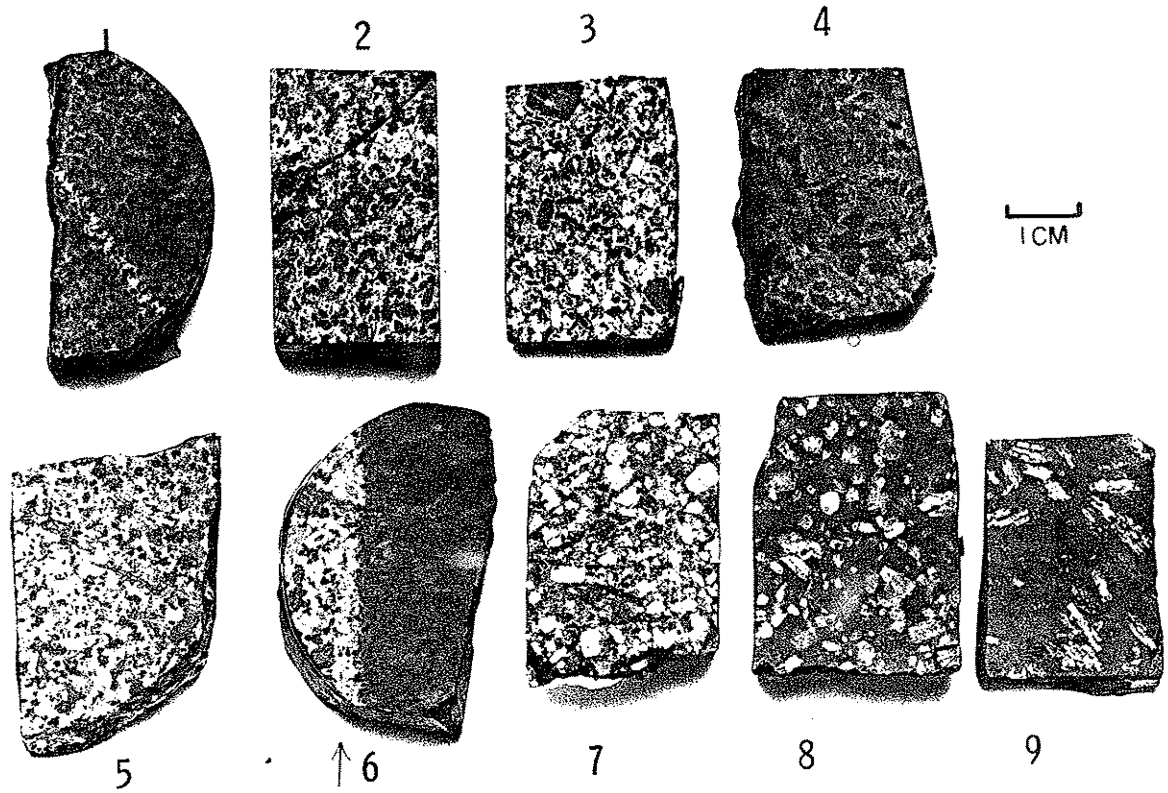
5: Medium-grained quartz diorite, DDH-9

6: Aplite, DDH-9 (arrow). These dikelets are normally not restricted to contacts

7: Quartz diorite porphyry, DDH-23

8: Dacite porphyry (quartz-feldspar porphyry subphase), 1.3 km north-northeast of Flagg Mountain

9: Andesite porphyry, 1.5 km southeast of Flagg Mountain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diorite. Heating permits the substitution of significant iron in the intermediate plagioclase, which exsolves as magnetite upon cooling. Outward diffusion of iron produces the inclusion-free rims (Poldevaart and Gilkey, 1954).

Medium-grained quartz diorite. Light gray equigranular quartz diorite forms a crescent-shaped body (in the western end of the complex) and dikes that cut both dioritic phases (Plate I and II). Quartz diorite contains 50 to 70 percent subhedral andesine, at least 8 percent interstitial quartz, and subequal biotite and hornblende, all 1 to 5 mm long. Magnetite and zircon are accessories. The rock is only weakly chilled near contacts with older units. Southwest of Flagg Mountain, the quartz diorite is locally subporphyritic with variable amounts of plagioclase phenocrysts.

Small dikelets of aplite and aplite-pegmatite cut only medium-grained quartz diorite and older rocks. They contain quartz and andesine, but lack mafic minerals. Larger dikelets are zoned, with aplitic edges and coarser-grained to pegmatitic cores. Myrmekitic textures locally characterize the aplite. Such dikelets are probably late differentiates of the medium-grained quartz diorite.

Quartz diorite porphyry. Quartz diorite porphyry crops out (1) 1.5 km north of Flagg Mountain; (2) near the summit of Fawn Peak; and (3) west of lower Fawn Creek. Abundant andesine and lesser hornblende and biotite phenocrysts impart a "crowded" texture. Quartz, mostly in the groundmass, constitutes 15 to 35 percent, and is commonly not megascopically evident. Rarely, quartz occurs as anhedral phenocrysts. Slight textural variations between the three bodies of quartz diorite porphyry suggest their correlation is not beyond doubt. The plagioclase phenocrysts in the two eastern bodies are smaller, and the hornblende more acicular, than in the westernmost plug.

Contacts between quartz diorite porphyry and medium-grained quartz diorite are gradational, but map patterns (Plate II) and the lower copper grades in the porphyry suggest that it is younger. The southeastern body of quartz diorite porphyry contains xenoliths of fine- to medium-grained diorite, and related dikes cut coarse-grained diorite.

Dacite porphyry. Strongly porphyritic felsic rocks with aphanitic groundmasses occur as volumetrically minor dikes, primarily in the Mazama prospect, and as the matrix of the Molly intrusion breccia. Dikes of the quartz-feldspar porphyry subphase cut all other intrusive units except fine-grained quartz diorite and andesite porphyry. Andesine laths, rounded quartz phenocrysts, and minor hornblende and biotite are set in light to medium gray groundmass of quartz, plagioclase, mafic minerals, and magnetite. Because hydrothermal alteration of the dikes varies markedly (even in the core of the deposit), several pulses of dacitic magma may have occurred.

Similar rock, lacking quartz phenocrysts, forms the matrix of the Molly breccia (Figure 4). This feldspar porphyry subphase contains xenoliths of quartz-feldspar porphyry.

Andesite porphyry. Intermediate dikes up to 1 m thick commonly trend east-northeasterly to northeasterly. Because they are significantly more abundant in the country rocks, some probably predate the intrusion of the complex. Although some andesite dikes are strictly aphanitic, most contain aligned phenocrysts of labradorite 2 to 8 mm long in an aphanitic to fine-grained groundmass of plagioclase, amphibole, biotite, and locally quartz. Rarely, phenocrysts of hornblende also occur. Plagioclase porphyry dikes cut only diorites; whereas, hornblende-plagioclase porphyry intrudes quartz diorite porphyry on Fawn Peak.

TABLE 5. Major element analyses of intrusive rocks and Midnight Peak andesite. All analyses by X-ray Assay Laboratories, Don Mills, Ontario.

	MIDNIGHT PEAK ANDESITE	FINE- TO MEDIUM-GRAINED DIORITE		COARSE-GRAINED DIORITE	MEDIUM-GRAINED QUARTZ DIORITE	QUARTZ DIORITE PORPHYRY		DACITE PORPHYRY	ANDESITE PORPHYRY
Sample No.	274A	120	190	349	260	320	948	430	348
Alteration Zone	Actino-lite	Actino-lite	Actino-lite	Biotite-chlorite	Actinolite-chlorite	nearly fresh	Seri-cite	Biotite-chlorite	Actinolite-chlorite
SiO_2	50.8	49.7	56.1	52.2	64.6	60.8	62.9	64.5	59.3
TiO_2	1.01	1.26	0.83	0.90	0.55	0.58	0.43	0.43	0.90
Al_2O_3	17.6	18.1	17.4	18.6	16.3	16.7	15.4	15.5	17.0
ΣFe as FeO	7.86	10.8	6.39	6.70	3.95	4.62	3.44	3.54	6.38
MnO	0.18	0.19	0.11	0.14	0.09	0.08	0.01	0.03	0.14
MgO	3.29	5.46	3.52	3.01	1.92	2.67	1.56	1.91	1.44
CaO	9.06	9.49	7.37	5.83	3.56	5.69	2.36	3.40	4.29
Na_2O	3.73	3.34	4.53	3.97	4.93	5.00	5.18	3.92	5.39
K_2O	0.79	0.29	1.02	3.15	0.49	0.63	2.10	2.76	1.17
P_2O_5	0.41	0.26	0.29	0.39	0.15	0.18	0.13	0.13	0.33
Lost on igniting	3.12	0.91	1.12	2.85	2.05	1.88	4.49	1.14	2.22
TOTAL	97.85	99.70	98.58	97.74	98.59	98.83	98.09	97.26	98.56

Analysis by X-ray Assay Laboratories, Don Mills, Ontario

APPENDIX 3. RECOMMENDATIONS FOR FURTHER EXPLORATION OF THE FAWN PEAK COMPLEX

The Fawn Peak complex contains a significant resource of low-grade, incompletely explored copper mineralization. The controls of mineralization presented in this paper suggest that future exploration might aim at areas peripheral to the higher grade zones presently delineated:

(1) The southwestern portion of the zone of 0.2% copper in Plate II is poorly defined to date. Only DDH-30 intercepts this lobe; drilling to the northeast and southwest is recommended. The outcrops 150 m south-southwest of DDH-30 contain some of the highest copper grades on the surface. Ore controls as presently understood do not account for this lobe of mineralization.

(2) Intrusive contacts and associated mineralized zones dip easterly (Plate III, Figure 14). Section A-A' suggests that the better grade zones thin and disappear with depth. However, the trend of the 0.2% zone in Section B-B' implies the presence of significant mineralization below the bottom of DDH-6. The unexplored area east of DDH-14 probably contains better grade mineralization near the contact between coarse-grained and fine- to medium-grained diorites.

(3) The modes of origin hypothesized for both the American Flag and Molly breccias suggest that larger intrusions, possibly mineralized, may lie at depth. The Molly pipe probably overlies a body of feldspar porphyry, which postdates most mineralization. (The copper in the Molly pipe may have been cannibalized from a mineralized zone intersected during brecciation.) Drilling east and northeast of DDH-32 might clarify the poorly understood distribution of sulfide-rich matrix within the pipe

(p. 11). Moreover, the percussion holes east of the Molly workings (Figure 5) intercepted poor copper but significant molybdenum values; this trend and the sericitic alteration suggest a slight possibility of supergene copper mineralization at depth in this area.

The American Flag breccia is weakly mineralized, but may be a guide to a presently unknown mineralized intrusion beneath Flagg Mountain. Moreover, because this breccia is southwest of the synclinal axis, its geometry might clarify the age of tilting of the deposit. The workings are presently inaccessible, and drilling would require helicopter support.