

DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

A preliminary study of thermometry and metal sources of the  
Spar Lake strata-bound copper-silver deposit,  
Belt Supergroup, Montana

By

Timothy S. Hayes<sup>1</sup>

Open-File Report 90-0484

1990

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<sup>1</sup>Denver, Colorado

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## ABSTRACT

Fluid inclusions found in ore-stage authigenic quartz, carbonate, and albite at the Spar Lake deposit still record ore-stage conditions despite post-ore burial metamorphism at greater than 325 °C. Quartz overgrowth and carbonate cements were either synchronous with or slightly pre-ore, and albite was either synchronous with or post-ore; all are part of a zoned system of Middle Proterozoic Revett Formation sandstone cements that includes the ore sulfides. Ore-stage microtextures and microzonations are preserved in these and other ore-stage cements.

Ore-stage fluid inclusions are  $<5\mu$  in size and occur as isolated, 2-phase, liquid-vapor (L-V) inclusions with tiny gas bubbles or as 1-phase liquid (L) inclusions. The L inclusions may be metamorphically homogenized equivalents of the L-V's, or they may have been trapped at near-ambient temperature.

L-V inclusions homogenize to liquid at a range of temperatures varying from 74 °C, in the fringing GALENA-CALCITE zone, to more than 175 °C in orebody BORNITE-CALCITE and CHALCOCITE-CHLORITE zones. No homogenization temperatures ( $T_h$ 's) under 130 °C are found in the orebody, and no  $T_h$ 's above 130 °C are found in the fringe GALENA-CALCITE zone.  $T_h$ 's also decline from the orebody across the CHALCOPYRITE-ANKERITE zone, so that this zone could not have been a feeder. Instead, it was an ore-stage, thermal equivalent in pre-ore hematitic sandstone of the CHALCOPYRITE-CALCITE and GALENA-CALCITE zones that formed in pre-ore pyritic sandstone. Ore fluids must have fed from below, then spread along permeable layers.

Four L-V inclusions in authigenic albite from a newly described albitic zone have  $T_h$ 's no less than 230 °C. The ALBITE zone lies on a projection of mineral zoning towards a hypothetical ore fluid source from both the CHALCOPYRITE-ANKERITE and CHALCOCITE-CHLORITE zones. Anomalously low copper contents, the mineral zonation constraints, and the higher temperatures strongly suggest that the ALBITE zone was a major source of metals for Revett-hosted deposits.

## INTRODUCTION

The Spar Lake deposit has been described by Hayes and Einaudi (1986) as a peneconcordant strata-bound copper-silver deposit of the type commonly associated with red beds. Its sulfide mineral zonation is directly comparable with that of deposits like White Pine, Mich., the Kupferschiefer in northern Europe, and the Zambian Copperbelt. It is even more directly comparable with sandstone-hosted Russian deposits of the Udokansk and Dzhezkazkan ore fields. It shares petrographic features to a truly remarkable degree with descriptions of Dzhezkazkan ores (Gablina and Tsepina, 1975).

Before mining began in 1981, the Troy orebody in the Spar Lake deposit contained 64 million tons of 0.74 percent Cu and 1.58 oz/ton (Troy) Ag. The Spar Lake deposit is located 13 miles south of the town of Troy near Montana's western border (fig. 1).

The Spar Lake deposit is hosted by the upper member of the Revett Formation, Ravalli Group, Middle Proterozoic Belt Supergroup (fig. 2). It is

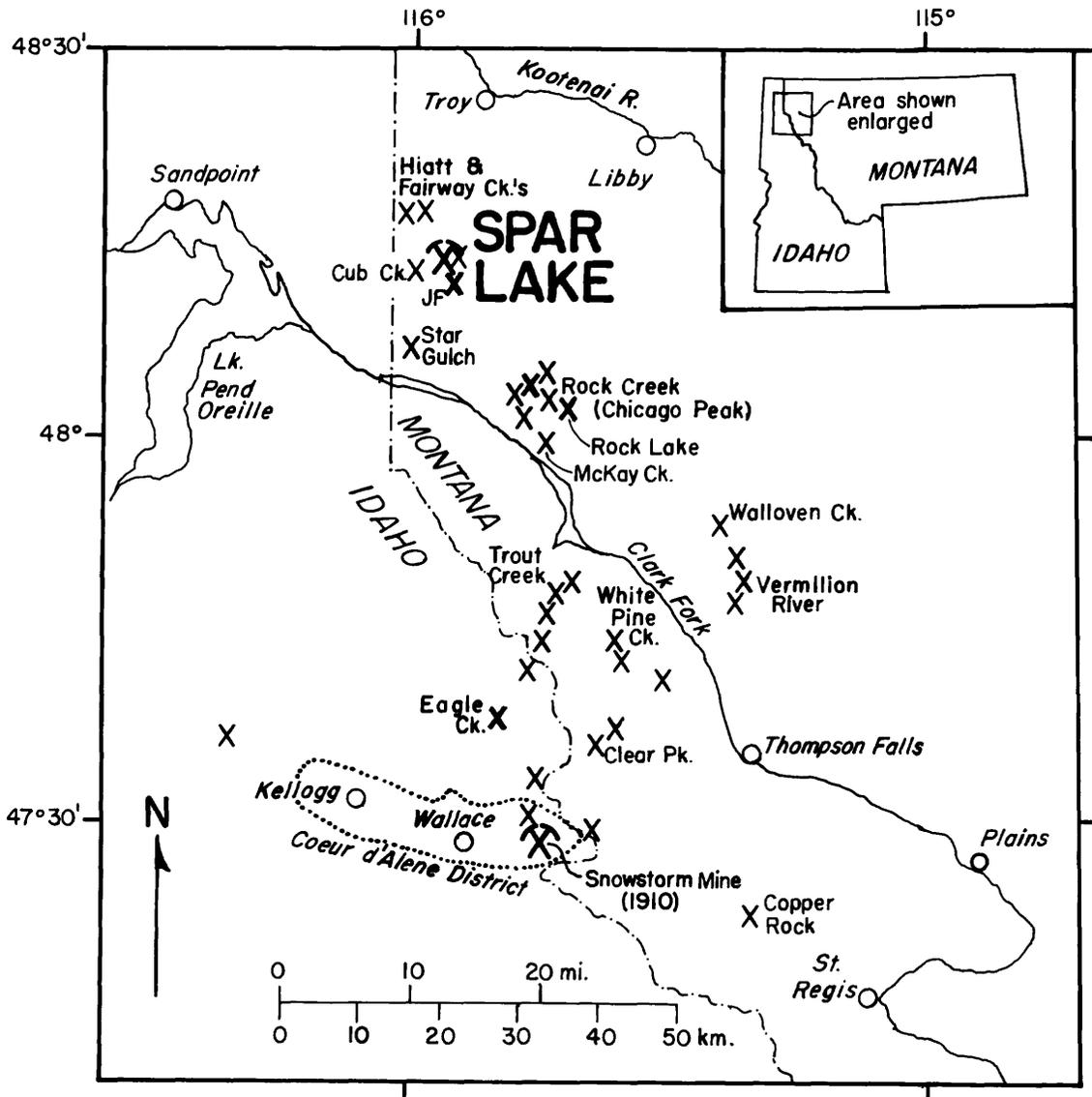


Figure 1. Location map for mines and prospects at Revett Formation-hosted strata-bound copper-silver deposits. Figure from Hayes and others, 1989.

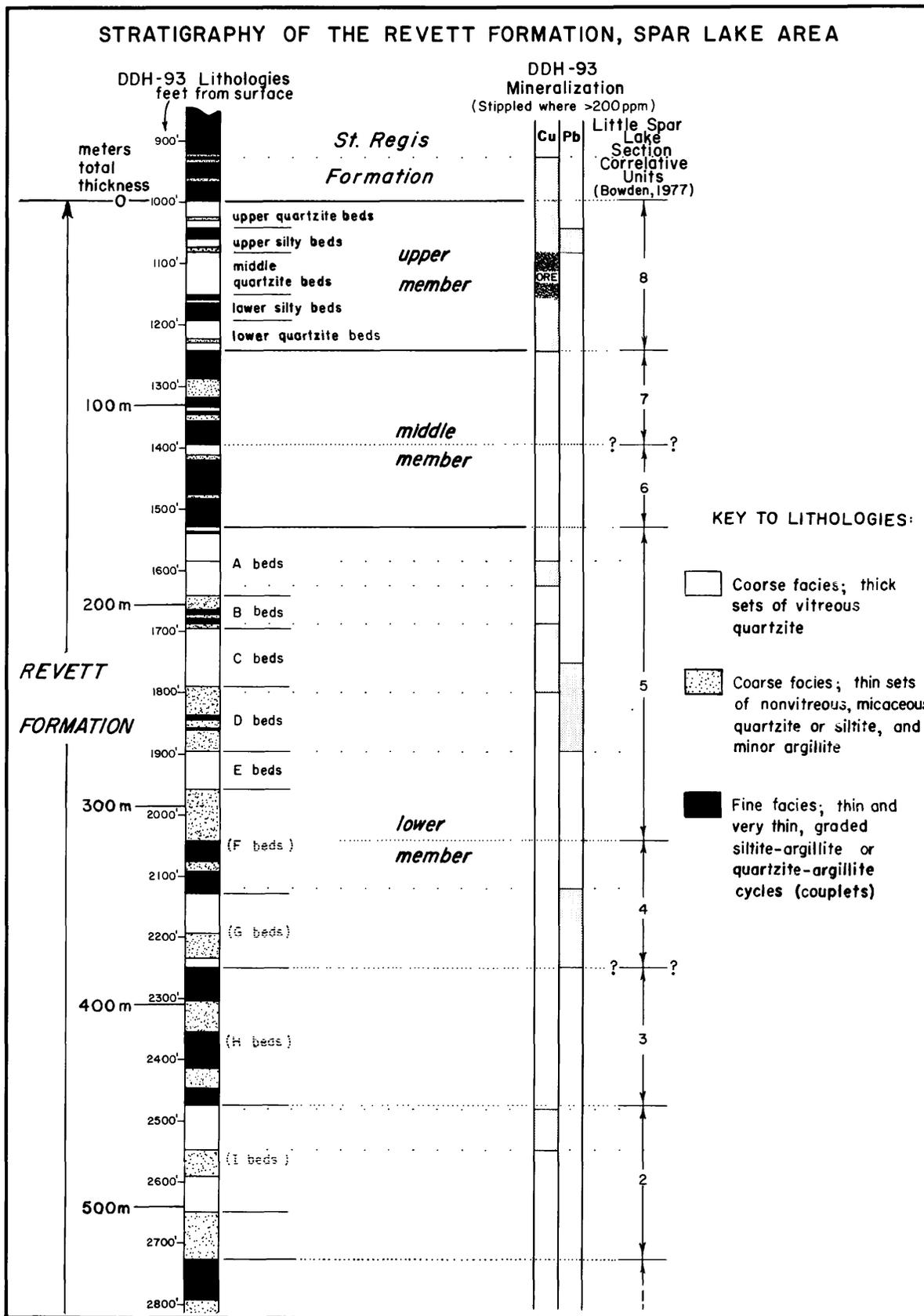


Figure 2. Revett Formation stratigraphy and anomalous Cu and Pb in drill hole 93 penetrating the center of the Troy orebody at Spar Lake. Figure from Hayes and Einaudi, 1986.

a tongue-shaped body of chalcocite- and bornite-bearing (meta)sandstone (fig. 3).

This paper will first review results from studies that led up to work on fluid inclusions, next, discuss a preliminary study of fluid inclusions that resulted in new insights about mineral zonation and the sources of copper for the deposit, and, third, discuss a newly identified mineral zone that is the probable source of metals for the deposit.

#### EARLIER STUDIES

Earlier work dealing with the relation of the copper-silver ore to its host rocks (Hayes and Einaudi, 1986) found that the peneconcordant orebody formed during cementation of the sandstone host rock. Ore minerals precipitated from a solution that spread along permeable sandstone layers (fig. 3). That work described an extensive system of zonally arranged authigenic gangue minerals (fig. 4) with appearance/disappearance boundaries that parallel the boundaries of chalcocite, digenite, and bornite appearance. All such boundaries cross through both stratigraphic and sedimentational units to describe tongues into (meta)sandstone beds and "tails" across argillites (figs. 3 and 4). Smaller-scale, rich disseminations of each of the authigenic minerals occur within this system. Some of these rich disseminations, bedform disseminations, are conformable; some others, ore rods, are discordant, occupying seepage pillars, a type of water escape structure; and others, bands, lie nearly conformable with master bedding but sharply discordant to cross-lamination of the (meta)sandstone (Hayes and Einaudi, 1986).

Detailed petrographic study (Hayes, 1984) established that most ore mineral grains are cements of the sandstone. Other ore minerals replaced detrital components, particularly phosphatic mud intraclasts, but also plagioclase and probably even quartz. The paragenetic sequence of any one thin section is actually a cementation sequence (fig. 5). In summary, the combined paragenetic observations from the different zones found that certain minerals characterizing the GALENA-CALCITE zone were younger than those characterizing the PYRITE-CALCITE zone, and that certain authigenic minerals of the CHALCOPYRITE-CALCITE, BORNITE-CALCITE, and CHALCOCITE-CHLORITE zones were precipitated sequentially later. The albite found most abundantly in the CHALCOCITE-CHLORITE and adjacent near-ore CHALCOPYRITE-ANKERITE zones was the youngest authigenic mineral of all. From this sequence and figure 3, Hayes (1984) and Hayes and Einaudi (1986) concluded that ore solutions had moved laterally northwestward along the sandbodies, and, from the details of mineralized water-escape structures, that ore solutions had moved upward as well.

Hayes (1984) took the first steps towards establishing that the deposit straddles a pre-ore mineralogical interface in the middle quartzite sandbody. Petrographic evidence indicates a pyrite/hematite interface at the pre-ore "dust-rimming" stage, the first stage of diagenesis (fig. 6).

Based upon the observed zonation and paragenesis (figs. 3, 4, and 5), quartz and K-feldspar syntaxial overgrowths marked the onset of ore deposition. The overgrowths locally contain tiny (10  $\mu\text{m}$ ) inclusions of ore sulfides: galena in the GALENA-CALCITE zone, bornite in the BORNITE-CALCITE

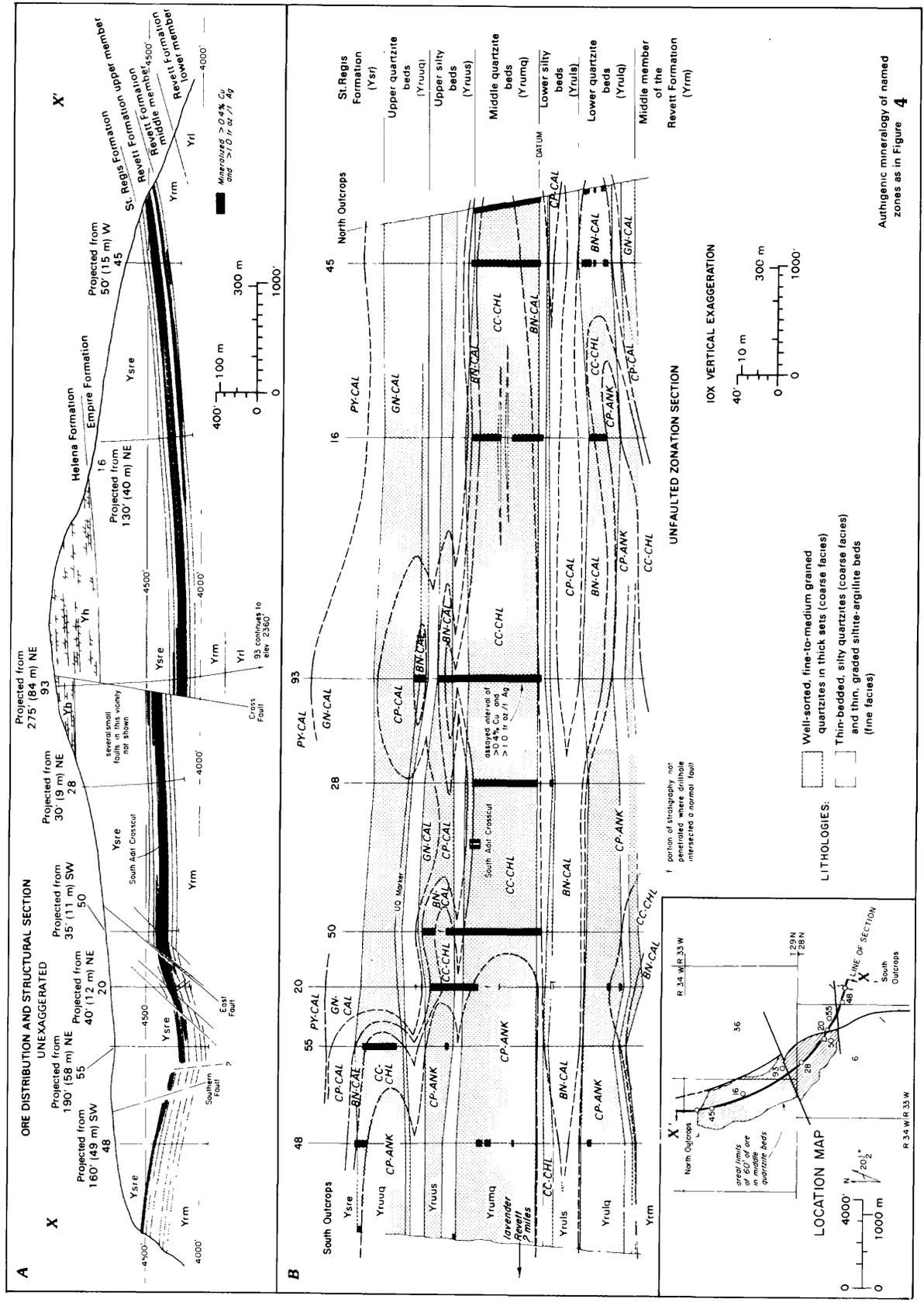


Figure 3. North to southeast, curving, longitudinal cross section of the Spar Lake deposit showing mineral zonation and assuming only post-ore fault offsets. A. Section showing ore distribution and structural geology with no vertical exaggeration. B. Section along the same line of drill holes showing mineral zonation with 10X vertical exaggeration reconstructed across faults with the assumption that all fault offset is post-ore. Mineral zones are abbreviated as in figure 4. Figure from Hayes and Einaudi, 1986.

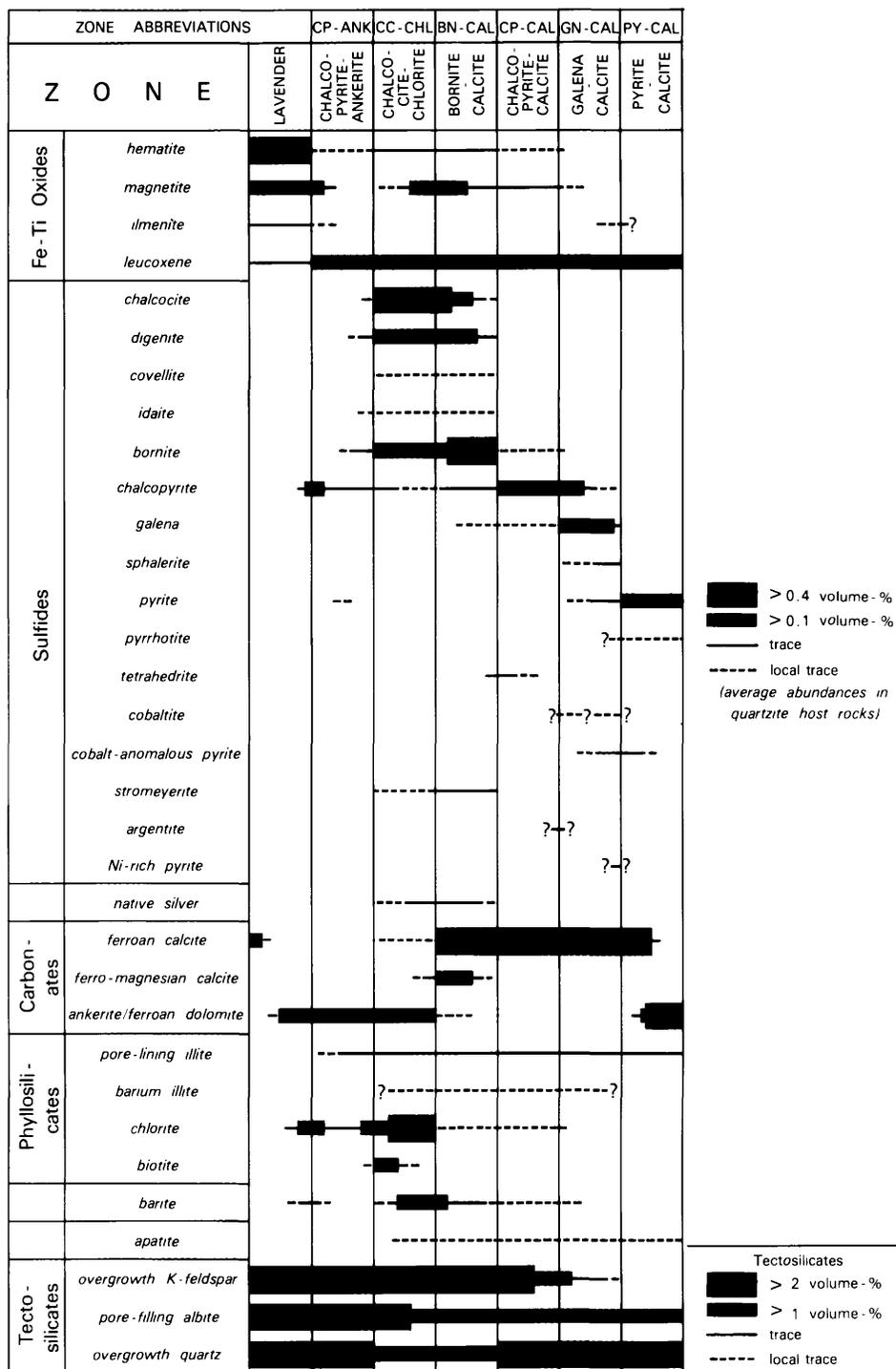


Figure 4. Authigenic mineral zonation of the Spar Lake deposit as known in 1984. The diagram gives no information about paragenesis, only about distribution of authigenic minerals in space, and shows certain minerals assumed to have formed during metamorphism. Changes in concentration of a mineral in space are generally gradual but are presented as sharp changes in the diagram in order to avoid confusion of this diagram with any paragenetic diagram. Figure from Hayes and Einaudi, 1986.

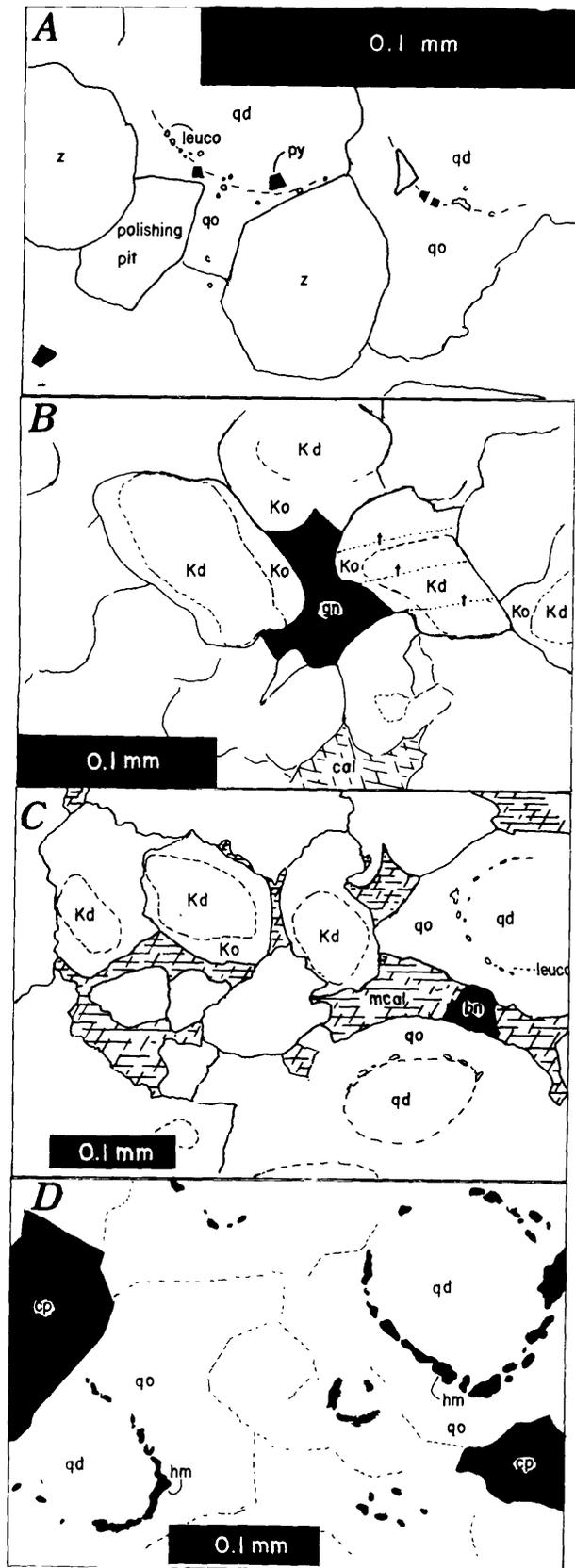


Figure 5. Cementation sequences in different mineral zones of the Spar Lake deposit. Line drawings were made by tracing features from a cross-polarized transmitted light photomicrograph, a plane-polarized reflected light photomicrograph, and a cathodoluminescent photomicrograph, all of the same field of view.

A. Pyrite-Calcite zone showing the apparent sequence detrital quartz (qd), pyrite and leucoxene dust rims (py and leuco), then quartz overgrowth (qo).

B. Galena-Calcite zone showing the apparent sequence detrital K-feldspar (Kd), K-feldspar overgrowth (Ko), then galena and calcite pore-filling cements (gn and cal).

C. Bornite-Calcite zone at its boundary with Chalcocite-Chlorite showing the apparent sequence detrital quartz and K-feldspar, leucoxene (only) dust rims, quartz and K-feldspar overgrowth, then manganese- and magnesian-calcite and bornite (mcal and bn) pore filling. From a "clot." Note the appearance that there is not a clast-supported framework. From other sites, this is probably due to clast replacement of certain unstable clasts now represented by calcite.

D. Chalcopyrite-Ankerite zone showing the apparent sequence detrital quartz, hematite dust rims (hm), quartz overgrowth, then pore-filling and replacive chalcopyrite (cp). Figure from Hayes and others, 1989.

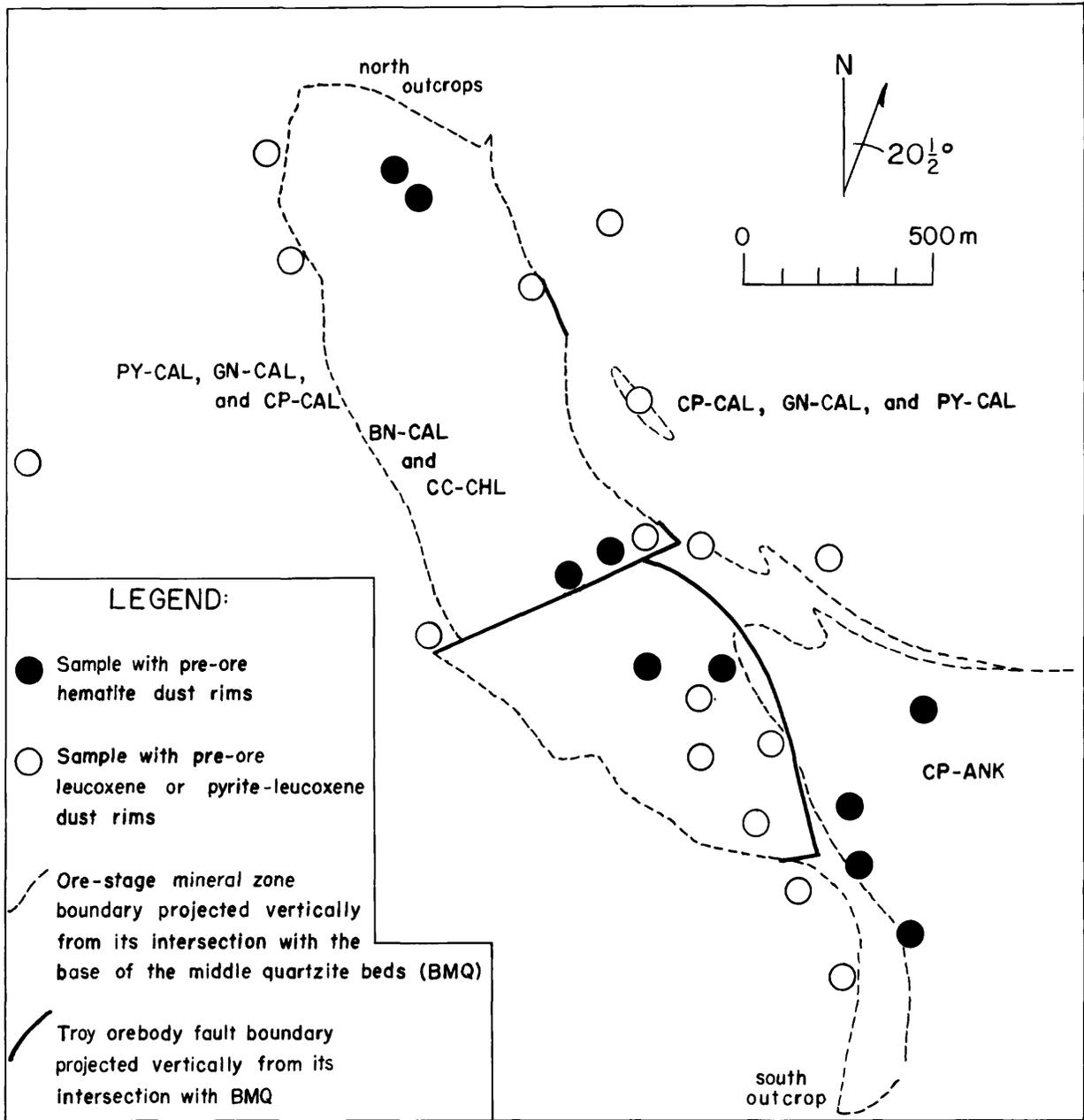


Figure 6. Locations of hematite dust-rimmed vs. pyrite-leucoxene dust-rimmed or just leucoxene dust-rimmed detritus in samples from the middle 15 m of the middle quartzite beds. Ore-stage mineral boundaries parallel the boundaries of a pre-ore pyrite-leucoxene-hematite interface. Abbreviations as in figure 4. Figure from Hayes and others, 1989.

zone, etcetera. However, at most places major amounts of the ore sulfides did not precipitate until later, after overgrowth and after local pore-lining by a white mica or chlorite. Overgrowth quartz and the post-overgrowth carbonates, calcite in the pre-ore pyritic rocks and ankerite in the pre-ore hematitic rocks, were locally replaced by the pore-filling stage sulfides (fig. 5D), indicating that cements from early in the ore-stage were locally replaced by later ore-stage cements. Albite replaced not only calcium-bearing plagioclase detritus but also replaced both detrital and overgrowth K-feldspar. Most samples were dominated by paragenetically uninterpretable sulfide-sulfide contacts, but textures that could be interpreted also suggested progressively younger minerals towards the center of the tongue-shaped body and, perhaps, to the southeast. No paragenetic relations were observed between barite and any sulfide that co-existed as a cement. Two different interpretations of major fluid movement could be hypothesized. In the first, the CHALCOPYRITE-ANKERITE zone to the southeast (fig. 3) might be the analogue of the altered tongue of a roll-front uranium deposit but indicating a far different ore solution, namely one that was capable of bleaching hematitic sandstones (fig. 5D). In the second, ore fluids might have moved dominantly up from below, then spread as permeability permitted in all directions along sandstones. In this second hypothesis, the CHALCOPYRITE-ANKERITE zone would merely represent a poorly mineralizable host—the pre-ore hematitic sandstone (fig. 6). As a result, the orebody geometry might be considered a gigantic pseudomorph of the pre-ore pyrite-hematite interface produced during the earlier dust-rimming stage (fig. 6).

The direct test of the two hypotheses was to determine solution conditions in various zones. Because minerals like the ore-stage feldspars were present, temperatures were suspected to be elevated well above ambient levels, and we (Hayes and others, 1989) sought to determine temperatures. If hypothesis 1 (roll-front-like hydrology) was correct, then the CHALCOPYRITE-ANKERITE zone would have higher temperatures than all other zones. If hypothesis 2 was correct, then CHALCOPYRITE-ANKERITE zone would not necessarily have higher temperatures and might even have lower temperatures than the CHALCOCITE-CHLORITE zone.

Sulfur isotope studies were undertaken, though with trepidation about whether the sulfides could have reached isotopic equilibrium at the suspected middle diagenetic temperatures.

Sulfur isotope values from galena-chalcopyrite pairs proved to have approached equilibrium, and the isotope values yielded a very systematic arrangement of calculated temperatures (fig. 7). Temperatures increased regularly as the orebody was approached from the pyritic fringes of the deposit. Proportions of a cobalt-anomalous generation of pyrite also increased in the same direction, in apparent support of the isotope temperatures. However, the extremely small amounts of sulfide minerals, and the poor knowledge of fractionation of the sulfide pair bornite/chalcopyrite, did not allow calculation of sulfur isotope temperatures from the CHALCOPYRITE-ANKERITE zone. Notably, though, sulfide separates from that zone were found to locally have very scant traces of each sphalerite and galena never before seen. The sphalerite and galena of that zone is less than 1 volume percent of a separate from a rock that itself is generally only about

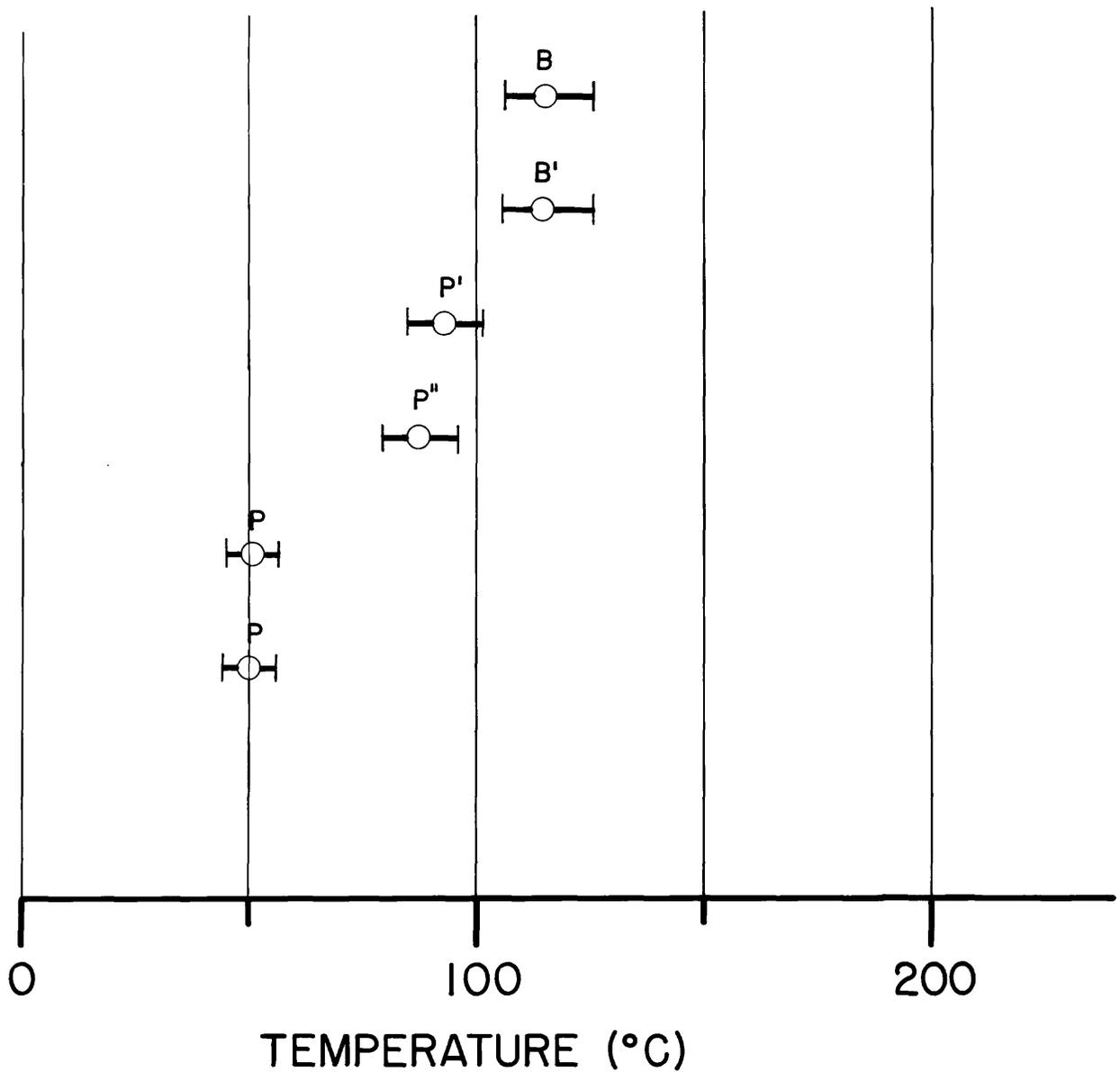


Figure 7. Calculated sulfur isotope temperatures from galena-chalcopyrite pairs in an approach to the orebody from the Pyrite- Calcite zone. Sample B contains trace bornite; B' is from 1 m away from bornite appearance; P' and P'' are dominated by the cobalt-anomalous ore-stage generation of pyrite, and samples P are dominated by ordinary, pre-ore pyrite. Figure from Hayes and others, 1989.

0.1 volume percent total sulfides. That and further work would eventually lead to important revisions in the zonation diagram (fig. 4).

Sulfur isotope studies demonstrated that the deposit represents a mixing zone between ore fluids at over 120 °C and pre-ore pore waters at less than 50 °C (Hayes and others, 1989). Work then began on fluid inclusions, again, with trepidation. The orebody and its enclosing rocks have been metamorphosed to the biotite isograd of greenschist facies. The metamorphism is due only to deep burial conditions. In the mine vicinity, a phengite-chlorite assemblage in the Middle Proterozoic Empire Formation, 700 feet upsection, changes progressively downward to a phengite-chlorite-biotite assemblage and then to a phengite-biotite assemblage about 100 feet above the orebody. This chlorite-destructive metamorphic reaction occurred in argillites and siltites but not in the interbedded quartzites. Adopting a high-temperature, low-pressure metamorphic path because there is no dynamothermal component in this pure burial metamorphism (there was no lateral pressure component), any of several different chlorite-consuming, biotite-forming reactions that have been studied predict that maximum metamorphic conditions reached in the argillites immediately above and below ore and, therefore, certainly also by the orebody itself, were about 375-425 °C and 1600-1200 bars (Ernst, 1963). Exsolution textures and mineral proportions of certain grains of bornite-digenite also demonstrate that temperatures greater than 315 °C were reached in metamorphism, provided that isolated sulfide grains each acted as closed systems in metamorphism (Kullerud, 1960). Textures like those in figure 5 support that the grains acted as closed systems.

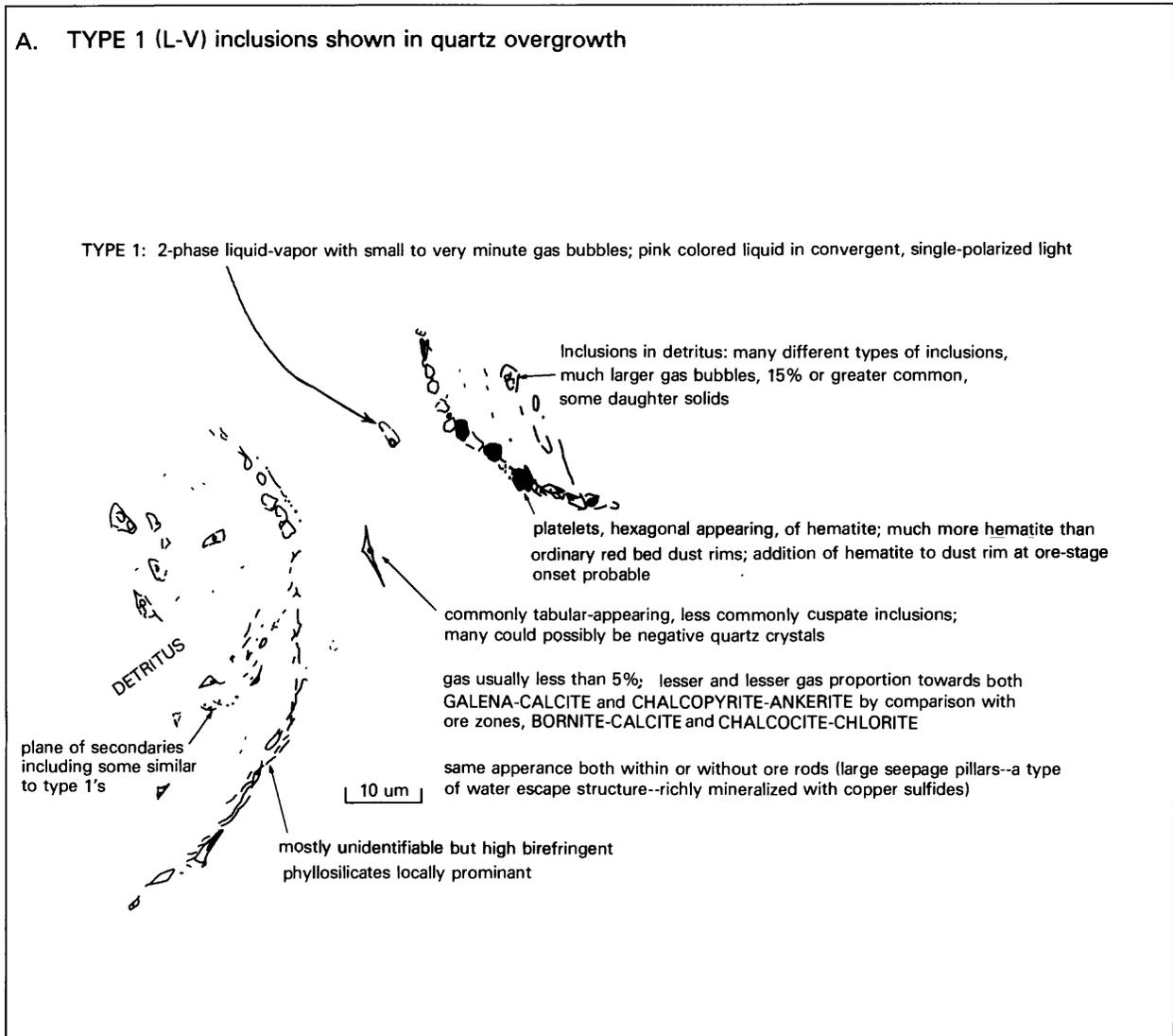
Despite the known metamorphism, it seemed possible that fluid inclusions would prove useful. Additional petrographic study demonstrated that "pore-lining" chlorite was not consumed by metamorphism in the quartzite-hosted ore, a second change needed on the zonation diagram (fig. 4). The ore is dominated by unrecrystallized cementation textures (fig. 5), so that annealing and recrystallization must not have taken place during metamorphism. Even microscopic oscillatory zonation has been preserved in growth of carbonate cements towards pore centers (Hayes, 1984).

#### FLUID INCLUSION STUDIES

The fluid inclusions in authigenic, ore-stage cements are of two types (fig. 8). Both types of inclusions are very small, ranging from less than 1 to as much as 8 micrometers in largest dimension. Type 1 inclusions are 2-phase liquid-vapor (L-V) inclusions with gas bubbles generally less than 5 percent by volume, commonly less than 3 percent. In GALENA-CALCITE and some CHALCOPYRITE-ANKERITE zone samples (not yet studied by microthermometry), gas bubbles are less than 1 percent by volume and detectable only by their motion. Conversely, the L-V inclusions in authigenic albite cements usually have gas bubbles of greater than 5 percent by volume. Type 2 inclusions are 1-phase liquids (L). These L inclusions were suspected but not confirmed until the sample from GALENA-CALCITE zone with a 74 °C-homogenizing L-V inclusion was overheated to 230 °C (fig. 9). Upon cooling, gas bubbles had appeared in several nearby inclusions that did not previously contain bubbles. The new bubbles probably formed as the result of inclusion stretching during overheating (E.L. Rowan, verbal communication, 1985). In another case, an inclusion from a sample from GALENA-CALCITE zone homogenized at 108 °C but

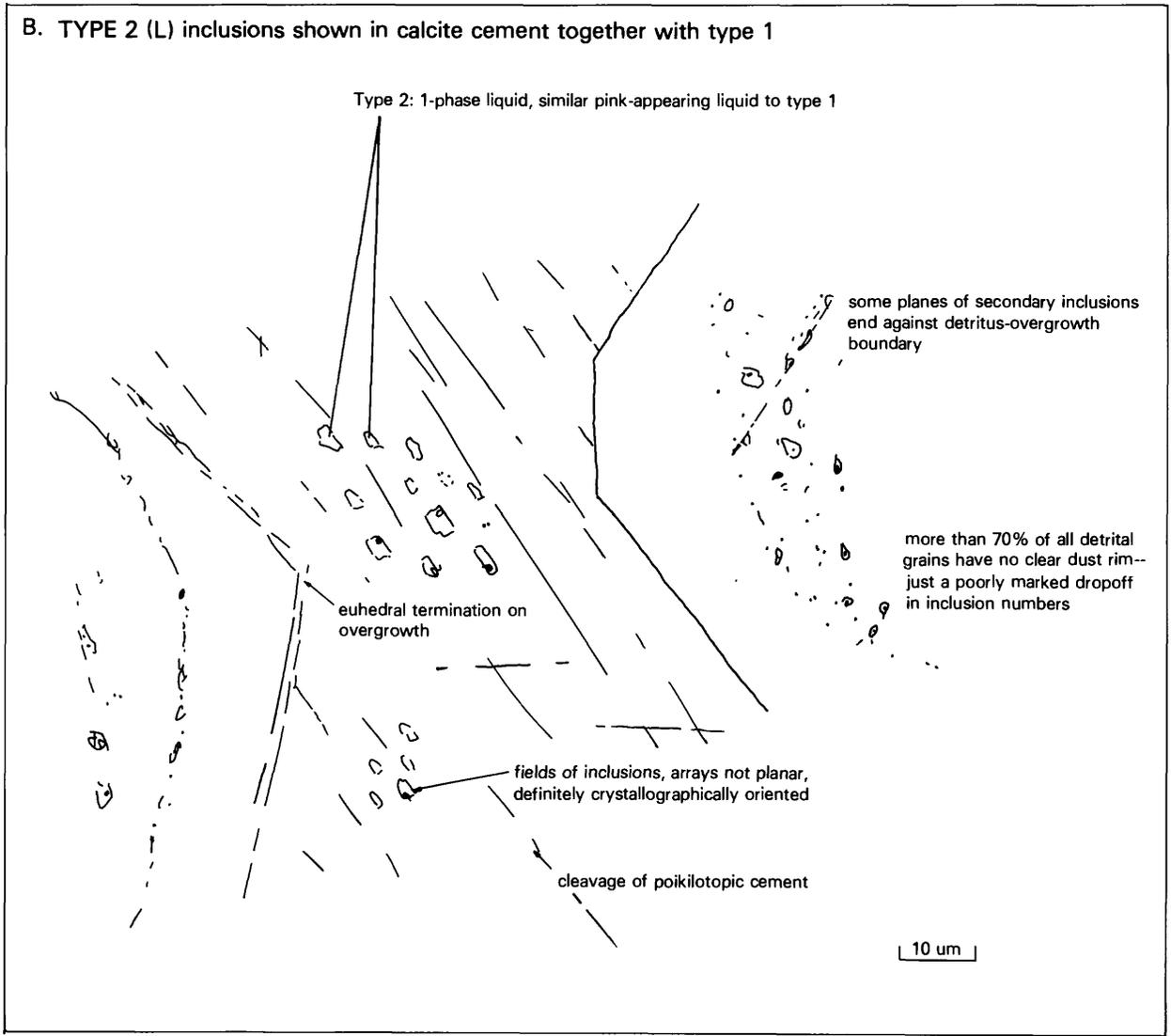
## FIGURE 8. SKETCHES OF INCLUSION TYPES

### A. TYPE 1 (L-V) inclusions shown in quartz overgrowth



# FIGURE 8. SKETCHES OF INCLUSION TYPES

## B. TYPE 2 (L) inclusions shown in calcite cement together with type 1



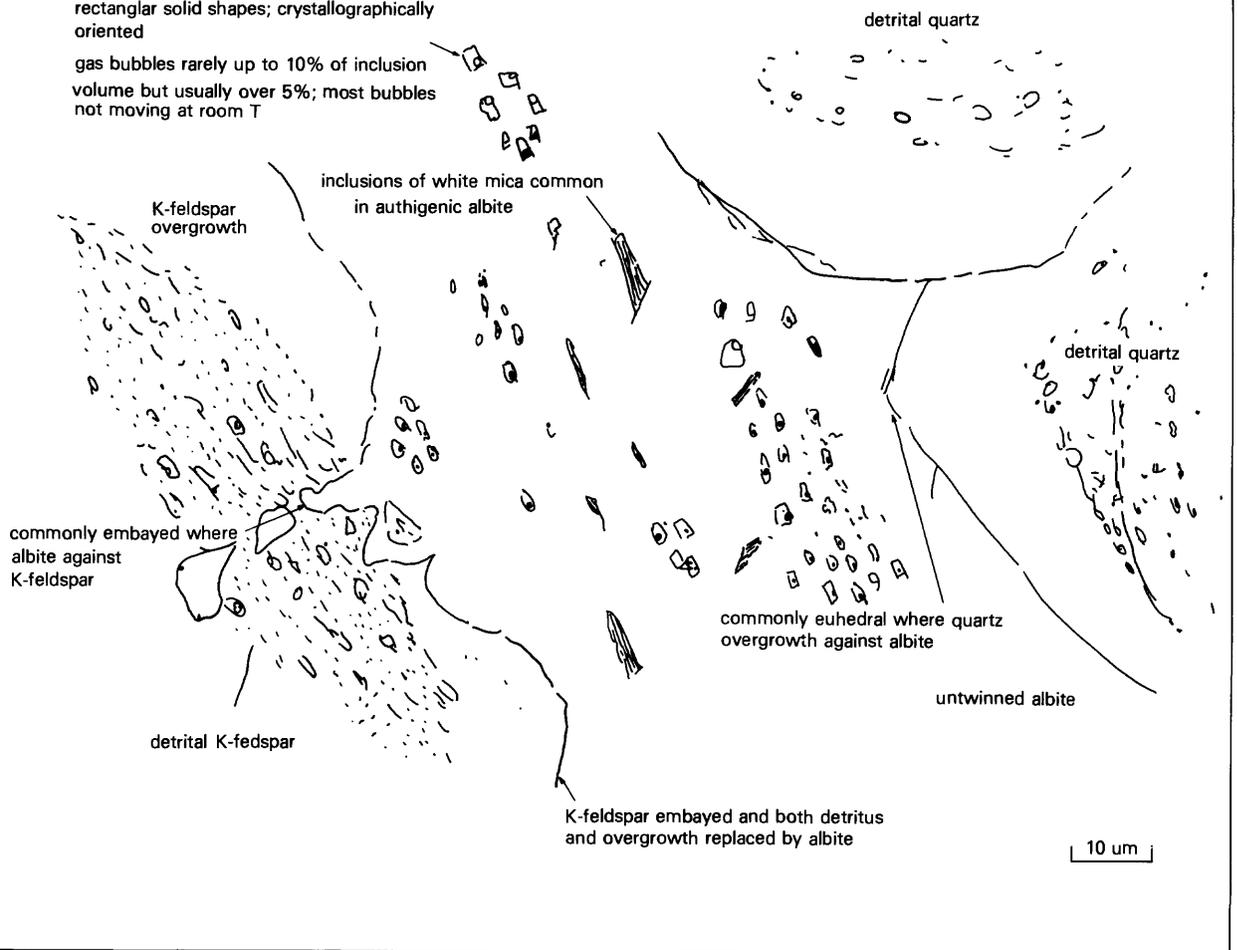
## FIGURE 8. SKETCHES OF INCLUSION TYPES

### C. TYPE 1 inclusions shown in albite

type 1 inclusions far more abundant than in either quartz or calcite;

rectangular solid shapes; crystallographically oriented

gas bubbles rarely up to 10% of inclusion volume but usually over 5%; most bubbles not moving at room T



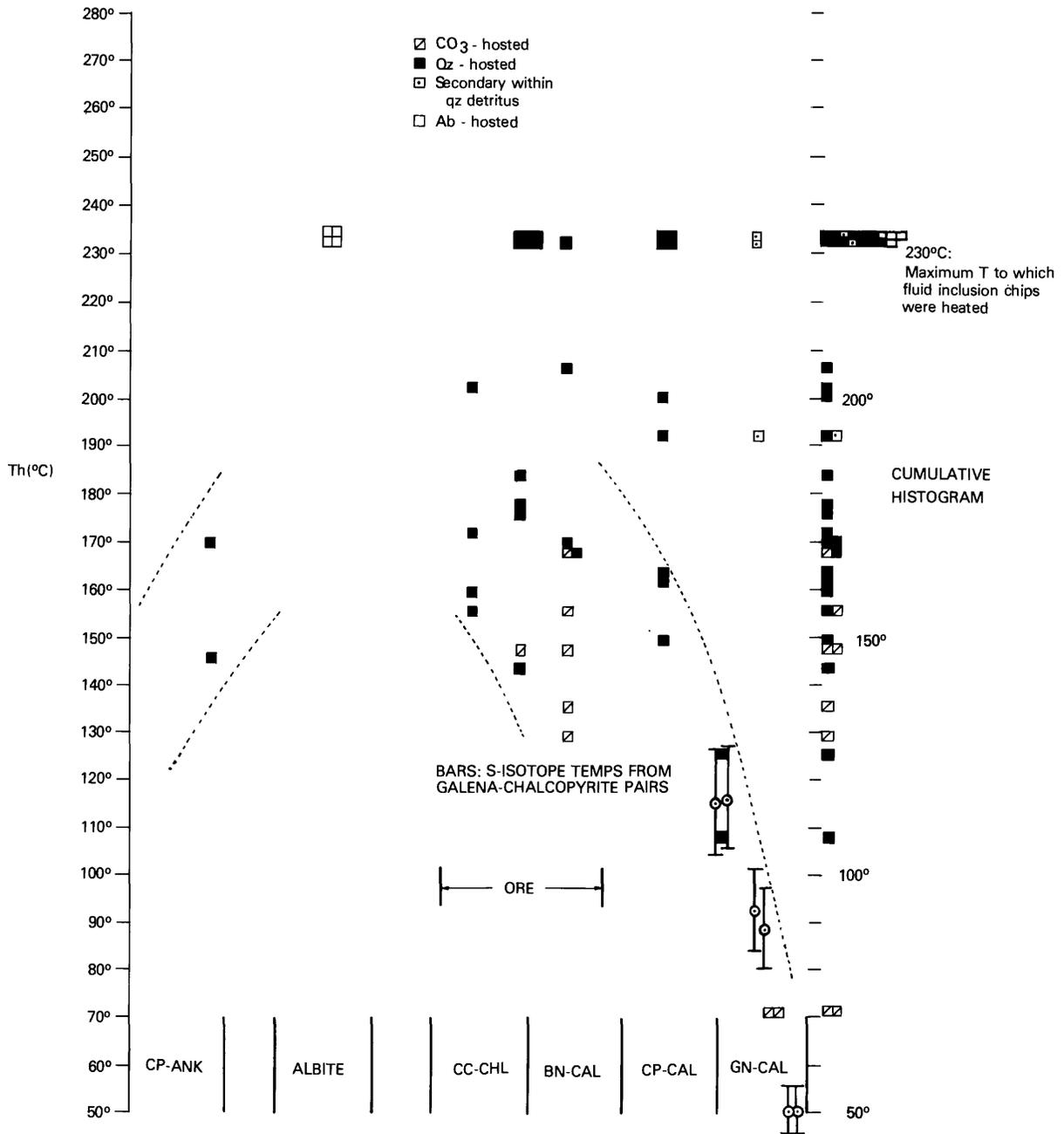


Figure 9. Homogenization temperatures in type 1, L-V inclusions by mineral zone.

failed to renucleate a gas bubble on cooling. The bubble returned after a 2-day treatment in an icewater bath following which the sample, still in icewater, was ultrasonified. As it came back, an adjacent L inclusion also nucleated a bubble. Given the rock's history and certain homogenization temperatures down to 74 °C, it is suggested preliminarily that the 1-phase liquid inclusions are either very low temperature end members or have been metamorphically homogenized. The latter is possible because L inclusions are present even in samples from which homogenization temperatures ( $T_h$ ) of around 70 °C, but none less than 130 °C, are found in L-V inclusions (BORNITE-CALCITE zone); presumably these L inclusions from the BORNITE-CALCITE zone are not low temperature inclusions.

Vapor bubbles in most L-V inclusions move rapidly around their inclusion at room temperature. Those with proportionally smaller bubbles have the most active bubbles.

Homogenization temperatures in L-V inclusions indicate temperatures of over 130 °C in the ore zones and indicate that those zones had temperatures higher than those in either the GALENA-CALCITE or CHALCOPYRITE-ANKERITE zone. The L-V inclusions homogenize to the liquid at a great variety of temperatures (fig. 9). Importantly, inclusions from one GALENA-CALCITE zone sample where a sulfur-isotope temperature had earlier been established include two that homogenize at temperatures within the error of the sulfur isotope measurement. Two more  $T_h$ 's fall within the general range of sulfur isotope temperatures (fig. 9). Those samples, and all other samples, also have other inclusions, not visibly different in any way, that homogenize only above 190 °C. These other inclusions may be L-V inclusions that were stretched or necked in later diagenesis or metamorphism, thereby ruining their systematics (Bodnar and Bethke, 1984; Goldstein, 1986). Ore zone (BORNITE-CALCITE and CHALCOCITE-CHLORITE) samples have no inclusions that homogenize under 130 °C, but the GALENA-CALCITE zone, which had a maximum measured sulfur isotope temperature of about  $115^{+10}_{-9}$  °C, has none that homogenize between 130 °C and 190 °C (fig. 9). The  $T_h$ 's that fall within sulfur isotope errors and the very regular gradations of  $T_h$ 's, zone to zone, with directions consistent with an extrapolation of the sulfur isotope T's, suggest that all measured  $T_h$ 's below the (?stretched?) group at 190 °C—and-above are valid. As a result, the data indicate that BORNITE-CALCITE and CHALCOCITE-CHLORITE zone temperatures were above 130 °C, probably around 150–170 °C, and most importantly, that ore zone temperatures were higher than the temperatures in either the GALENA-CALCITE or CHALCOPYRITE-ANKERITE zones.

Salinity measurements on 21 inclusions are widely scattered with little correlation between temperature and salinity (fig. 10). However, all final meltings from the GALENA-CALCITE and CHALCOPYRITE-ANKERITE zone to date have been metastable (>0 °C). This may be a problem with controlling temperature-ramping rate of the stage and not any characteristic of the inclusions, themselves. Visual characteristics of inclusions with metastable final-melting temperatures (smaller, fast-moving bubbles at room T) suggest that this preliminary salinity data set does not yet clearly represent the part of the mixing zone where the pre-ore, very dilute porewater was dominant. Combined observations, including  $T_h$ 's, inclusion behaviors, and bubble sizes, strongly suggest that the CHALCOPYRITE-ANKERITE zone did not form at



temperatures greater than the CHALCOCITE-CHLORITE zone, and that it therefore was not a higher-temperature feeder zone. The second hypothesis on ore fluid hydrology is thus supported. This is further supported by the occurrence of trace amounts of galena and sphalerite found in the CP-ANK zone suggesting conditions more like the GALENA-CALCITE zone. Microprobe measurements of Mn in the carbonate cements also support the conclusion that temperatures were lower in CHALCOPYRITE-ANKERITE zone than in the ore zones (fig. 11). Manganese in the carbonates is at a maximum near the boundary of BORNITE-CALCITE and CHALCOCITE-CHLORITE zones and falls off both towards the GALENA-CALCITE and CHALCOPYRITE-ANKERITE zones.

From all of these studies, it is concluded that the hottest part of the ore system of the Troy orebody was the CHALCOCITE-CHLORITE zone, not the CHALCOPYRITE-ANKERITE zone. Thus, ore solutions at Spar Lake fed principally from below before spreading along permeable sandstones (fig. 12).

#### IDENTIFICATION OF METAL-SOURCE ROCKS

The above findings suggest that (1) all mineral zones mapped and described at and near the Troy mine (fig. 4) are rocks that have been metasomatized under conditions of falling temperature and mixing between ore fluids and pre-ore porewaters, and (2) there should be a feeder zone and the feeder zone is not CHALCOPYRITE-ANKERITE. The feeder zone should be an extrapolation of the zonation diagram of figure 4 from both left and right toward the boundary between CHALCOPYRITE-ANKERITE and CHALCOCITE-CHLORITE zones, and beyond, as if spatially back towards the source of metals. Hypothesis 2 correctly represents the ore fluid hydrology. The deposit is essentially a large scale pseudomorph of the pre-ore pyrite/hematite interface, an interface that approximates what is now the CHALCOCITE-CHLORITE/CHALCOPYRITE-ANKERITE zone boundary (fig. 12).

Because of earlier work by U.S. Geological Survey colleagues, it was clear that the extrapolative feeder zone had already been sampled and partially described. Connor and others (1981), working at Blacktail Mountain, 70 miles east of Spar Lake, described four different lognormal populations of copper abundance from a set of over 3,500 samples (fig. 13). They interpreted that a lognormal sub-population of samples with very low copper values were the source rocks providing copper to rocks with high abundances. The same four populations of copper abundance were also apparently found in sparse regional sampling of the Ravalli Group basin-wide, including the Spar Lake area (J.E. Harrison, personal commun., 1979). Many of Harrison's regional thin sections and hand samples were still available for examination. His correlation of the old copper analyses to Connor and other's (1981) findings was first confirmed (fig. 14). Then, using Harrison's other analytical data, numerous additional elemental cross plots were made to attempt to relate elemental characteristics to the known authigenic mineral zonation and paragenesis with many of the rocks now assignable to a Spar Lake mineral zone (fig. 15).

The population of "depleted" rocks collected by Harrison included samples from near Plains, Montana, where petrographic study had earlier established much of its mineralogy and petrogenetic history (fig. 16).

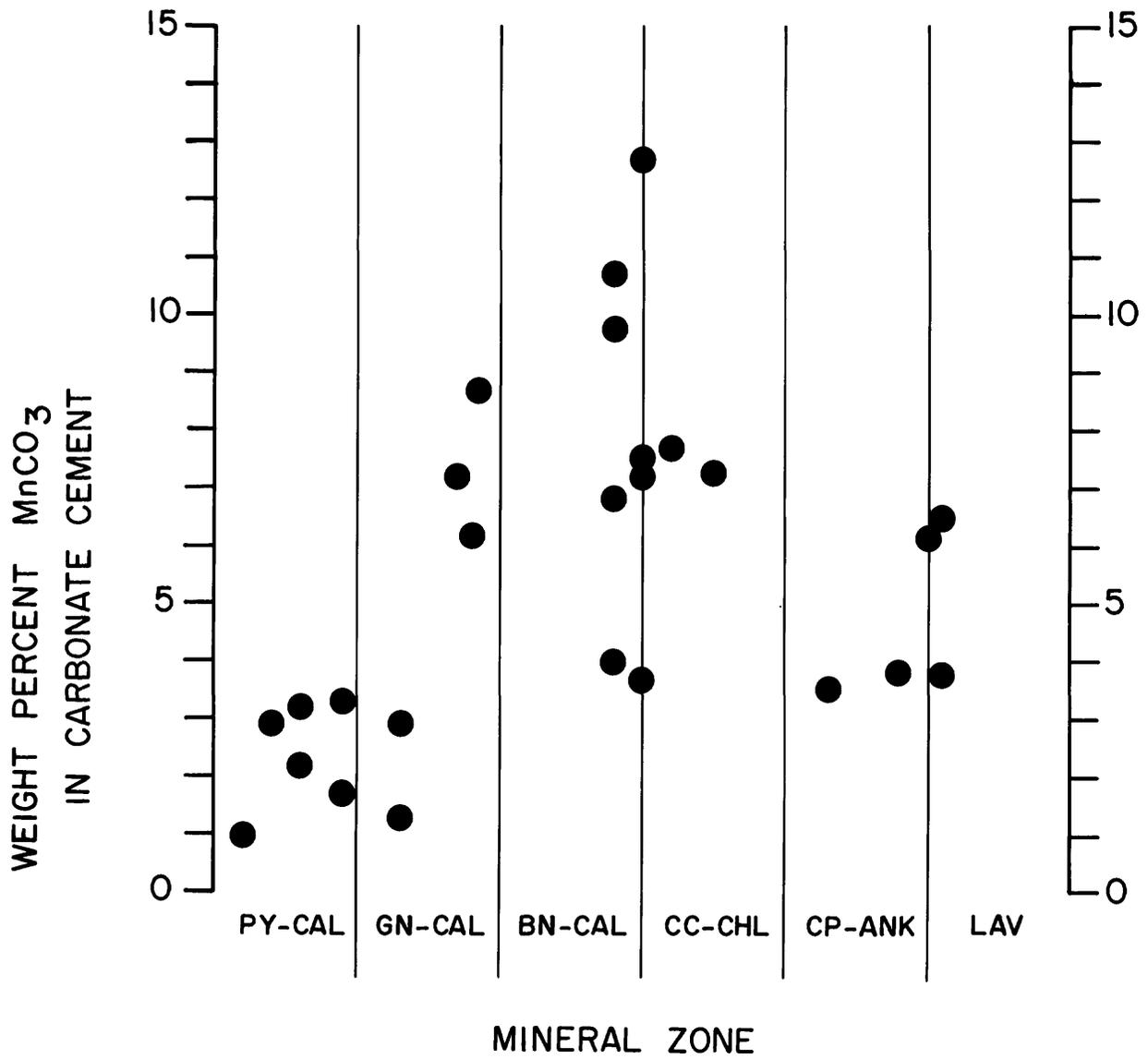


Figure 11.  $MnCO_3$  contents of carbonate cements across the mineral zonation, determined by electron microprobe. Abbreviations as in figure 4. Compare with figure 9.

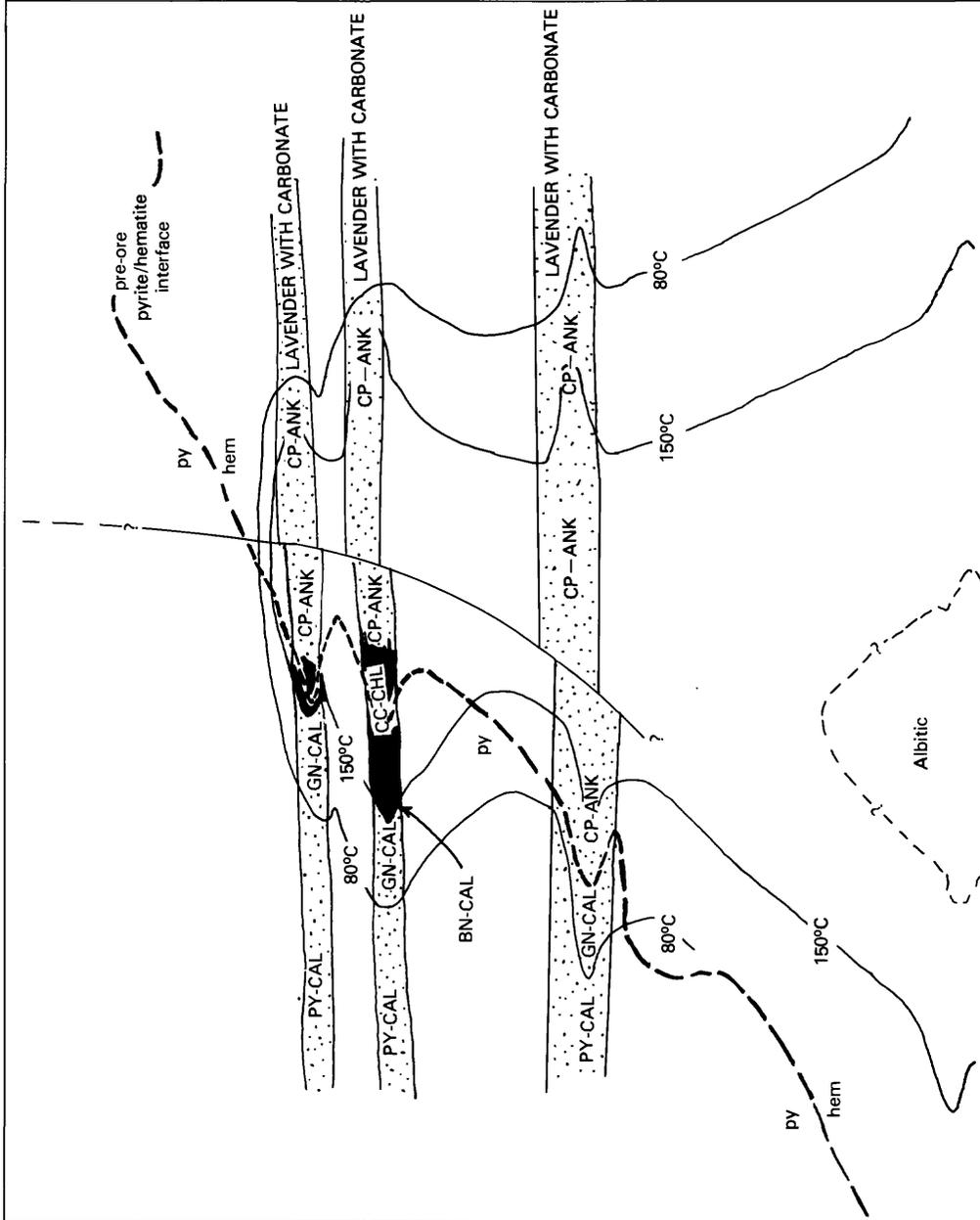


Figure 12. Model of genesis of Revett Formation-hosted strata-bound copper-silver deposits. Elevated temperature isotherms represent lines of equal ore fluid flux. Ore deposits form only along pre-ore pyrite-hematite interfaces within a much larger fluid flow system. Upward fluxes were probably greatest around zones of cross-stratal permeability such as early faults. Abbreviations as in figure 4.

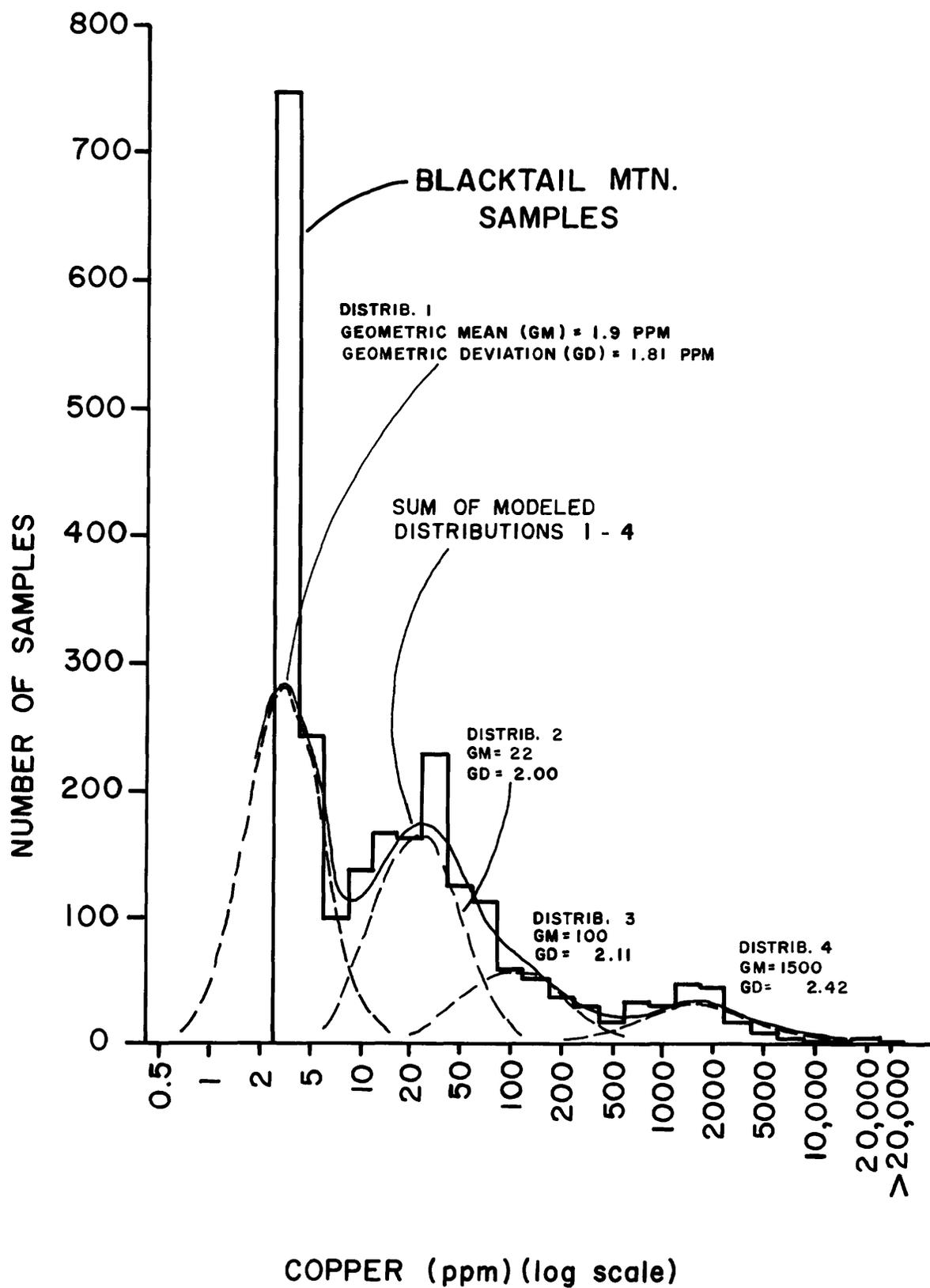


Figure 13. Copper abundances in samples from Blacktail Mountain, Montana. From Connor and others, 1981.

WALLACE 1° X 2° QUADRANGLE, MT. & ID.  
 X-RAY SPECTROSCOPIC COPPER  
 BURKE & REVETT FORMATIONS

108 samples

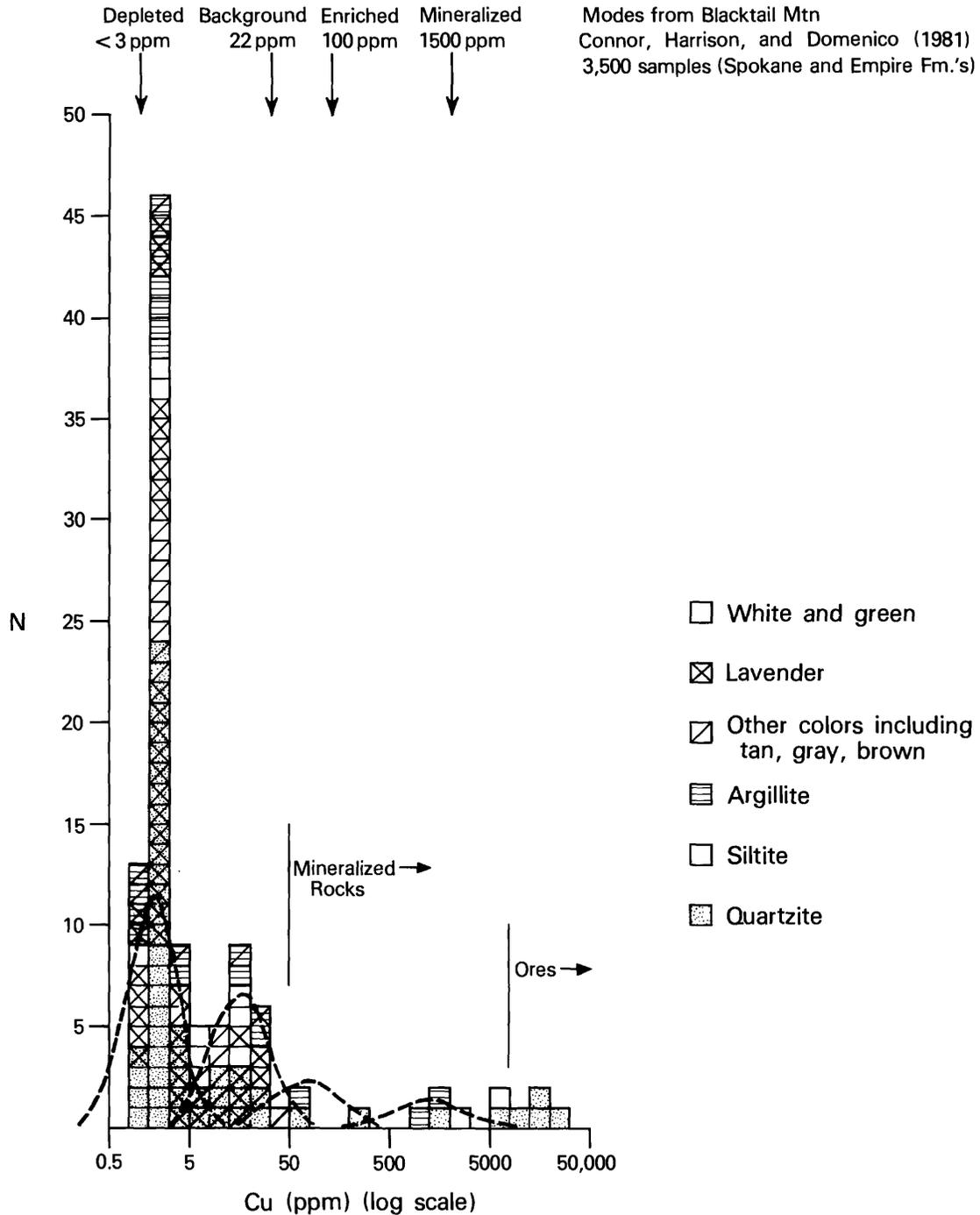


Figure 14. Copper abundances in samples of the Burke and Revett Formations, Wallace 1°x2° quadrangle and adjacent areas. Data from J.E. Harrison (written communication, 1987).

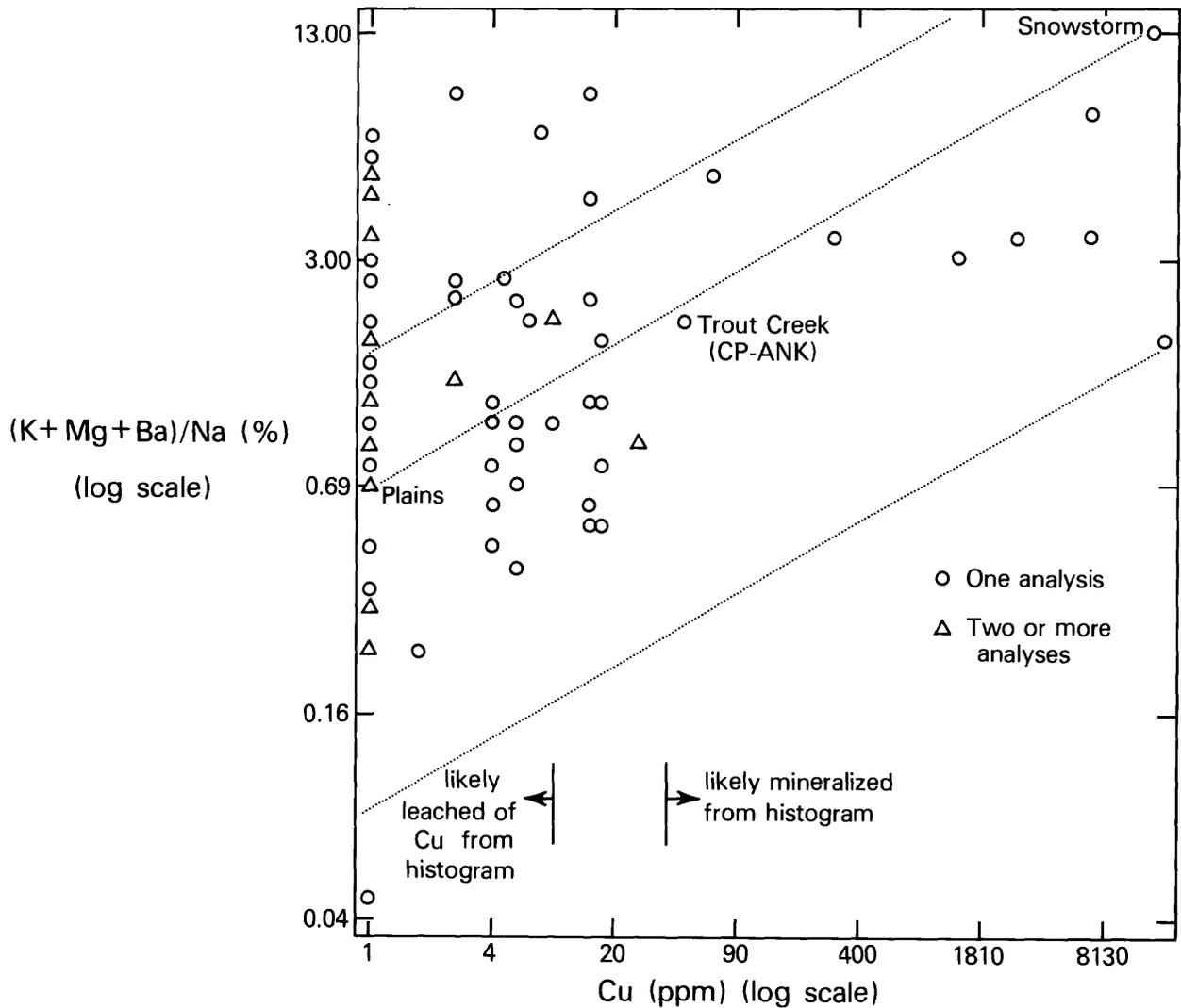


Figure 15. Cross plot of the derived metasomatic variable,  $\frac{K+Mg+Ba}{Na}$ , versus Cu, in samples of the Burke and Revett Formations, Wallace 1°x2° quadrangle, and adjacent areas. K metasomatism is due to K-feldspar overgrowths. Mg metasomatism is due to chlorite and carbonate cements. Ba metasomatism is due to barite, barium-rich K-feldspar overgrowth, and barium-rich mica cements. Na metasomatism is due to albite cements and replacements. Cu, Mg, and Ba analyses by X-ray spectroscopy. K and Na analyses by flame atomic adsorption spectroscopy. Compare with figures 5 and 17. Dotted lines indicate general bi-metasomatic trends in a regional, lateral- and vertical-secretion ore system. Interpretations of copper "leached" and copper "mineralized" come from figures 13 and 14. Abbreviations as in figure 4. Plains, Trout Creek, and Snowstorm are individual sample location results from locations shown in figure 1.

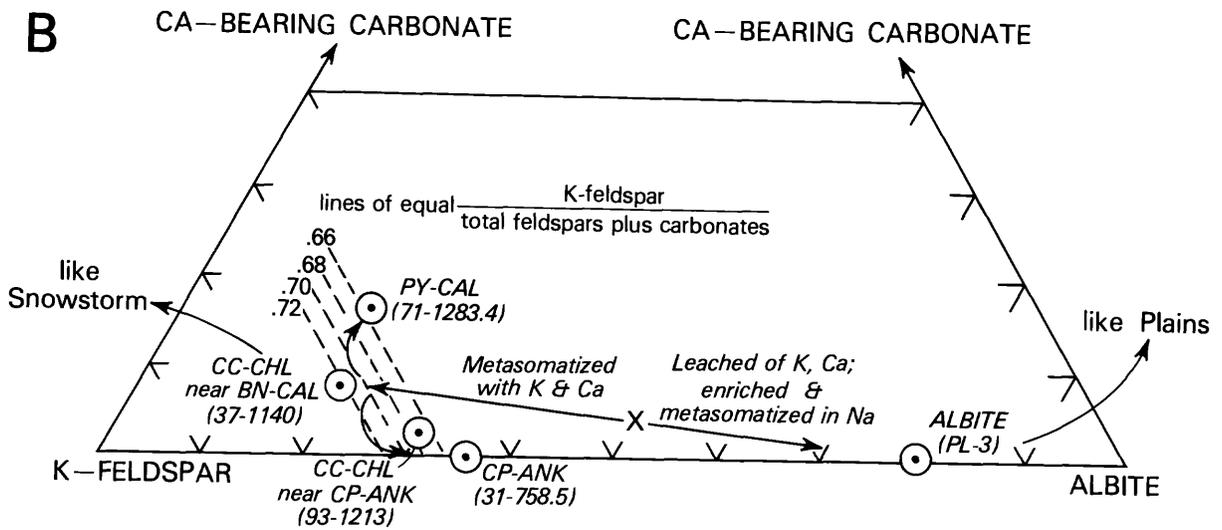
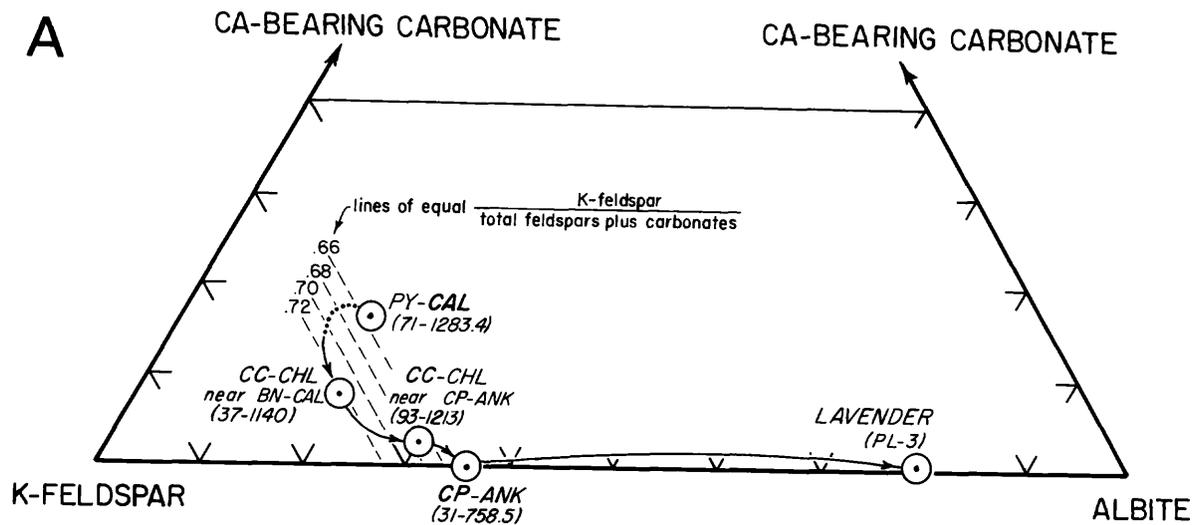


Figure 16. Petrographic point-counting data from Revett quartzites of identical depositional lithofacies but different mineral zones from Hayes and Einaudi (1986) interpreted (A) as with hypothesis 1 (roll-front-like hydrology), and (B) according to the correct hypothesis 2 (upwelling and spreading with differently reactive pre-ore wallrocks, the pyritic and hematitic sides of the pre-ore front of figures 5 and 12). 2,000 points were counted per thin section. Abbreviations as in figure 4.

This work identified the ALBITE zone (fig. 17), a zone of copper mobilization that probably represents copper source rocks. ALBITE zone rocks are hematite- and magnetite-bearing, very albitic, carbonate-free rocks that are devoid of all sulfides and relatively depleted in potassium (figs. 15, 16, and 17). They are Ravalli Group pre-ore red beds that have been albitized in areas adjacent to, and probably downsection from the deposits. The rocks are commonly lavender-gray but may be green, yet still magnetite-bearing and carbonate-free. Notably, in both Connor's extensive local data and Harrison's sparse regional data, approximately 70 percent of the total number of all samples from the Ravalli Group are depleted of their original copper and probably belong within the ALBITE zone.

Authigenic, untwinned, cementing albite from the ALBITE zone was examined for its fluid inclusions (fig. 8C). Four L-V inclusions in the first examined sample from Plains did not homogenize by 230 °C (fig. 9).

### CONCLUSIONS AND DISCUSSION

Results from the combined studies of the Spar Lake deposit, particularly the studies of petrogenesis and thermometry, combine to demonstrate that the deposit is epigenetic, not syngenetic as interpreted by Garlick (1987, 1988). Most of the fluid inclusions measured here are in overgrowth quartz that is demonstrably the earliest part of the ore-stage paragenesis. The majority of the ore sulfides are younger than this overgrowth quartz at any one site, but sulfide inclusions do occur within the overgrowths, confirming the overgrowth's early ore-stage interpretation. Dust rims of hematite or pyrite/leucoxene post-date sedimentation but pre-date the overgrowths, so ore mineralization was a second stage of cementation. Syntaxial quartz overgrowths could not have been precipitated on still-suspended sediment grains without the overgrowths showing some re-abrasion. The detrital quartz grains must have been at least stabilized prior to overgrowth. Both the sulfur isotope temperatures and the fluid inclusion homogenization results show that the site of mineralization was a thermal anomaly relative to the surrounding, laterally continuous sandstones.

Other conclusions are that:

1. The Spar Lake deposit formed at a subsurface mixing zone between an introduced ore solution with temperature over 130 °C and salinity over 10 weight-% equivalent NaCl and pre-ore porewaters that were very little saline and under 50 °C.
2. The deposit mimics a tongue-shaped pre-ore pyrite-hematite interface. (All other well-described red bed-associated strata-bound copper deposits also mimic pre-ore pyrite/hematite interfaces; at most the pre-ore pyrite/hematite interface was a sedimentational contact between an underlying red bed section and an overlying pyritic, carbonaceous siltstone, dolostone, or shale.)
3. The CHALCOPYRITE-ANKERITE zone is not an "alteration tongue" feeder zone, but rather is the thermal equivalent of GALENA-CALCITE zone formed in pre-ore hematitic sandstone (fig. 12). Ore-stage reactions bleached the CHALCOPYRITE-ANKERITE zone by replacing or dissolving the hematite dust

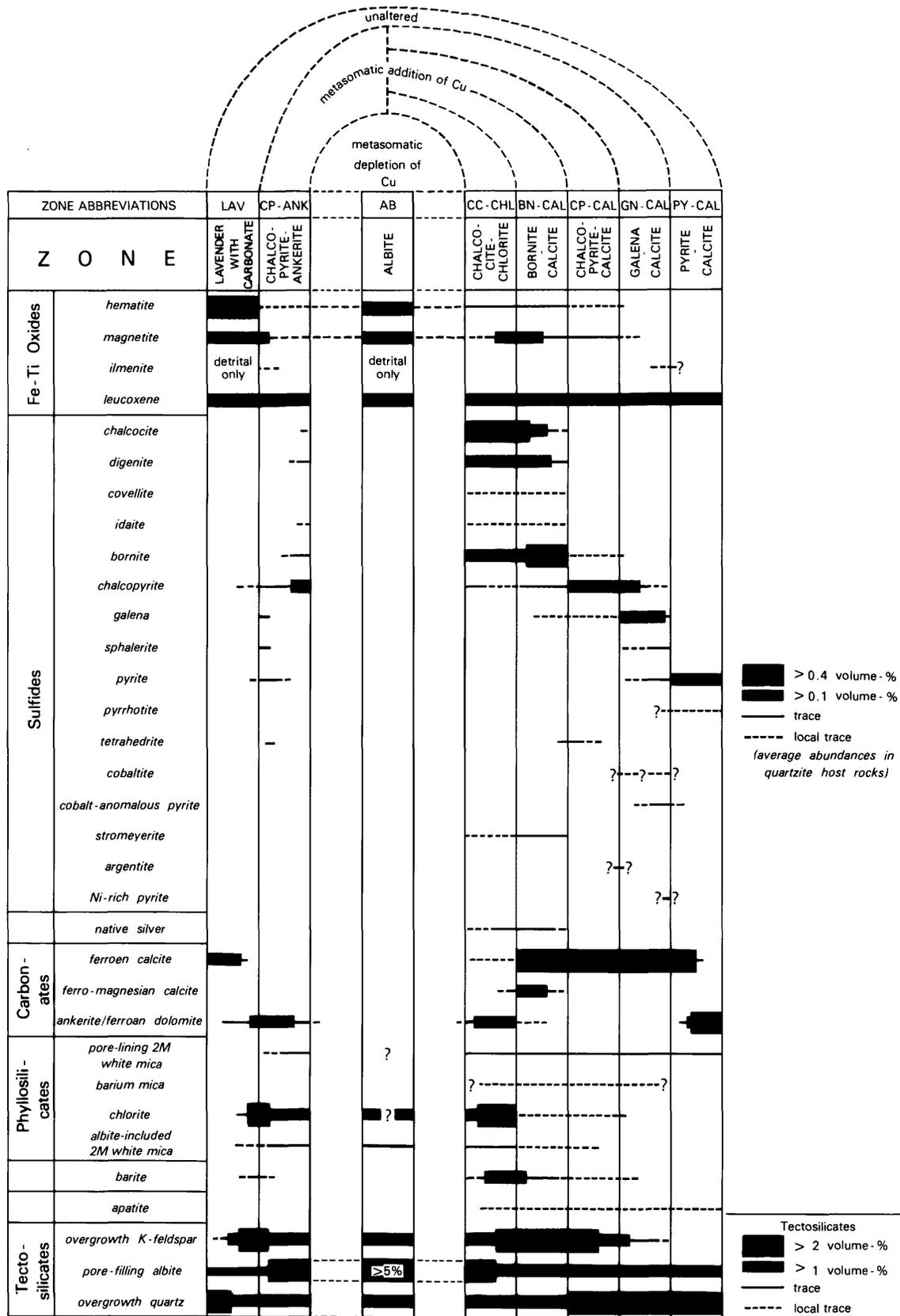


Figure 17. Revised diagram of authigenic mineral zonation of Revett, Burke, and St. Regis Formation quartzites in the western Montana copper sulfide belt. Compare with figures 4 and 12.

rims. Ore solutions welled up from below, employing or creating water-escape structures, then spread laterally along permeable sandstones. Corollary: The proper direction to explore from a known GALENA-CALCITE/CHALCOPYRITE-ANKERITE zone boundary (fig. 12) is laterally along the pre-ore pyrite/hematite interface moving either upsectionward or downsectionward as necessary towards intersections with a zone of greater ore fluid flux within favorable metasandstones. Water escape probably also occurred along growth fault zones. One possibility that is supported by several lines of evidence, but cannot yet be demonstrated, is that Spar Lake's East graben was probably such a growth fault zone, with faulting active at a time post-dating upper member host rock deposition.

4. Carbonate-free, hematitic (though not everywhere lavender-colored), magnetite-bearing, strongly albitic, Ravalli Group rocks are a zone of copper mobilization for Revett-hosted deposits. They are metals source rocks, UPSTREAM (Brown, 1989). Though such rocks have not yet been found plumbed into a deposit site, all petrographic and geochemical characteristics of these rocks suggest such a place will be found. Recognition of the albitic zone as the probable metal source is of importance in both exploration for new deposits and mineral resource potential assessment. The ALBITE zone rocks have lost virtually all of their original copper and so are absolutely non-prospective for deposits of this specific type. The ALBITE zone might be quickly mappable by airborne geophysics employing potassium gamma spectrometry to sense its depletion in K relative to all other zones together with magnetics to sense its magnetite (figs. 15, 16, and 17). Vast areas of non-prospective ALBITE zone rocks are already identifiable from Harrison's regional geochemical sampling. With additional work, other mineral zones may also be mappable through their outcrop areas by this proposed airborne geophysical method. ALBITE zone rocks are very strictly non-prospective. Such mapping might be useful in mineral resource potential assessments needed by government public land administrators and would be useful to mining companies needing to limit the areas they wish to explore.
5. In that the rocks of the ALBITE zone are depleted in potassium, magnesium, barium, calcium, copper, lead, and others, and are enriched in Na, some constraints are imposed on geochemistry of the ore solution, particularly if temperatures of mobilization can be determined. Data collected to date clearly indicate that this was not the Na-Ca-Cl-type brine suggested by Sverjensky (1987). The Revett ore solution stripped virtually all of the rock's calcium and carried it with it. At the site of mobilization, the ore solution was vastly undersaturated with respect to all calcium minerals. At that site it must have been very low in calcium. Furthermore, the fluid inclusion salinities measured to date generally do not indicate the necessary presence of large concentrations of divalent ions; only one inclusion had a final melting temperature under -22 °C. From these and currently unreported sulfur-isotope studies of orebody barite (Hayes and others, in prep.), the ore solution was very likely a Na-Cl-SO<sub>4</sub>-type brine, a member of the group of Salt Lake-type brines of Hardie and Eugster (1970).
6. Deposits of the Revett Formation were probably produced by thermally-driven basinal dewatering (Jowett, 1986) of the connate waters of a then-

buried proto-oceanic rift basin filled with Burke, Revett, and St. Regis Formation red beds. Thermometry studies clearly indicate that the orebody is the site of a temperature gradient of over 100 °C and indicate that temperature differences of up to 200 °C existed between the copper source (ALBITE) zone and its sink (the orebody). The deposits are gigantic examples of lateral and vertical secretion. Second stages of ore mineralization (Mauk, 1989) would be predicted with each succeeding thermal pulse affecting such a buried basin. Such pulses might be marked by renewed, probably basaltic, magmatism and repeated depositional sequences of continental red bed-up-to-marine carbonate cyclic deposition. In fact, it might be predicted that red bed-associated copper deposits will be found only in basins where a repeat of that sedimentary cycle is found, signalling the existence of the heat flow drive. Each succeeding stage of mineralization would be increasingly veinlet-controlled because earlier stages increasingly cemented (lithified) the sediments.

7. Truly syngenetic deposits are easily possible with our current understanding of processes. The thermal plume produced by basinal dewatering ore fluids need only reach the sediment-water interface (fig. 12). Spar Lake, though, is not syngenetic, and any truly syngenetic deposits of this class were not formed from ambient temperature, continentally derived fluids of the types called for in current syngenetic theories.

#### ACKNOWLEDGMENTS

Though this work has shown that Bill Garlick was in error about the syngenetic origin of the Spar Lake deposit, Bill's years of careful observations in red bed-associated stratabound copper deposits contributed immeasurably to the knowledge of this class of deposits. He has stalwartly continued an important debate, and his bringing of that debate to Spar Lake was partial impetus for continuing this work. As noted in conclusion 7, Bill may still prove correct at many places about syngenetic timing of some among this class of deposits. I know my feelings will be shared by many who have worked on these deposits as I say that Bill Garlick is deserving of recognition for his lifetime of contributions to our science.

ASARCO, Inc., Northwest Exploration Division provided access to the Troy mine and five other Revett-hosted prospects. They also provided long-term financial and other support. Some of the work reported here was supported by a National Research Council post-doctoral associateship at the U.S. Geological Survey isotope geology labs in Denver. Earlier work by Jon Connor and Jack Harrison, USGS colleagues, contributed critically to understanding the ALBITE zone. Dave Leach, Bob Burruss, Al Wallace, Al Hofstra, and Lanier Rowan, also USGS colleagues, have helped me with work on the fluid inclusions. Joe Whelan and Bob Rye, yet other USGS colleagues, also provided discussion, and Joe reviewed the abstract of this paper and suggested significant improvements. Al Wallace and Al Bush reviewed earlier versions of this manuscript and also suggested improvements.

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