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SULPHIDE MINERALIZATION, ZONING AND PARAGENESIS AT WHIPSAW CREEK, PRINCETON AREA, SOUTHERN BRITISH COLUMBIA

by
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Mineralography 409 Report

8th April, 1971

ABSTRACT

Examination of 18 mineral showings around Whipsaw Creek has revealed pyrite-molybdenite-chalcopyrite mineralization in a central stockwork structure, and pyrite-sphalerite-chalcopyrite-galena mineralization in a peripheral quartz vein and breccia zone network. Sulphides and gangue are zonally arranged, suggesting decreasing temperature outward from a heat source. Sulphide textures, peripheral breccias and quartz veins show a complex paragenesis of three brecciation events interjecting hydrothermal mineral deposition, suggesting decreasing temperature (650° to 200°C) with time.

Sulphide mineralization, zoning, paragenesis, and hydrothermal alteration are final expressions of late stage magmatic activity of a central porphyry body, not presently exposed. The deposit is a Porphyry Copper type with peripheral lead-zinc mineralization.

SUMMARY

1. Examination of 18 exposures of sulphide mineralization in the Whipsaw Creek area was carried out in 1970.

2. Field evidence indicates that copper-molybdenum mineralization occurs in a central stockwork structure, and that copper-lead-zinc (-gold-silver) mineralization occurs in a peripheral network of quartz veins and breccia zones.

3. Sulphide and gangue mineral zoning of central quartz + pyrite + molybdenite + chalcopyrite to marginal sphalerite + galena + carbonate has been delineated.

4. Examination of 16 polished sections substantiates field inferences as to a complex paragenetic history of deposition from 600° to 200°Centigrade.

5. Mineral deposition followed initial fracturing and three suceeding brecciation events, producing the paragenesis: molybdenite--pyrite--sphalerite + chalcopyrite--chalcopyrite--galena.

6. Mineralization, zoning and paragenesis are genetically related to a porphyry intrusive underlying the stockwork.

7. Both lead-zinc-silver-gold and copper-molybdenum are of economic potential.

RESPECTFULLY SUBMITTED

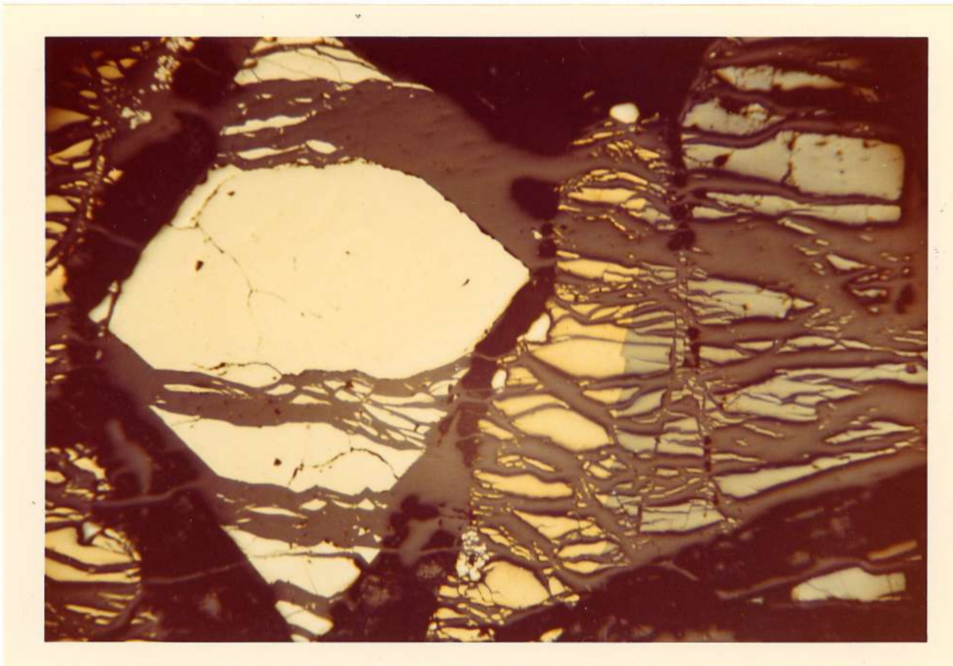
Phillip Anderson (Geologist)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF PLATES

PLATE 1



Photomicrograph of brecciated sulphides, W showing, Whipsaw Creek. Pyrite (white), chalcopyrite (yellow) and sphalerite (off gray) have been extensively shattered by later quartz veining (here crosswise to the sulphide "grain"). Large brecciated pyrite cube is 2 mm wide. Polarized light.

1. INTRODUCTION

(a) Purpose and Scope

This report is the description and interpretation of sulphide mineralization and its associated features at Whipsaw Creek, Princeton area, southern British Columbia. All other major aspects of the Whipsaw Creek geology have been discussed in detail by the author separately in an unpublished thesis (Anderson, 1971).

The results of this report are an integral part of an intensive study carried out by the author on the geology of the upper Whipsaw Creek area in the summer of 1970. In this connection, the valuable assistance of R.B. Stokes and D.G. Leighton of Stokes Exploration Management Co. Ltd. is gratefully acknowledged. This report is a compilation of both extensive field data collected by examination of 18 exposures of sulphide mineralization (showings), and mineralographic data obtained by examination of 16 polished sections.

Whipsaw Creek is a western tributary of the Similkameen River and lies between the Similkameen River to the south and the Tulameen River to the north. The study area, located 16 miles south-west of Princeton, includes the upper 2½ miles of Whipsaw Creek lying above its Fourtyseven Mile Creek tributary. The study area corresponds to the "detailed thesis area" shown on figure 2 (abstracted from Anderson, 1971). The study area is seven square miles, extending from 49°15'20" to 49°17'40" north latitude and from 120°43'00" to 120°46'30" west longitude.

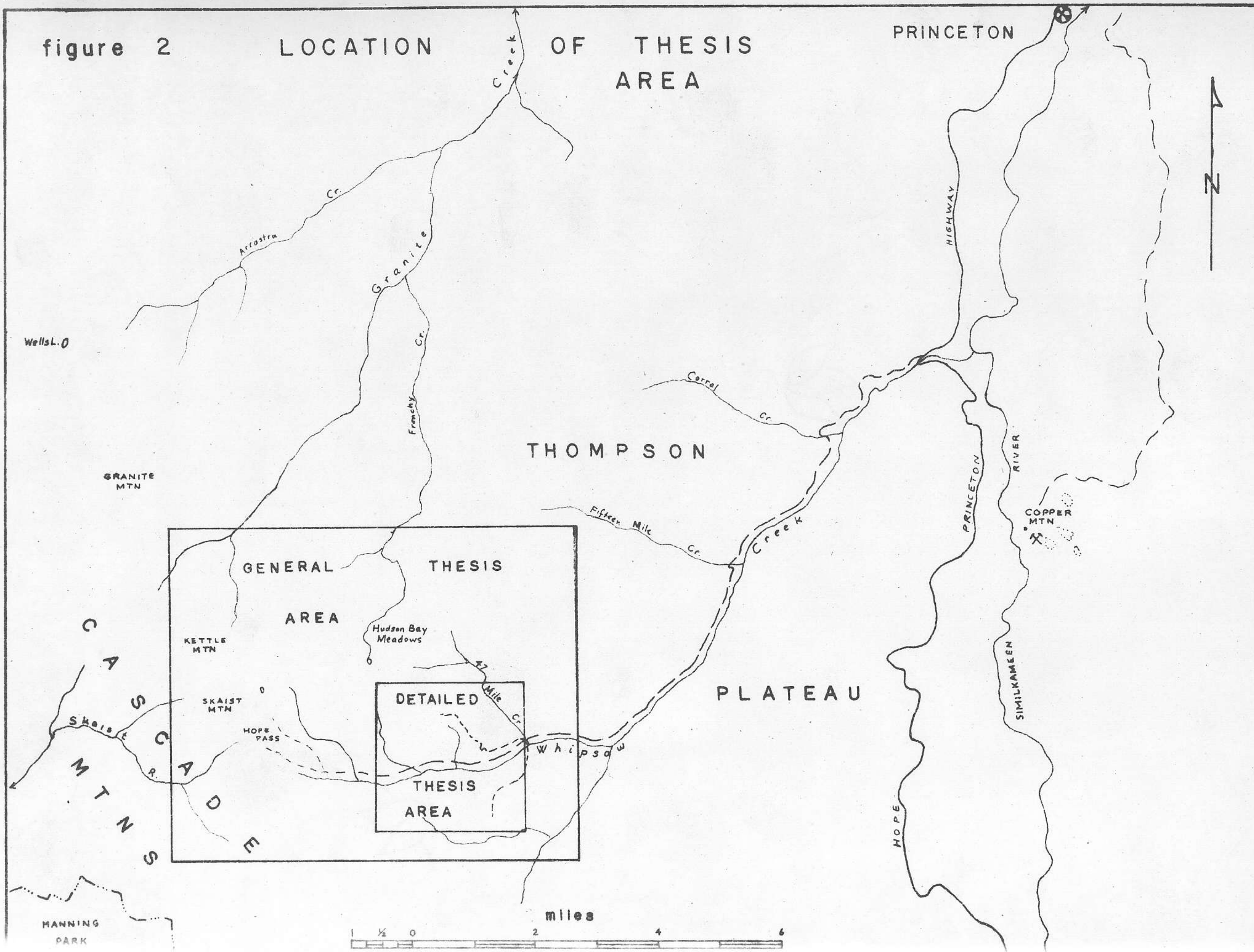


figure 2 LOCATION OF THESIS AREA
PRINCETON
Creek
Arrastra Cr.
Granite
Frenchy Cr.
Wells L.
GRANITE MTN
HIGHWAY
Corral Cr.
THOMPSON
Fifteen Mile Cr.
Creek
PRINCETON
RIVER
COPPER MTN
GENERAL THESIS AREA
KETTLE MTN
Hudson Bay Meadows
47 Mile Cr.
DETAILED THESIS AREA
SKAIST MTN
HOPE PASS
Skaist R.
Whipsaw
PLATEAU
SIMILKAMEEN
HOPE
CASCADE MTNS
MANNING PARK
miles
1 ½ 0 2 4 6
N

Figure 1, an expanded scale (1"=1000') of this area, is the Sulphide Mineral Zoning map (in pocket).

(b) History

Whipsaw Creek was first explored for its mineral potential and gained interest when placer gold and platinum were discovered there in the late 1800's. It became an active area when lead-zinc deposits were discovered on either side of Whipsaw Creek by about 1915. These small lode deposits were mined for silver and gold up to about 1950.

H.M.A. Rice, in compiling the Princeton memoir, visited the area and described veins and narrow breccia zones comprising what he called a "belt of shearing" along the east side of the Eagle "Granodiorite". In the mineralized structures he records a complex history of cementation and brecciation, which will be discussed later. The reader is referred to Rice's description (1947, p102-104) of the vein paragenesis as well as the complete list of references he gives, rather than repeating them here.

The most recent announcements are by Newmont Mining Corporation Ltd., who plan to bring the Ingerbelle and Copper Mountain properties into production (see figure 2). Mineralization in the Whipsaw Creek area has not yet proven to be of economic grade.

(c) Geologic Setting

The geology of the upper Whipsaw Creek area has been discussed in considerable detail by the author elsewhere (Anderson, 1971) to whose work this section is referenced. Mineralization occurs near the contact of the Eagle "Granodiorite" (renamed the Eagle Tonalite-Gneiss Complex by Anderson, 1971) and the Upper Triassic Nicola Group.

The Eagle Complex is a long linear belt of foliated granitoid and gneissic rocks extending from near the International border (see Rice, 1947, map 888A) about 70 miles north-north westerly toward Ashcroft. The Nicola Group, which lies to the east of the Eagle Complex, generally consists of weakly metamorphosed and gently deformed volcanic flows, pyroclastics, tuffs and intercalated sediments covering vast areas of the interior plateaus.

In the upper Whipsaw Creek area, bedding in the Nicola Group dips steeply westward (155°/65° SW). Rocks are predominately hornblende gneisses and schists which increase from greenschist grade to amphibolite grade of metamorphism westward toward the Eagle Complex. Gneissosity paralles bedding. Minor folding only affects incompetent sections of the stratigraphy. Gneissic banding and schosity in the Eagle Complex are conformable with structures in the Nicola Group and the actual contact of the two units is gradational, forming an 800 feet wide Migmatite Zone.

A suite of tonalite to granite and alaskite dykes and sills, pegmatite and aplite veins, and a separate suite of plagioclase porphyry dykes and sills cut both the Eagle Complex and the Nicola Group rocks. Porphyry bodies are most important to the present discussion for they are directly associated with the processes of mineralization and alteration. Porphyry bodies are highly deuterically altered biotite-plagioclase dacite porphyries averaging five to 30 feet in width. In a broad sense, porphyry sills and dykes are zonally arranged around a centre of porphyry intrusion. Peripheral porphyry bodies are relatively basic (mafic-rich dacites) whereas central porphyry bodies have been found as acidic as sanidine quartz-latite. This zonal arrangement is taken to reflect fractionation of a common porphyry magma during its upward intrusion (Anderson, 1971).

Sulphide mineralization and its associated features in the Whipsaw Creek area ~~is~~ are an expression of late stage magmatic activity of this central porphyry intrusion. The porphyry body (stock size) is not presently exposed at the surface, bnt its existence at a shallow depth has been inferred from a variety of features, including porphyry zoning. In the Whipsaw Creek area, sulphide mineralization is not a contact phenomenon of the Eagle Complex, since this body is not of intrusive origin (Anderson, 1971). This situation is unfortunate in the sense that similar mineralization is not necessarily to be expected along the length of the Nicola-Eagle contact, as would be the case if mineralization were of the contact-metamorphic type.

2. MINERALIZED STRUCTURES

Although mineralization in the Whipsaw Creek area is genetically related to a single magmatic event, sulphides have a variety of ocurrences. Specifically, six different catagories of mineralized structures have been recognized:

1. a central copper-molybdenum stockwork;
2. large quartz veins up to ten feet wide;
3. smaller veins or fracture fillings;
4. long linear breccia zones up to 100 feet wide;
5. mineralization intrinsic to porphyry bodies;
6. mineralization in limestone ("skarn").

The stockwork, quartz veins, fracture fillings and breccia zones are all related by the fact that they form a suite of sulphide and gangue minerals filling fractured parts of the host rock. That is, they are expressions of the same mineralizing process, only developed to different degrees. Fracture fillings are the least developed structures,quartz veins more so, and breccia zones are highly developed, showing repeated events of breakage and filling. The stockwork corresponds to lesser developed structures -- fracture fillings and quartz veins.

Mineralization in porphyry bodies and in limestone is distinguished from the above types because sulphides are disseminated throughout the host rock, and do not occur in veins. The morphology of these six different structures will now be discussed, treating the simplest types first.

Mineralization in porphyry bodies is syngenetic and usually occurs in the groundmass as disseminated sulphides interstitial to plagioclase phenocrysts. Pyrite is essentially always present, but rather than chalcopyrite, copper sulphides are usually bornite or chalcocite with supergene covellite. Molybdenite has not yet been positively identified as intrinsic to porphyries, although it is to be expected. It is logical to assume that the last watery fluid (after most of the porphyry body had crystallized), which was responsible for deuteric alteration, also caused syngenetic mineralization of the porphyries.

Mineralization in the limestone bed (see figure 1, L and S showings) is somewhat unusual. The mineralized rock, especially in the S showing, is a skarn in all respects (calcium-silicate minerals, calcite and sulphides) but has not formed by contact metamorphism, pyrometasomatism, or other such methods usually ascribed to mineralized skarns; rather, mineralization has been introduced by quartz veins which cut the limestone bed, and is not related to an intrusive body. This explains why mineralization in the limestone is irregular (Rice,1947, p103-104).

Quartz veins and fracture fillings are the most common type of mineralized structure, making up about half of the showings in the Whipsaw Creek area. Features of quartz veins are entirely gradational into those of breccia zones for reasons which will soon become apparent. The distinction between a quartz vein and a fracture filling is somewhat arbitrary, but fracture fillings generally are narrow sheared zones, one to three feet wide, containing ground-up altered host rock without extensive silicification, whereas quartz veins, although formed by the same process, are wider zones (up to ten feet) in which quartz dominates. Mineralization is usually pyrite + sphalerite (dominant) ± chalcopyrite ± galena.

The central copper-molybdenum stockwork (MJ showings) consists of a series of veins, veinlets and microveinlets (see Lowell and Guilbert, 1970, for distinction) filled primarily with quartz and sulphides. The stockwork structure can be visualized by considering these veins and veinlets as an interconnecting network forming a matrix in which unrotated polygonal blocks of host rock (Eagle tonalite) lie. Veins, commonly half an inch to three inches in width, are filled with vuggy quartz and pyrite. A thin layer of molybdenite (with sericite) often lines the veins; chalcopyrite occurrence is sporadic. Alteration envelopes around a one inch vein may be one to several feet wide. Hypogene sulphide minerals are singuarly pyrite, molybdenite and chalcopyrite in the average ratios of 10-50:1:1.

Breccia zones are one of the most interesting and revealing structures, for they show a complex paragenetic history. The zones are up to 100 feet wide and several thousand feet long; some are narrower and discontinuous (figure 1). These zones are associated with an extremely high density of fracturing (with slickensiding) near their margins. Intensity of fracturing increases toward the centre where extensive fragmentation occurs. Breccia zones record repeated events of shattering followed by sulphide and gangue filling.

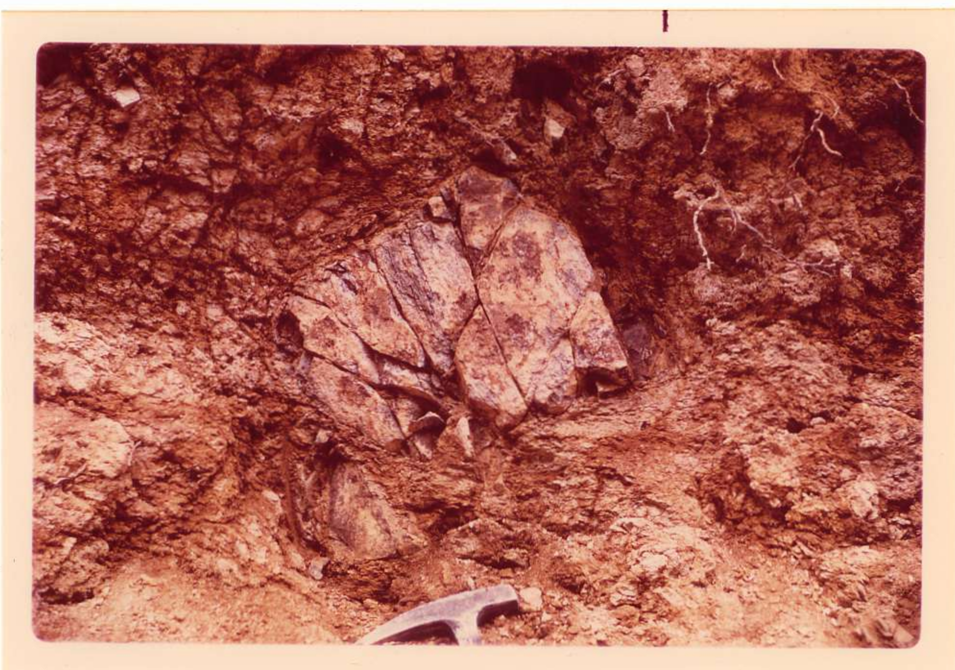
Distinction between breccia zones and quartz veins (or fracture fillings) is not always a simple matter. Since every quartz vein and fracture filling shows at least one period of brecciation, it is possible to classify every vein as a breccia. However, the author uses three criteria to distinguish "true breccia zones" from other features:

1. breccia zones are considerably larger features,
2. they contain rotated and rounded fragments,
3. characteristically, sandy brown ankerite (or, in some cases, white dolomite and calcite -- Appendix I) forms a matrix to rotated blocks.

The introduction of carbonate into the zones has been the latest stage of vein history (see paragenesis) and has produced a "true breccia", since carbonate introduction is associated with granulation and, particularly, rotation of fragments. Breccia zones contain pyrite (extensively shattered as in plate 1), sphalerite, galena and other minor sulphides. Weathering of breccia zones, especially where ankerite rich (plates 2a and 2b), is often extreme, making interpretation difficult.

It is evident that the distinction between fracture fillings, quartz veins and breccia zones made above in order to classify structures, is artificial if one considers their genesis. They merely represent different stages in the development of intensely fractured channelways produced by escaping fluids and volatiles. It has repeatedly been shown (for example: Sales, 1954; Perry, 1961; Burnham, 1967; Anderson, 1971) that porphyry magmas are unusually rich in volatiles, and their last liquid fraction after

PLATE 2 (a) Weathered fractures in breccia zone, B showing. Breccia consists of silicified fragments of Nicola rocks and porphyry in a friable orange ankerite cement. Fracture intersection defines trend of this breccia zone - north south.



(b) Silicified block in breccia zone, B showing. Partly rounded block is a fragment of silicified Nicola schist rotated in the ankerite matrix. Blocks such as this show earlier internal brecciation. Fragment sizes range from several feet to millimeters.

most silicates have crystallized, is greatly enriched in metals and sulphur (Sales, 1954). Volatile pressure can therefore increase to the point where it exceeds load pressure, so explosive escape ensues (Perry,1961).

Since brecciation has occurred several times in the area, structures which record all explosive events will be more developed (breccias) than those which record only the first, and possibly second events. If, therefore, the initial explosive event which opened the first channelways at a particular place was confined to a narrow shear zone, the opening would quickly be "welded" by deposition of hydrothermal minerals, and consequently sealed to later events. A fracture filling results. If initial brecciation caused a much wider zone of weakness, openings could persist through several suceeding periods of brecciation, until the final ankerite filling occurred. The structure is then a breccia zone.

The stockwork has originated in a fundamentally different manner. there has not been explosive release of volatiles or significant rotation of blocks. Perry (1961, p367) gives an excellent description of a stockwork, which suggests its passive formation:

> "Rock breaks in a variety of ways and complete fragmentation often occurs without rotation of individual pieces. A finely broken rock mass may fit into a tight jig-saw pattern, each fragment having mutually concordant boundaries with its neighbours. The result is a stockwork of innumerable cracks that, once cemented by mineralization, forms a complicated intersecting network of individually insignificant but collectively important seams and veinlets."

The vuggy nature of the veins indicates that the stockwork has formed by a removal of material at depth (E.M. Anderson,1936), thus creating additional space so that hydrothermal minerals may fill the open veins. An overall volume increase of about 1 to 5% has occurred. The stockwork has therefore resulted by slight subsidence of a "hood" of rock presumably overlying a crystallizing porphyry magma (cf. Sales' (1954) sub-hood cupola development and Anderson's (1936) cauldron subsidence).

3. HYDROTHERMAL ALTERATION

(a) Stockwork

Hydrothermal alteration developed in the MJ stockwork is typical of that found in Porphyry Copper deposits (see Lowell and Guilbert, 1970, p392). However, insufficient is known, at present, about the extent and boundaries of alteration facies in the stockwork to give an extensive discussion. Recently, an excellent paper by Rose (1970) has done much to clarify the concepts of hydrothermal alteration. It is his scheme that will be adopted, rather than the more involved (and in some cases unnecessarily complex) ones of Lowell and Guilbert (1970), Meyer and Hemley (1967), Burnham (1962) and Creasey (1959 and 1966).

Rose (1970) suggests that hydrothermal alteration facies, outward from the core, are biotite-orthoclase type, quartz-sericite type and propylitic type, indicating that argillic alteration does not constitute a hypogene facies. At the present level of erosion, a core of biotite-orthoclase alteration has not been found, although its recognition is hampered by the presence of pre-mineralization pegmatite dykes. Quartz-sericite characterizes the alteration type developed in the stockwork. It is not pervasive but forms envelopes from one inch (for microveinlets) to several feet wide (for veins), depending on the width of the opening. Quartz occurs with pyrite in the centre of veins whereas sericite lines veins and is disseminated into the host rock.

Surrounding quartz-sericite alteration around veins is a propylitic alteration facies of quartz + epidote + chlorite +

pyrite + calcite + sericite + albite (Meyer and Hemley, 1967, p170; Anderson, 1971). Though propylitic alteration is, in places, pervasive, it more characteristically occurs as vein fillings in a propylitic zone peripheral to the central quartz-sericite alteration of the stockwork. Argillic "alteration" is abundant to depths of several hundred feet, but is considered to be a supergene effect.

From the above brief review of stockwork alteration (see Anderson, 1971 for more detail), it is evident that there are two spatially distinct but genetically related processes controlling alteration types -- zoning and paragenesis. Around any one vein, there are sequential envelopes of quartz-sericite and propylitic alterations, indicating that the chemistry of the vein fluids (see Sales, 1954; Burnham, 1962 and 1967; Lowell and Guilbert, 1970) changed with time. Although the author does not wish to initiate a discussion of vein fluid chemistry here, it is intuitive that deposition of large quantities of hydrothermal minerals from a solution must substantially alter its chemistry, therefore favouring deposition of a new assemblage with time.

Alteration zoning of propylitic around quartz-sericite is most readily understood as reflecting the same change of solution chemistry outward from a heat source as does paragenesis reflect a change with time. Propylitic alteration grades outward indistinguishably into gangue minerals of the surrounding quartz vein and breccia network.

(b) Gangue Minerals

The paragenetic history of gangue deposition in the quartz vein and breccia zone network surrounding the central stockwork is complex and reserved for later discussion. Zoning, however, is substantially more simple.

The main gangue minerals are simply quartz and the carbonates calcite, dolomite and ankerite (see Appendix I). Quartz tends to be an early mineral and is most abundant closer to the stockwork; carbonates tend to be late and proliferate in the outer margins of detectable mineralization (N showing, figure 1), although this is not a hard and fast rule (e.g. B showing). The simple gangue mineralogy is complicated in "skarn" showings (S and L) by the presence of calc-silicate host rock minerals.

As well as depositing gangue minerals, solutions have caused hydrothermal alteration in surrounding "wall" rocks. This fact is rarely mentioned in the multitude of papers on alteration in porphyry copper deposits and has only been seen discussed by Meyer et al. (1968) in regard to Butte, Montana. Commonly it is lumped together as "marginal propylitic alteration". Though a propylitic assemblage is common, the author has observed varying types and degrees of silicification, chloritization, pyritization, sericitization, calcification and ankeritization differing greatly from a propylitic assemblage. Silicification halos around breccia zones are about 100 feet wide; those of quartz veins are commonly five to ten feet wide.

4. SULPHIDE MINERALOGY

Having discussed the variety of occurrences of sulphide minerals in different structures, it seems remarkable that each sulphide should display the same habit and brecciation features in every showing in which it occurs. It is therefore possible to generalize entirely on the textures and structures of sulphides, rather than discussing their variations.

In Appendix I, polished sections of representative samples from eight showings which revealed sulphide mineralization best, are described in detail. As well, six thin sections of brecciated veins, and two polished thin sections of veins in the stockwork have been examined but not tabulated. It is on these studies that the results of "sulphide mineralogy" are based.

(a) Pyrite

Pyrite characteristically forms euhedral cubes one to two millimeters in size that are most closely associated with euhedral quartz crystals. However, it is extremely rare to find a pyrite cube intact. Most have been extensively granulated (plate 1), partly replaced by later minerals, or both. Pyrite contains numerous inclusions of quartz (plate 4), occasionally sphalerite, and rarely pyrrhotite or gold.

Since cubic pyrite is the earliest sulphide in the vein and breccia zone network, it is the most extensively brecciated mineral (figure 5), showing breakage during all three brecciation events, B1, B2 and B3 (figure 4). Ankerite brecciation has frequently reduced pyrite to a mortared paste of tiny angular grains (for example, HF showing, Appendix I). An interesting feature is that pyrite becomes more markedly discordant to later sulphides as one goes outward to marginal parts of the vein and breccia network. This due to both zoning and paragenesis.

A different type of pyrite is found as the latest sulphide in the network. It occurs as euhedral pyritohedra (not cubes) introduced with ankerite, and is best displayed in the L showing. To the author this implies that there is a fundamental difference in composition or paragenesis governing the formation of pyritohedra rather than cubes, but no confirmation of this hypothesis has been found in the literature.

(b) Molybdenite

Molybdenite occurs almost solely in the central stockwork but is rarely found outward to the S showing (figure 1). Characteristically it forms small flakes which line the borders of veins and veinlets; occasionally it forms inclusions in pyrite.

Molybdenite is most likely the earliest sulphide, but is largely contemporaneous with pyrite (figure 5). It is distinctly earlier than chalcopyrite, which is seen to replace both pyrite and molybdenite in the stockwork veins.

(c) Sphalerite

Sphalerite competes with pyrite in being the most abundant sulphide in veins, and becomes dominant over pyrite in one zone (figure 1). It is characteristically absent in the stockwork. Sphalerite forms an interlocking network of grains, which nearly everywhere show consistent 10% inclusions of chalcopyrite. These inclusions (plates 3 and 4) form blebs and trains which are, in places, crystallographically aligned, but elsewhere are randomly oriented.

Certain suites of inclusions fit every one of Ingerson's (1955, p360) criteria for exsolution, and are therefore taken to be formed by exsolution. Other suites of chalcopyrite inclusions are clearly related to replacement of sphalerite, being more abundant near grains of chalcopyrite. Similarly, chalcopyrite frequently occurs as grains with a totally ambiguous "replacement" relation to sphalerite, and can only be taken to indicate simultaneous deposition. These grains are more common where chalcopyrite inclusions indicate exsolution.

Elsewhere, chalcopyrite evidently has replaced sphalerite (for example, plate 4, or S and R showings, Appendix I), showing "patchwork replacement" texture, cuspate boundaries and so forth. Of very minor occurrence is sphalerite which apparently replaces chalcopyrite (figure 5). The precedence, contemporaneity and suceedence of chalcopyrite relative to sphalerite is understood by considering sphalerite deposition as short-lived and voluminous (figure 5), whereas chalcopyrite deposition was long-lived and dissociated (in accordance with relations in the stockwork).

Sphalerite shows two periods of brecciation (figure 4); it is therefore less fragmented than pyrite and approxiametely equally fragmented as quartz (figure 5).

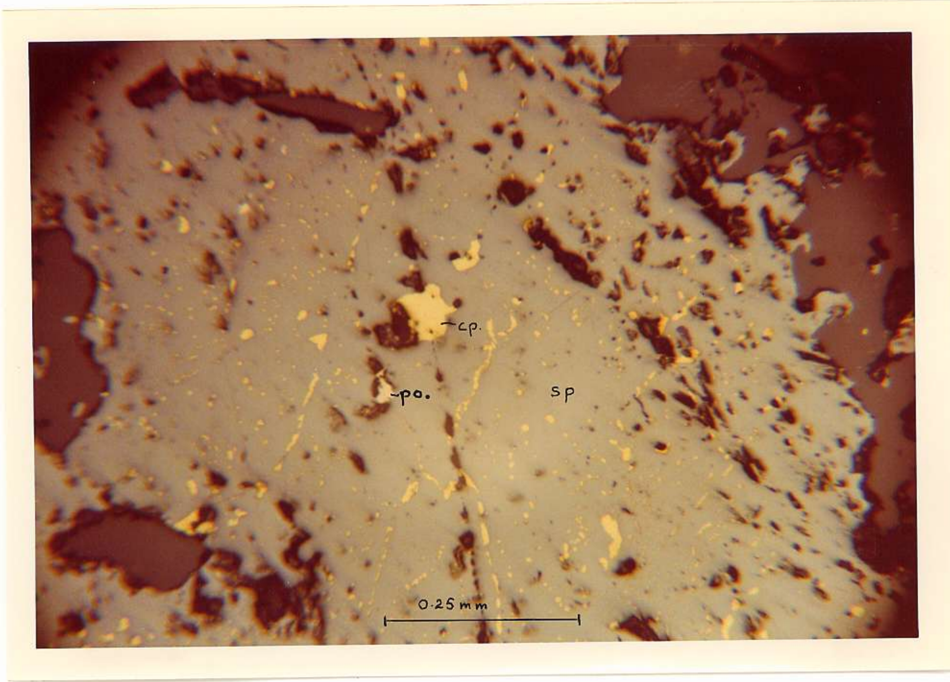


PLATE 3 Sphalerite textures, M showing. Sphalerite (sp) contains exsolution blebs of pyrrhotite (po), exsolution blebs and trains of chalcopyrite (cp) and is also replaced by chalcopyrite.

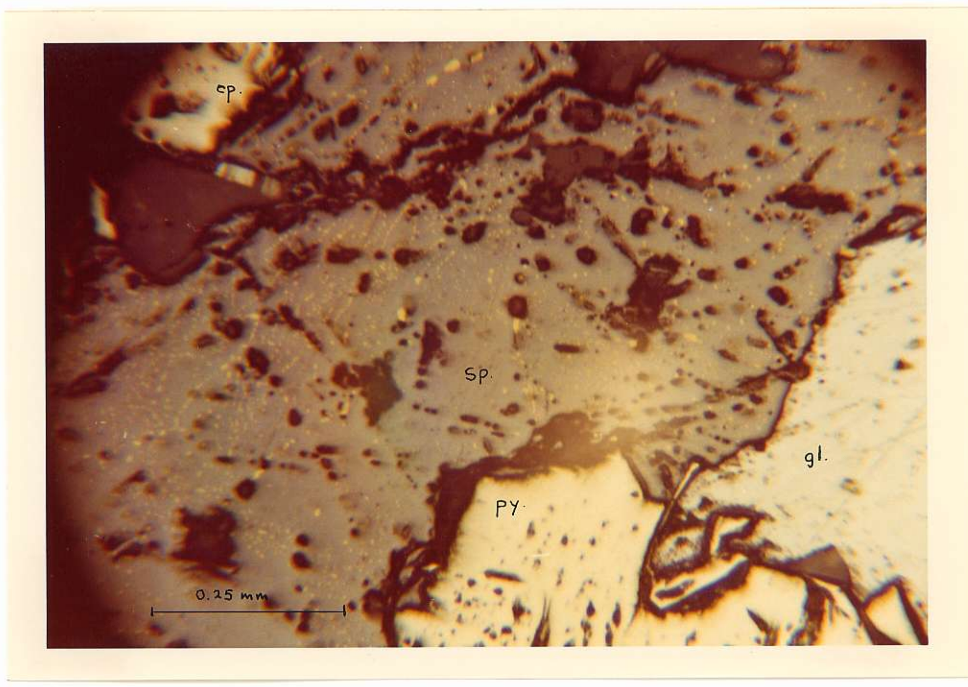


PLATE 4 Replacement textures, F showing. Photomicrograph shows sphalerite (sp) replacing pyrite (py); and galena (gl) replacing both sphalerite and pyrite. Chalcopyrite - sphalerite relation is freguently ambiguous. (plane polarized light).

(d) <u>Chalcopyrite</u>

Many features of chalcopyrite have been discussed in relation to sphalerite. Chalcopyrite is the only non-major sulphide occurring in nearly all showings in the area (figure 1). It is characteristic of both the stockwork, where it replaces molybdenite and pyrite, and the vein and breccia network, where it replaces pyrite and sphalerite. It is moderately brecciated (two periods).

Chalcopyrite is a "garbage bag" for many sulphides whose occurrence is too minor to be discussed separately. Chalcopyrite contains inclusions, in order of abundance, of pyrrhotite, chalcocite, bornite, tetrahedrite (tennantite?) and rarely gold. Since the copper minerals only occur as inclusions in chalcopyrite, they most likely formed by exsolution. Pyrrhotite is interesting in that it occurs as inclusions in sphalerite mainly (plate 3), in chalcopyrite and in pyrite, but never occurs free. This also suggests exsolution. Finally, chalcopyrite contains small star-shaped inclusions of sphalerite indicating exsolution that is consistent with the common chalcopyrite exsolution from sphalerite.

(e) <u>Galena</u>

Galena is the last sulphide deposited in veins before post-mineralization ankerite brecciation, and characterizes the outer parts of the vein and breccia network. Interstitial to most minerals and anhedral, galena is a scavenger that substantially replaces pyrite, sphalerite and chalcopyrite (figure 5, plate 4).

In places, galena appears to be introduced with, and interstitial to quartz; elsewhere, carbonate.

Commonly galena contains inclusion relicts of sphalerite and chalcopyrite that are almost completely replaced. Minute inclusions of pyrrhotite with chalcopyrite are likely exsolutions from galena. Although some showings were once mined for silver, the author has found virtually no silver minerals in polished sections. Galena would be expected to be the host for silver.

(f) Gangue Minerals

Quartz (alpha) is the major gangue mineral of all veins, being repeatedly introduced following each brecciation event (see figure 4). Typically, quartz forms euhedral crystals whose intergrowth in the stockwork remains vuggy, but in the vein and breccia network is filled by later minerals. Although quartz is present in every showing, it is dominated by calcite in marginal zones. Quartz also shows brecciation.

Carbonate minerals are ankerite (L,B,M,HF and R showings), dolomite and calcite (W,F,N and H showings). Following the final brecciation event, carbonate formed a matrix to broken rock fragments, quartz and all sulphides. Characteristic of dolomite and calcite is their cockade structure in breccia zones, and colloform banding in quartz veins, which have either been precipitated around breccia fragments, or precipitated lining vuggy openings, respectively. Colloform calcite is repetitively and extremely delicately colour banded, suggesting late stage circulation of large amounts of relatively cool "hydrothermal" or ground water.

5. ZONING

Although zoning is to be expected surrounding a Porphyry Copper deposit (cf. Meyer et al., 1968), it is remarkable that all sulphide minerals should conform to a strict, regular zonal sequence. At least one would expect that the variability in openness of the different channelways would cause irregular limits to mineral boundaries; such is not the case.

Three factors (which have been assessed by examination of showings in the field, not individual samples) are used to delineate mineral zones. These are:

1. relative proportions of intermediate abundance sulphides -- molybdenite, chalcopyrite and galena;
2. limits of the above three minerals;
3. relative dominance of major minerals -- pyrite and sphalerite.

Using these parameters, ten mineral zones have been recognized. These are shown on the Sulphide Mineral Zoning map (in pocket); the map is self explanatory and the zones will not be repeated here. It is suggested that pyrite is normally the dominant sulphide, but, at an intermediate position in the channelways, sphalerite was rapidly "dumped", thus giving rise to a zone of sphalerite dominance. It is interesting to note that the macroscopic limit of chalcopyrite is also the limit of chalcopyrite inclusions in sphalerite.

The zoning suggests a decreasing temperature of mineral deposition outward from the porphyry source magma, as defined by the classic sequence:

molybdenite

pyrite

sphalerite-chalcopyrite

galena.

Although the validity of this zonal sequence has been established for many years, metallogenesists still cannot agree as to the form in which metallic ions are transported by solutions so that they will exhibit this sequence with decreasing temperature. A discussion of mineral solubilities and complexing ions is not in the purpose of this report, so the interested reader is referred to Park (1955), Park and McDiarmid (1964), or to Barnes and Czamanske (1967) for a more recent discussion.

Zoning of gangue minerals also represents a decreasing temperature outward from the source, in accordance with the experimental results of Holland (1967). Quartz is most abundant near the central stockwork, ankerite becomes important in intermediate zones (B, L and HF showings), whereas calcite and dolomite characterize the peripheral zones (W, F and N showings).

FIGURE 3

Vein paragenesis in vein and breccia-zone network surrounding central stockwork.

	GANGUE DEPOSITION	TECTONIC EVENT	SULPHIDE DEPOSITION
earliest		~ brecciation ~ in zones (and fracturing)	
	silicification		pyrite
		~ brecciation ~	
	quartz crystal filling of veins	--	main stage mineralization - massive sulphide replacement and disseminated sulphides -- pyrite, chalcopyrite, sphalerite (with exsolved chalcopyrite); possibly galena.
	quartz changing to calcite	fracturing	mainly galena, some sphalerite, possibly silver.
		~ MAJOR BRECCIATION OF VEINS ~	
	sandy ankerite forming breccia cement		euhedral pyritohedra
youngest	hematite along minor faults	oxidation	supergene chalcocite, bornite.

6. PARAGENESIS

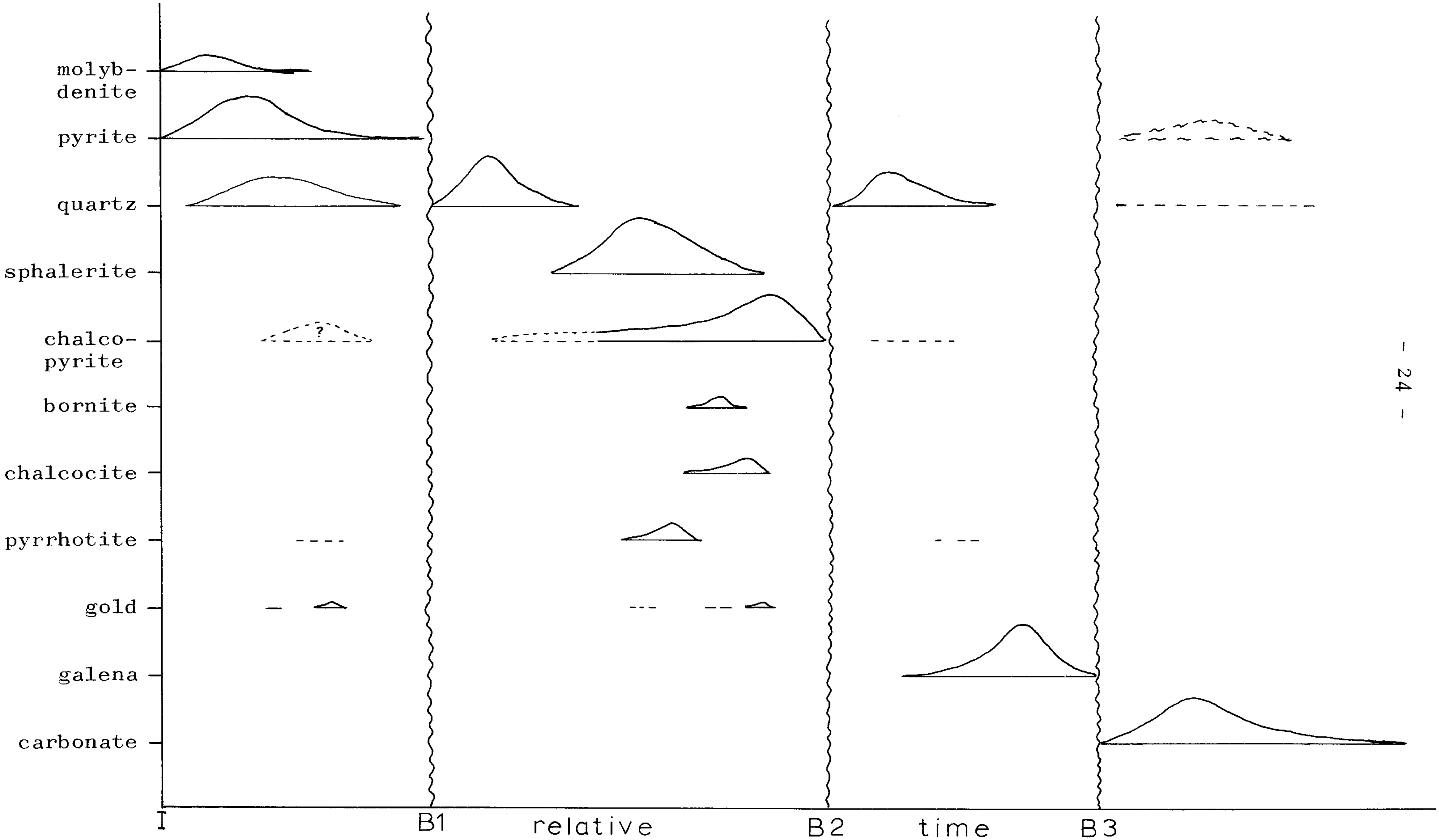
From the foregoing discussion of sequential replacement and brecciation displayed by sulphide minerals, it is evident that an extensive paragenesis of events exists. Indeed, were it not for repeated brecciation events, the paragenesis could not have been solved with any reasonable degree of certainty.

Firstly, there must have been an initial fracturing event which opened channelways to allow escape of fluids. This initial event (designated "I", figure 4) which corresponds to a regional event of non-systematic fracturing (Anderson, 1971), most probably occurred as tensional fracturing, thus creating the stockwork and the initial vein pattern in peripheral areas. Filling of these openings with quartz + pyrite + molybdenite in the stockwork ensued.

As mentioned previously, in the final stages of porphyry crystallization, volatiles are highly concentrated in the last remaining melt, since the volatiles, existing in significant amounts in the original porphyry magma, are in the process of being forced into a smaller and smaller volume. Build up of pressure will therefore cause explosive escape of volatiles. The first escape (denoted "B1" in figure 4) largely followed preexisting zones of weakness, but elsewhere formed new fractures. B1 was followed by main stage mineralization of sphalerite + chalcopyrite + minor sulphides + quartz crystal filling (figures 3 and 4).

It is extremely difficult to estimate how well stockwork formation and mineralization correlate with apparently equivalent

FIGURE 4. Line diagram showing relation of mineral deposition to brecciation events



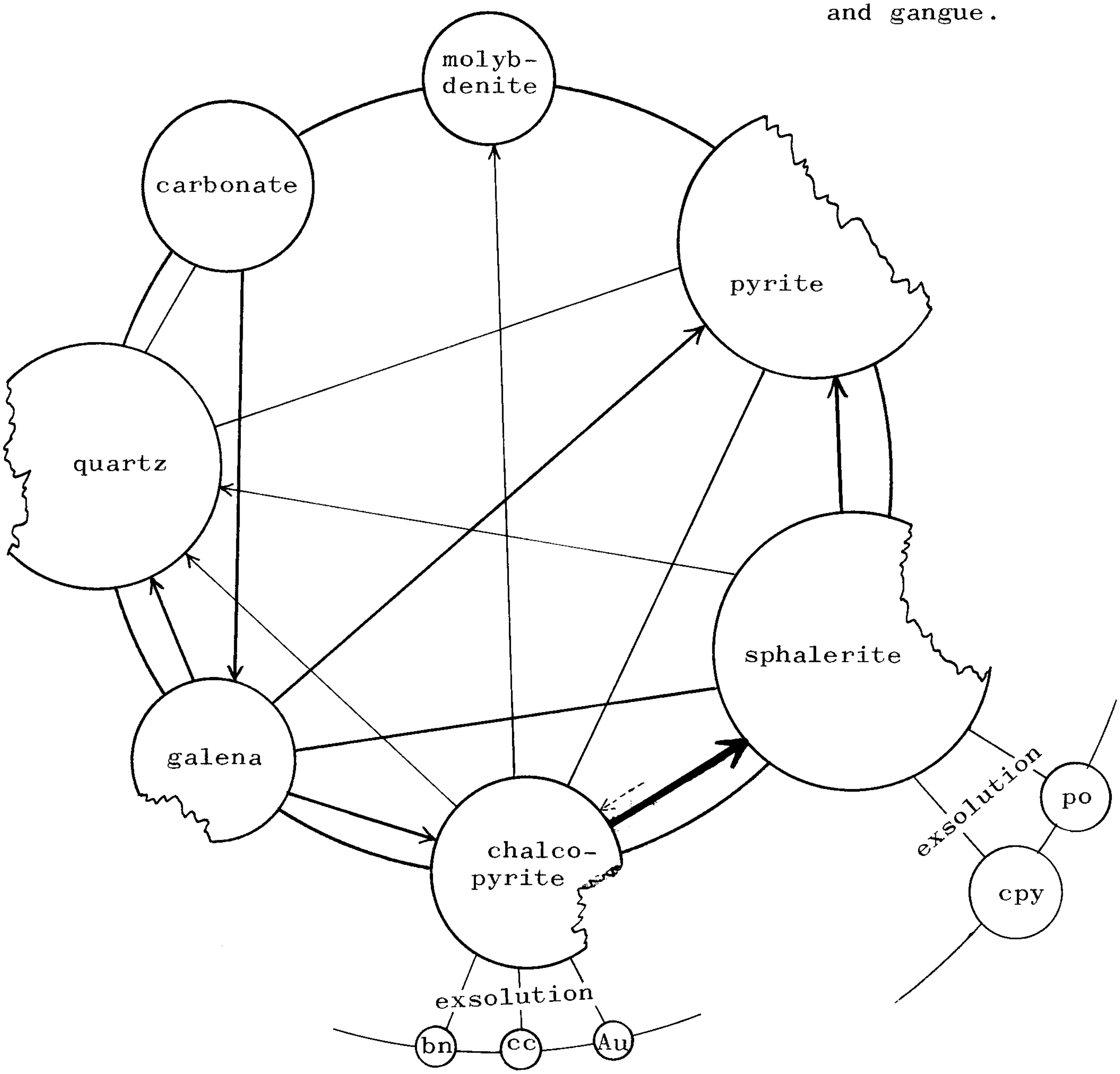
(dashed lines mean possible deposition; wavy lines indicate a different type of pyrite) events (mineralogically) in the surrounding vein and breccia network. Presumably, most of the stockwork was sealed to events later than B1 and chalcopyrite deposition. A minor event of brecciation, B2, interceded main stage mineralization, causing fragmented pyrite, sphalerite and chalcopyrite to be filled by quartz (plate 1 is a classic example). Galena, at this stage, was introduced.

Terminating main stage mineralization, after galena deposition, a major stage of brecciation occurred in the veins. Evidently, only open spaces (weaknesses) remained in the largest of zones, thus permitting an explosive event to brecciate everything in the zones -- silicified wall rock, mineralized rock, sulphides and quartz -- forming a true fragmental breccia (plate 2). Ankerite, calcite and dolomite were first finely deposited around breccia fragments, then coarsely filled the zones. This paragenesis is diagramatically shown in figures 3, 4 and 5.

Although zoning and paragenesis have been discussed separately, it is clear that they are two intimately linked processes. If we visualize mineral-bearing solutions travelling outward from the heat source along the network of channelways, they will progressively become cooler and change chemistry outward -- hence mineral zoning. Similarly, a solution which was once depositing (say) sphalerite or pyrite, will, through deposition of these minerals, change its chemistry and cool with time -- hence mineral paragenesis. However, it will reach the point where it has the same characteristics as a solution existing at

FIGURE 5

Van der Veer diagram showing exsolution and replacement textures, as well as degree of brecciation of sulphides and gangue.



(heaviness of line indicates extent of replacement)

bn=bornite cc=chalcocite po=pyrrhotite

Au= gold cpy=chalcopyrite

an earlier time in a farther-out part of the vein network. The result is that, at any one place in the vein network, we would record the same depositional sequence of minerals with time as we would in a traverse outward from the heat source at any one particular time. Therefore, the concepts of zoning and paragenesis are inseparable. They are simultaneous and interacting expressions of the cooling history of a mineralizing heat source such as a porphyry magma.

7. GEOTHERMOMETRY

In discussing a decreasing temperature outward from a heat source and a decreasing temperature with time, it is important to understand the magnitude of temperature changes; in other words -- what is the temperature of hydrothermal mineral deposition? It is commonsense that hydrothermal activity takes place between the temperature of the intrusive source and the temperature of groundwater. For a dacite (tonalite) magma, an intrusion temperature of 900°C is reasonable, but the last liquid fraction that we are concerned with, because of its high volatile content, would more likely be 800° to 750°C. The effective lower limit of deposition is 100°C, although Holland (1967) suggests that carbonate deposition may occur down to 50°C.

The temperature of deposition of main stage mineralization is what there is best control on. Firstly, post B1 quartz has been observed to be trigonal (alpha quartz) as close to the heat source as the S showing, necessitating a temperature of less than 573°C. Ingerson (1955, p360) suggests exsolution temperatures for:

chalcocite in chalcopyrite = 480°C
tetrahedrite in chalcopyrite = 500°C
bornite in chalcopyrite = 475°-500°C.

Assuming these sulphides in the showings are exsolutions from chalcopyrite (which is reasonable since they do not form separate phases), temperatures suggest chalcopyrite deposition at 500°C or more.*

Ingerson also cites chalcopyrite exsolution from sphalerite as 650°C, 550°C and 350°-400°C; evidently, variability is due to the iron content of sphalerite (Park and McDiarmid, 1964, p198). Pyrrhotite exsolution from sphalerite shows that the sphalerite is iron-saturated (near black in colour), therefore indicating a higher temperature of formation -- probably 400° to500°C. However, Barton and Skinner (1967) in a recent comprehensive paper on sulphide stabilities, have shown that the sphalerite-pyrrhotite "geothermometer" is virtually insensitive to temperature.

Barton and Skinner (1967, p274) put the upper limit of molybdenite + pyrite as 742° to726°C, placing an upper limit on stockwork formation. At the other extreme, Park and McDiarmid (1964, p201) place dolomite formation at typically 200° to 300°C.

---

* note that deposition temperature must be higher than exsolution temperature.

Holland (1967, p143) suggests that ankerite, dolomite and calcite indicate decreasing temperature of deposition in that order; this is in accordance with field evidence.

In summary, hydrothermal mineral deposition has taken place between 700^{o} and 200^{o}C, fluid temperature. It is evident, then, that much of the deposition was from a supercritical fluid or gas phase. Considering the error limits of the experimental data, pyrite + molybdenite was likely deposited about 650^{o} to 600^{o}C; sphalerite + chalcopyrite + pyrrhotite from 500^{o} to 400^{o}C; galena from approximately 400^{o} to 300^{o}C; and, finally, carbonates from 300^{o} to 200^{o}C. Quartz evidently was deposited over a larger temperature range -- 650^{o} to400^{o}C, thereby producing fine-grained beta quartz in the stockwork, and coarsely crystalline alpha quartz in the vein and breccia network.

Since it is virtually impossible to distinguish zoning from paragenesis with regard to geothermometry, one cannot sensibly assess a temperature gradient at any particular time, nor a rate of temperature decline at any particular place. Recently, Rose (1970) has shown that the "coolness" of wall rocks cannot be sufficient to cool the fluid, thereby suggesting that the zonal temperature gradient may only be slight, with most of the cooling taking place with time. Another interesting possibility is that early fluids never reached marginal areas; instead, the fluids progressed out in waves.

8. CLASSIFICATION

It has repeatedly been suggested that the MJ stockwork is typical of a Porphyry Copper deposit. If the features of the MJ deposit are compared with those of the 27 major porphyry copper deposits listed by Lowell and Guilbert (1970), it is evident that mineralization is of a Porphyry Copper type. The MJ deposit resembles Morenci, Arizona in the extensive development of peripheral breccias, but most closely resembles the large deposit at Butte, Montana. In fact, from the excellent description of Butte by Meyer et al. (1968), it seems that the whole sequence of mineralization, zoning and paragenesis, and alteration displayed at Whipsaw Creek, in gross aspects, is greatly similar to the Butte deposit.

It is possible to classify peripheral chalcopyrite, sphalerite and galena mineralization in Emmon's or Lindgren's mesothermal veins, but this is not normally done for a Porphyry Copper deposit. Indeed, the central copper-molybdenum mineralization defines the Porphyry Copper situation, and marginal copper-lead-zinc mineralization is a natural consequence of fluid escape out from the heat source. Porphyry Coppers are formed at high crustal levels (1 kilometer or so); in the Whipsaw Creek area, the fracturing environment substantiates this idea (Anderson, 1971). At such high levels, a large temperature difference between intrusion and host rock exists ($600^{\circ}C+$), thus causing a steep thermal gradient outward from the intrusion, and a rapid rate of temperature decline. The thermal environment is, therefore, more nearly "xenothermal".

CONCLUSIONS

From a study of sulphide mineralization, zoning and paragenesis (and geology) at Whipsaw Creek, it appears that a dacite porphyry magma intruded near the contact of the Eagle Complex and the Nicola Group. It has not yet been exposed by erosion. Geologic considerations (Anderson, 1971) indicate that its age is Tertiary.

Crystallization of the porphyry magma during its upward intrusion evidently halted the body at its present position. At this stage, only a small silicate-liquid fraction remained, but was highly enriched in volatile elements (such as sulphur), water, carbon dioxide, silica, and the base metals lead, zinc, copper, iron and molybdenum.

A series of events allowing escape of this volatile fraction and final crystallization ensued. Firstly, relaxation of intrusive forces (doming) resulted in slight collapse of the "roof rocks", producing a stockwork structure mineralized by chalcopyrite and molybdenite, and probably the initial fracture pattern surrounding the stockwork. Volatile pressure increase during final crystallization of the magma was released along marginal zones of weakness in a series of three brecciation events, each of which was followed by hydrothermal mineral deposition. Main stage mineralization of pyrite, chalcopyrite, sphalerite and galena followed the first two brecciation events, but was terminated by the third event that introduced "post ore" carbonates - ankerite, dolomite and calcite, into fragmental breccias.

As a consequence of these brecciation and filling events, textures of sulphides are dominated by sequential replacement and brecciation. The classic mineral deposition sequence of molybdenite -- pyrite -- chalcopyrite -- sphalerite -- galena is reflected in a mineral zoning around the heat source and in a paragenesis, both of which are inseparable expressions of the same process.

Finally, it is suggested that all features related to mineralization in the Whipsaw Creek area are natural expressions of the complex evolution of an intrusive porphyry body. All features -- sulphide mineralization, zoning, paragenesis; gangue mineral zoning and paragenesis; stockwork structure; peripheral quartz veins; peripheral breccia zones; and series of events -- are those typically found in Porphyry Copper deposits. Breccia zones are interesting in the history they record, but are particularly important features, for, in the famous words of Perry (1961, p376):

> "The significance of mineralized breccia pipes is that they are climactic expressions of general processes which, under differing local conditions, may also form the ring or dome-shaped fracture zones that control certain porphyry copper deposits. "

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A P P E N D I X

I

Polished Section

Descriptions

POLISHED SECTION DESCRIPTIONS

Notes:

1. Letter corresponds to showing letters as on sulphide Mineral Zoning map.
2. Mode of sulphide mineral is percentage of total sulphides (not necessarily indicative of showing as a whole).
3. Mode of gangue is percentage of total vein.
4. Grain size is in millimeters.
5. Mineral abbreviations as in Sulphide Mineral Zoning map.

(1) N J 11-3

Mineral	Mode	Grain Size	Texture	Association
pyrite	50%	1-2	subhedral	replaced by gal and sp
sphalerite	30%	1	minor (1%)	inclusion of cp; replaced by gal
chalcopy-rite	tr	.05		inclusions in sphalerite
galena	20%	.5	replacement	replaces sp and py; associated with carbonate
chalcocite) bornite) covellite)	supergene			
pyrrhotite	tr		in galena	also possibly gold(?)
ankerite	40%	network	cockade structure	matrix to all other minerals
quartz	30%		euhedral crystals	with pyrite

(2) F F 1-75

Mineral	Mode	Grain Size	Texture	Association
pyrite	35%	1.5-2.0	subhedral crystal	replaced by qtz gal sp
sphalerite	15%	1-2	inclusions	interstitial to qtz replaces pyr replaced by gal
chalcopyrite) pyrrhotite)	tr	.001	exsolution and replacement inclusions in sphalerite	
galena	50%	1	replacement	replaces py sp qtz
ankerite	25%	network	interstitial	matrix to all other minerals
quartz	45%	1-0.1	euhedral crystal	replaces (?) pyrite

(3) R A 19-3

Mineral	Mode	Grain Size	Texture	Association
pyrite	15%	1-2	euhedral	replaced by sph gl cp(?) qtz(?)
sphalerite	60%	network	few inclus.	apparently replaced by cpy
chalcopyrite	12%	variable	cuspate and sieve	replaces pyr qtz and sp(?)
galena	13%	1-2	embayments	replaces all minerals
chalcocite	tr	.05	inclusions	blebs in cpy
pyrrhotite	tr	.005		blebs in cpy and gal
argentite	tr	.005	slivers	in galena
quartz	30%	1 & up	euhedral crystal network (trigonal)	

(4) W A18-3 Three sections

Mineral	Mode	Grain Size	Texture	Association
pyrite	15%	1-3	cavity texture brecciated	replaced by all other sulphides
sphalerite	45%	1-20	brecciated and replacement	replaced by cpy inclusions of cpy
chalcopyrite	10%	.5-3	replacement, brecciated	veins cutting, and inclusions in sp largly replac.sp
galena	30%	4	replacement, fractured	replaces all sulphides filled by qtz + carbonate along fractures
quartz	30%	network	veins	extensive microbrecciation, veins of sulphides filled by quartz
carbonate (dolomite)	30%	.5	breccia cement	forms cement for all above brecciated minerals

— — — — —

W showing displays an excellent paragenesis:

1. pyrite

   replaced by

2. sphalerite (cp exsolution) minor qtz?

   replaced by

3. chalcopyrite

4. x x x x x x x x x x x brecciation

5. quartz crystal filling and breccia veining

6. galena (interstitial, replaces earlier sulphides)

7. x x x x x x x x x x x brecciation

8. dolomite cementation

   (later qtz veins?)

(5) M   A4-3 two sections
A4-4, A4-5, M2-129

(average of 5 samples)

Mineral	Mode	Grain Size	Texture	Association
pyrite	30%	2-3	euhedral crystals brecciated, mortar	replaced by other sulphides; related to or replaced by qtz
sphalerite	50%	variable	inclusion texture	consistently 10% inclusions of cpy + lesser po replaces pyr
Chalcopyrite	12%	1	replacement (exsolution?)	inclusions in sp; also replaces sp; brecciated with sp
pyrrhotite	10%	.005	inclusion	exsolution from sphalerite
bornite	tr	.01	closely assoicated with cpyr	
galena	7%	1	replacement	replaces all other sulphides
quartz	10-50%	1-5	euhedral crystals	may be two stages - early qtz following pyr and later one preceeding galena
carbonate	5%	.1	minor veins	cement for all other mineral where granulated

Paragenesis displayed by 5 samples is:

pyrite

(quartz?)

sphalerite (+ chalcopyrite + pyrrhotite)

chalcopyrite (+ bornite)

x x x x x x x x x x brecciation

quartz

galena

x x x x x x x x x x brecciation

dolomite.

(6) HF A30-H

Mineral	Mode	Grain Size	Texture	Association
pyrite	60%	.5-2	granulated mortar	replaced by sp and cpy shattered fragments in qtz matrix
Sphalerite	25%	1	inclusion	up to 20% cp inclusions; some are exsolutions trains
chalcopyrite	15%	1u to 1mm	exsolution replacement	as inclusions in sp; replacing sp; and inclusions of sp
chalcocite	tr	.001	inclusions	in cp
gold	tr	.001	inclusions	in cp and chalcocite
quartz	75%	network	crystals	matrix of pyrite breccia replaced by sp and cp

carbonate minor; occurs in narrow shear zones brecciating everything.

Paragenesis: pyrite

x x x x x x x brecciation

quartz

sphalerite + chalcopyrite

chalcopyrite + chalcocite

x x x x x x x brecciation

quartz?, carbonate.

(7) L A3-4, A3-10
A3-17

(average of three)

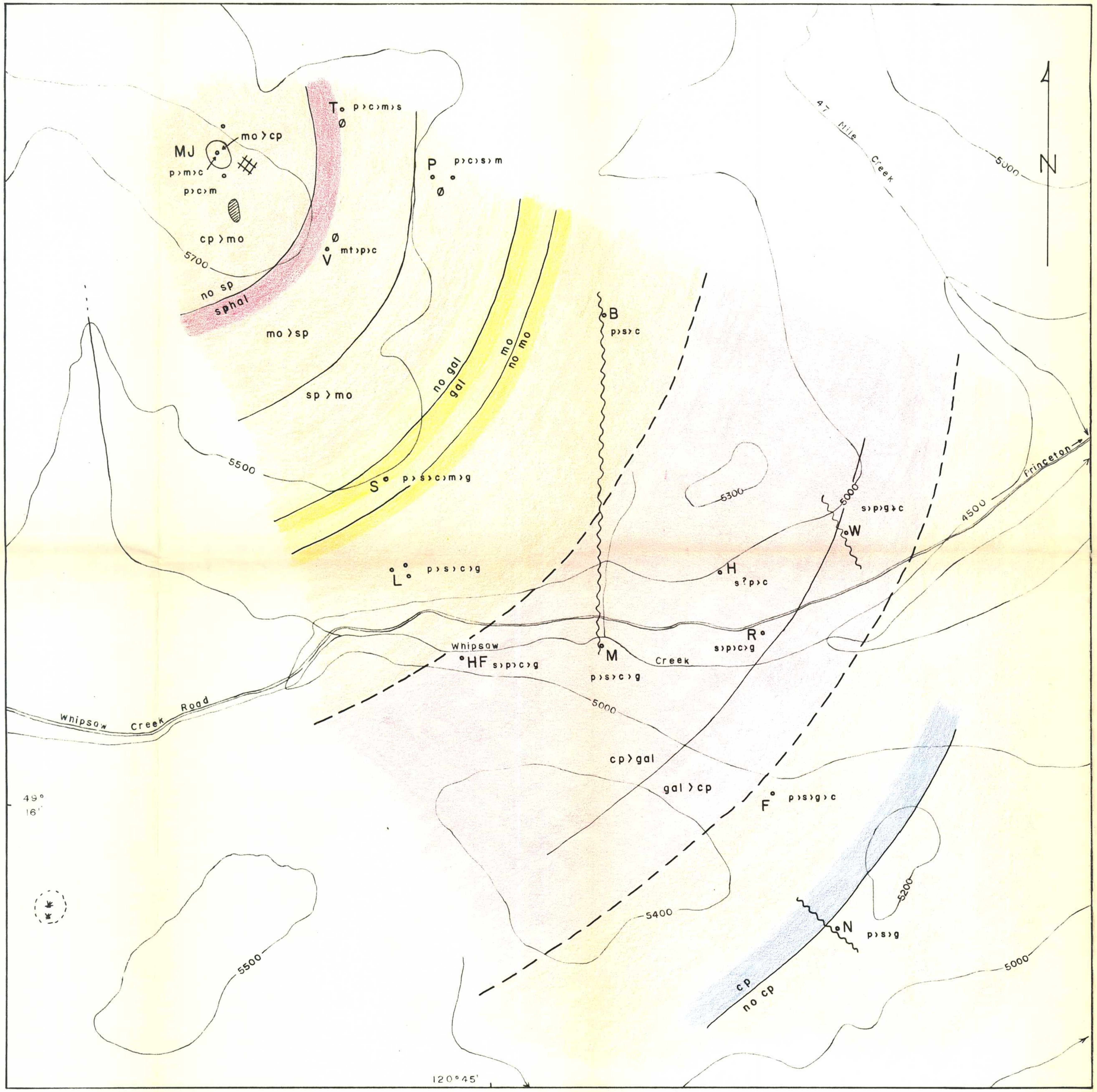
Mineral	Mode	Grain Size	Texture	Association
pyrite	15%	1	brecciated	replaced by all sulphides
sphalerite	50%	10-20	inclusion	abundant cp inclusions, replaces pyr; similt. with cp
chalcopyrite	30%	2-3	replacement	replaces sp and py
galena	5%	.5	replacement	replaces sulphides, replaced by carbonate
quartz	20%	2	euhedral crystals	brecciated by carbonate
carbonate	40%	network	cockade	extensive brecciation of all minerals in a carbonate matrix

Paragenesis: as before.

(8) S A13-7

Mineral	Mode	Grain Size	Texture	Association
pyrite	20%	1	replacement	replaces calc-silicate minerals
sphalerite	50%	5	inclusion	consistent, evenly distributed 15% inclusions of cp
chalcopyrite	30%	.5	replacement	extensive patchwork replacement of sphalerite
calc-silicate minerals + quartz	80%	various	skarn	replaced by sulphide minerals

Replacement paragenesis:
1. pyrite
2. sphalerite (+ chalcopyrite)
3. chalcopyrite.



LEGEND

- pyrite dominant
- sphalerite dominant
- boundary
- sphalerite limit
- galena limit
- molybdenite limit
- chalcopyrite limit
- boundary

Showings

- °H location and symbol
- mineralized stockwork
- Ø mineralized porphyry
- breccia zone
- ° quartz vein

Mineralogy

- p = pyrite
- m, mo = molybdenite
- c, cp = chalcopyrite
- s, sp = sphalerite
- g, gal = galena
- (mt = magnetite)
- > greater than
- ≥ " " or equal to
- ? uncertain
- s>p>c relative proportions of sulphides
- 5000 contours
- pond

SCALE 1" = 1000'

1000 0 1000 2000 3000 4000 5000
feet
1 mile

inches 0 1
0 1 2
centimetres

This reference scale bar has been added to the original image. It will scale at the same rate as the image, therefore it can be used as a reference for the original size.

SULPHIDE MINERAL ZONING

DETAILED THESIS AREA