CONTACT INFORMATION
Mining Records Curator
Arizona Geological Survey
416 W. Congress St., Suite 100
Tucson, Arizona 85701
520-770-3500
http://www.azgs.az.gov
inquiries@azgs.az.gov

The following file is part of the

James Doyle Sell Mining Collection

ACCESS STATEMENT

These digitized collections are accessible for purposes of education and research. We have indicated what we know about copyright and rights of privacy, publicity, or trademark. Due to the nature of archival collections, we are not always able to identify this information. We are eager to hear from any rights owners, so that we may obtain accurate information. Upon request, we will remove material from public view while we address a rights issue.

CONSTRAINTS STATEMENT

The Arizona Geological Survey does not claim to control all rights for all materials in its collection. These rights include, but are not limited to: copyright, privacy rights, and cultural protection rights. The User hereby assumes all responsibility for obtaining any rights to use the material in excess of "fair use."

The Survey makes no intellectual property claims to the products created by individual authors in the manuscript collections, except when the author deeded those rights to the Survey or when those authors were employed by the State of Arizona and created intellectual products as a function of their official duties. The Survey does maintain property rights to the physical and digital representations of the works.

QUALITY STATEMENT

The Arizona Geological Survey is not responsible for the accuracy of the records, information, or opinions that may be contained in the files. The Survey collects, catalogs, and archives data on mineral properties regardless of its views of the veracity or accuracy of those data.

ASARCO

Southwestern Exploration Division

September 7, 1976

TO: W. L. Kurtz

FROM: F. T. Graybeal

Fluid inclusions as guides
to porphyry copper deposits

Halite-bearing fluid inclusions occur in or near the ore zone in most known porphyry copper deposits and their recognition can be a useful exploration guide. The attached report presents a general summary of the occurrence of fluid inclusions in porphyry copper systems and a detailed description of how they can be studied using routine petrographic techniques.

I have also attached a new U.S.G.S. open file report with a similar title by J. T. Nash. His report briefly covers the same ground as mine, although his emphasis is mainly on the occurrence of halite-bearing inclusions. The Nash report is an outgrowth of his paper delivered at the 1972 AIME Annual Meeting and is to be published as a chapter in U.S.G.S. Prof. Paper 907.

My report is not meant for casual reading and will be of little use to anyone without access to a good petrographic microscope. Although my past work has been entirely concerned with porphyry copper deposits, it will be interesting to see whether useful work can be done on precious metal deposits as well.

F. T. Graybeal

F. T. Graybeal

FTG:lb
Atts.

FLUID INCLUSIONS AS GUIDES TO PORPHYRY COPPER DEPOSITS

F. T. Graybeal — July 28, 1976

INTRODUCTION

Recent fluid inclusion studies of porphyry copper deposits have demonstrated the existence of chemical variations in hydrothermal fluids which are systematically related to zones of ore-grade mineralization. These studies indicate that minerals of the potassic alteration zone, particularly chalcopyrite, possess a close space-time relationship to a dense, high temperature brine. Evidence concerning the distribution of these brines is preserved in fluid inclusions and can be easily recognized using standard petrographic techniques.

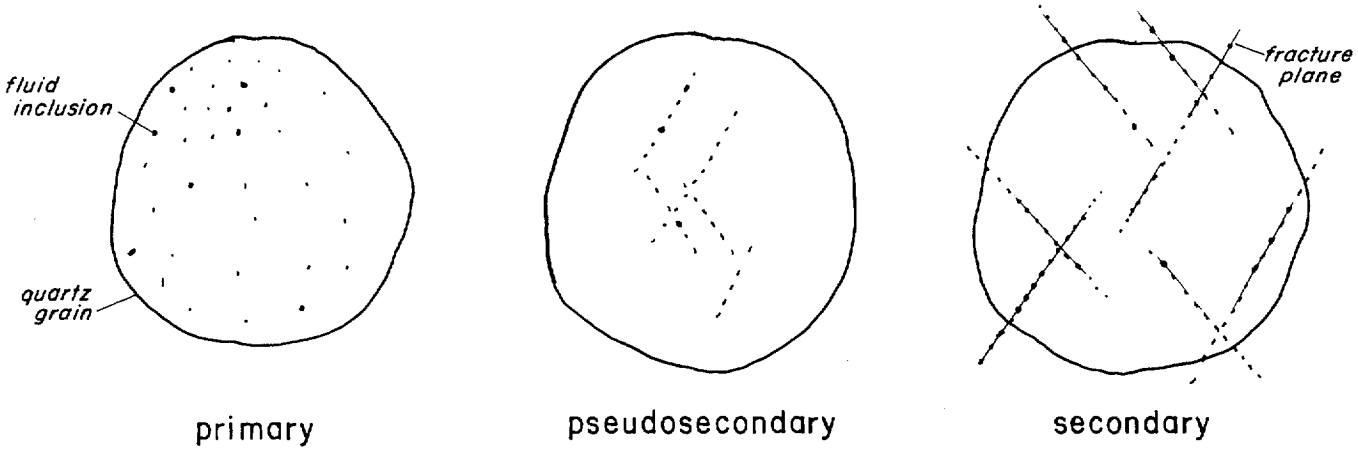
The purpose of this report is to discuss the distribution of fluid inclusions in porphyry copper deposits and the procedures involved in fluid inclusion studies. The practical value of such studies was first noted by Nash and Theodore (1971) and was subsequently emphasized by Nash in a paper presented to the 1972 Annual Meeting of the A.I.M.E. Since then I have corresponded with Nash several times, have reviewed all pertinent literature, and have studied fluid inclusions in roughly 1000 thin sections from more than 40 porphyry copper deposits. The majority of the references cited are primarily concerned with fluid inclusions in porphyry copper deposits and do not include many excellent papers on other types of ore deposits.

TYPES OF FLUID INCLUSIONS

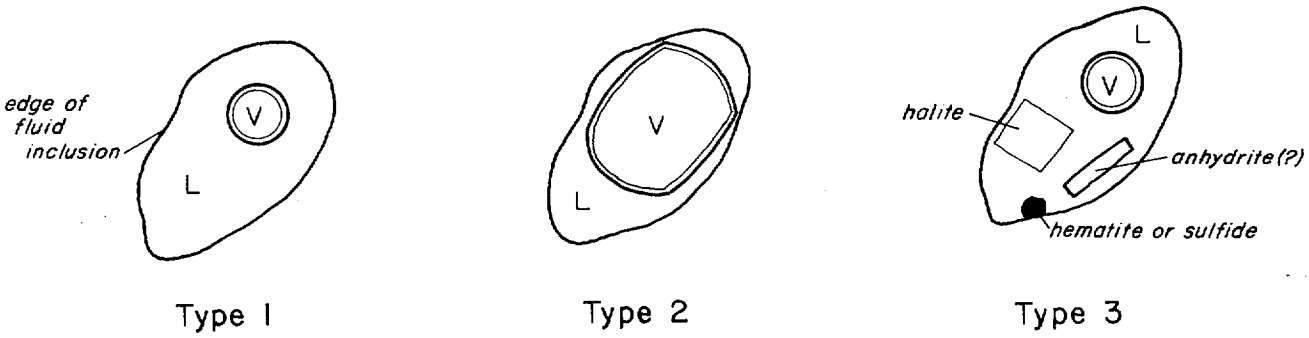
Fluid inclusions are tiny drops of liquid or bubbles of gas which become trapped on the surfaces or in cross-cutting fractures of growing crystals. Fluid inclusions do not generally leak during cooling and are thus thought to represent samples of the fluid present in the rock at the time of entrapment. Most inclusions are less than 0.01 mm. in diameter and they rarely form more than 0.1 volume percent of the sample. Where abundant they may contribute to the milky color seen in some varieties of quartz. One of the best summaries of fluid inclusion theory is the paper by Roedder (1968).

Several classifications of fluid inclusions are possible, as shown on Figure 1. The classification according to age or occurrence recognizes three different types. Primary inclusions are those trapped during growth of the host mineral. Their distribution is either random or related to crystal growth zones and they are often larger than other inclusion types. Pseudosecondary inclusions are those trapped along a fracture during growth of a mineral. They are recognized by alignments of inclusions which terminate within a mineral, often at a growth zone; the controlling fracture plane is often not seen, presumably due to recrystallization of the mineral during later growth. Secondary inclusions are those trapped along a fracture after growth of the mineral was complete. They are often smaller than other inclusion types and the fracture plane along which they were trapped is often still visible.

According to occurrence (size of inclusion somewhat exaggerated)



According to phases present (other types also possible)



EXPLANATION

L - liquid
V - vapor

FIGURE-1 CLASSIFICATION OF FLUID INCLUSIONS

A second classification of importance to porphyry copper exploration is based on the composition of the fluid as determined from the nature of the phases present. Nash and Theodore (1971) used this classification as follows:

Type 1 - liquid and a small gas bubble
Type 2 - liquid and a large gas bubble
Type 3 - liquid, a gas bubble, and one or more daughter minerals.

Type 1 fluid inclusions are the most common variety and contain a variable amount of liquid, usually some type of water solution, and a small gas bubble. The bubble is the result of shrinkage of the originally homogenous fluid during cooling (the coefficient of contraction of the fluid upon cooling is several orders of magnitude greater than the host mineral). The gas bubble usually occupies less than 30% of the total inclusion. The volume of the bubble can provide a qualitative estimate of the original filling temperature with the larger bubble equivalent to a higher temperature, assuming similar trapping pressures, fluid compositions, and ages. Occasionally, a second liquid phase, commonly CO_2, is seen below about 25°C (77°F) occurring as a thin meniscus around the vapor bubble. Type 1 inclusions represent low salinity fluids which were too dilute to nucleate any daughter minerals. The relative abundance of Type 1 inclusions is greatest in the peripheral zones of porphyry copper deposits.

Type 2 fluid inclusions are recognized by a large gas bubble which forms 50-95% of the inclusion volume. They represent the entrapment of a gas, from which a small amount of liquid is formed by condensation during cooling. The salinities of the liquid are somewhat variable as will be discussed below. Type 2 inclusions indicate the former presence of boiling conditions, particulary when they coexist with Type 1 inclusions in the same growth zone or fracture. Their relative abundance is greatest in the central and upper portions of porphyry copper systems.

Type 3 fluid inclusions contain a liquid, a gas bubble of variable size, and one or more daughter minerals. These minerals form during cooling when the liquid becomes saturated with various components of the solution. Identification of the daughter minerals can yield a great deal of information concerning the chemistry of the liquid from which they crystallized. The number of minerals present in a single inclusion varies from one to ten or more depending on the density and chemical complexity of the fluid. In addition, because the distances in fluid inclusions are small and cooling is generally slow, the various daughter minerals have had time to reach a minimum surface free energy and, therefore, the number of crystals is equal to the number of different mineral species. Very small inclusions may fail to nucleate solid phases, although this phenomenon does not seriously distort statistical studies because very small inclusions can't be seen at normal petrographic magnifications. In addition, minerals such as sulfides and oxides occasionally nucleate several crystals of the same species, a phenomenon apparently related to their extreme insolubility.

Type 3 fluid inclusions containing halite, with or without other daughter minerals, are relatively most abundant within the higher grade chalcopyrite zones of porphyry copper deposits. The presence of halite at

room temperature means that the composition of the fluid exceeded 26 wt. percent NaCl at the time of entrapment. The nearly ubiquitous presence of halite within and immediately adjacent to hypogene ore zones makes its recognition a very useful ore guide; therefore, Type 3 inclusions containing halite should be distinguished from Type 3 inclusions containing other daughter minerals. Common daughter minerals also include opaques, sylvite, hematite, anhydrite, and a wide variety of other species.

An additional variety of fluid inclusion is commonly seen which is filled with liquid and contains no gas bubble. These inclusions are often amoeba-like in shape and are thought to have formed below 70°C. Numerous additional subdivisions of various inclusion types are possible depending on the varieties present and the purpose of investigation.

A possible source of confusion in the compositional classification of fluid inclusions concerns Type 2 fluid inclusions which contain a daughter mineral, usually a carbonate or sulfate. The daughter mineral is never halite indicating that the fluid was relatively dilute in chloride. For this reason I classify these as Type 2 inclusions due to the importance that a gas-rich inclusion has with respect to interpreting the position of the sample in the porphyry copper system. However, the presence and description of the daughter mineral should be recorded.

The shapes of fluid inclusions can be irregular, elongate, circular, or in the shape of the crystal morphology of the host mineral (negative crystal). The shapes may be due in part to post-entrapment recrystallization and their genetic significance is unclear.

DISTRIBUTION OF FLUID INCLUSIONS

Theory

The close space-time association of halite-bearing fluid inclusions and chalcopyrite in porphyry copper deposits has been well documented as will be discussed below. The association may be genetic due to the experimentally well-documented ability of chloride-rich brines to complex copper. This empirical relationship suggests that if the location of an NaCl brine could be predicted it would provide an excellent guide to the presence of zones of higher grade chalcopyrite.

The formation of a brine may occur in at least two ways. The first may involve simple separation of a brine from a silicate melt. This process is suggested by the presence of halite-bearing fluid inclusions which homogenize near the melting point of the host rock.

Brines may also be formed by boiling of a relatively dilute solution. Boiling in porphyry copper deposits is probably caused most commonly by a release of pressure, although the actual temperature and pressure at which boiling occurs depends on the composition of the liquid. Boiling develops two coexisting phases, a liquid and a gas. In the NaCl-H_2O system the compositions of the phases have been carefully studied by Sourirajan and Kennedy (1962) who found that at a given temperature and pressure the liquid is NaCl-rich and the gas is NaCl-poor. Continued boiling removes H_2O from

the liquid and enriches it in NaCl. Because the gas is lighter it will rise to the top of a system above the heavier brine which will remain at relatively deeper levels. Thus, a brine and associated chalcopyrite should be found within or below zones of strong boiling, a prediction which could be very useful during the evaluation of vertically zoned porphyry copper systems.

The occurrence of daughter minerals such as carbonates in Type 2 inclusions is partly explained by Takenouchi and Kennedy (1965). They found that the solubility of CO_2 is strongly reduced in NaCl-rich solutions as compared to pure H_2O. Thus, CO_2 will be partitioned into the NaCl-poor gas phase during boiling and, if present in sufficient concentrations, it will form carbonate minerals during the cooling of Type 2 fluid inclusions.

The presence of boiling is indicated by coexisting gas-rich (Type 2) and gas-poor (Type 1 or 3) fluid inclusions in the same grain. The evidence is generally considered conclusive when the two inclusion types coexist along the same fracture plane. Evidence from this study and the literature is strong that boiling of hydrothermal fluids was a common phenomenon during the cooling of porphyry copper systems and that knowledge of the distribution of boiling zones can be a useful exploration tool.

General Aspects

Table 1 is a summary of data from over 40 porphyry copper deposits and represents the average abundance within the ore zones or areas of strongest hydrothermal alteration. The data show that porphyry copper orebodies contain remarkably similar fluid inclusion populations. The data also show that the total abundance and abundance of primary, Type 2, and Type 3 (halite) fluid inclusions decrease from porphyry copper orebodies, through submarginal deposits, to barren intrusions. Table 1 also indicates what is obvious from a study of each deposit -- that the distribution of fluid inclusions is uniform within the ore zone down to the scale of a thin section.

Similar fluid inclusion abundances in the ore zones appear to be independent of:

1) rock type, which varies from quartz diorite in the Philippine Islands to granite porphyry at La Caridad

2) age of the deposit, which varies from Jurassic in British Columbia to Pliocene at Sar Cheshmeh

3) metallogenetic province, and

4) alteration type and strength, which vary from phyllic to potassic and nil to strong in degree of rock destruction.

However, the similar abundances must reflect dependence on some feature inherent to porphyry copper deposits. Presumably, as all samples studied were from the ore zones the fluid inclusion populations seen in the average porphyry copper are specifically related to the presence of copper sulfides.

TABLE 1: FLUID INCLUSIONS IN PORPHYRY COPPER DEPOSITS

PROVINCE[a)]	ABUNDANCE (0.04 mm^2.)	% PRIMARY	% TYPES 1	2	3
SW. U.S.A. (11)	100	70	40	40	20
CALIF.-NEV.-UTAH (5)	90	80	25	40	35
W. CANADA-ALASKA (7)	90	60	60	25	15
PHILIPPINE IS. (4)	20	70	50	20	30
IRAN (1)	120	80	50	30	20
PANAMA (1)	70	90	30	40	30
AVERAGE PORPHYRY COPPER (29)	80	75	40	35	25
AVERAGE SUBMARGINAL (11)	40	30	80	20	—
AVERAGE BARREN INTRUSION (5)	0-20	0-30	99	1	—

a) number of different deposits in each province given in parentheses

Lateral Variations

Nash and Theodore (1971) found that Type 3 fluid inclusions at Copper Canyon are centered on the east orebody, primarily in sedimentary rocks. They noted that Type 3 inclusions were not limited to or symmetrical about the adjacent intrusion. In a subsequent paper Theodore and Nash (1973) concluded that Type 3 inclusions were a better guide to ore than pyrite, which halo was too large, or rock geochemistry, which is anomalous over the intrusion.

In the Bingham district Roedder (1971) found that the abundance and volume of daughter minerals was sharply increased in the Cu-Mo core zone. Quantitative studies by Moore and Nash (1974) revealed that the distribution of high-salinity fluid inclusions followed the outline of the hypogene copper orebody. Similar relationships were found by Davis (1974) in the Kalamazoo orebody and by Cox et al (1975) in the Sapo Alegre prospect in Puerto Rico. Cox et al also found that the total abundance of all fluid inclusions was increased within the zone of higher grade copper mineralization. Nash and Cunningham (1974) also found that the major difference between fresh and altered rocks at Bagdad was that fluid inclusions were more abundant in the latter. Salinities of the inclusions were about the same in all zones of alteration. The only porphyry deposit not known to contain Type 3 inclusions is Ithaca Peak (Drake, 1972), although Type 2 inclusions are abundant. The above papers illustrate several practical aspects of fluid inclusion studies and should be reviewed by anyone

contemplating work of this type. Lateral variations similar to those described in the literature have been recognized at Silver Bell, Sacaton, Sierrita, Charleston (Tombstone district, Arizona), and Sunnyside (Patagonia Mtns., Arizona) and have been or will be reported on in considerably greater detail separately.

Vertical Variations

There is no data in the literature concerning vertical zoning of fluid inclusions and I suspect that very little data exists anywhere due to the rather limited number of deep drill holes in porphyry copper deposits. Several papers theorize the presence of a metal-rich brine below a boiling zone, the most notable being that by White et al (1971).

Data from Asarco drill holes at Charleston and Sunnyside provide one of the clearest pictures of vertical zoning of fluid inclusions in porphyry copper systems available anywhere. Both areas show that Type 2 fluid inclusions, often with daughter minerals, overlie a zone of Type 3 fluid inclusions which is closely associated with increased concentrations of chalcopyrite. In these two areas abundant Type 2 inclusions are restricted to areas of pervasive hydrothermal alteration and extend into the higher grade chalcopyrite zones. Type 3 inclusions are absent at the surface but become continuously present about 1000 ft. above and extend into the higher grade chalcopyrite zones. A somewhat similar zoning was noted by Cunningham (1976, p. 905). The zoning picture is exactly that predicted from theoretical studies and suggests that these concepts should have a wide application during porphyry copper exploration.

Discussion

It is not presently possible to place quantitative limits on the size of certain fluid inclusion zones with respect to the size of the porphyry intrusion, the size of the alteration zone, or the size of the ore zone. The extent of the inclusion zones appears to vary according to depth of exposure of the system and the permeability of the wall rocks and is complicated by the tendency for the various fluid inclusion zones to have gradational boundaries. Certain types of fluid inclusions are more common in certain alteration zones than others and in a general way the size of the fluid inclusion zones probably correlates most closely with alteration and sulfide mineral zones -- a reasonable observation considering they all resulted from passage of the same hydrothermal fluid.

The association of Type 3 fluid inclusions and the presence of chalcopyrite in porphyry copper deposits is so close as to be universal, the lone exception being Ithaca Peak, and leads to the speculation that the relationship might be quantified. Initial attempts at quantification led to the plotting of the abundance of Type 3 fluid inclusions against the hypogene grade of the deposit. Although a crude linearity was suggested a wide scatter was obvious particularly for Santa Rita and Morenci where hypogene grades are low and the abundance of Type 3 inclusions high. To adjust for the wide scatter I then plotted the average grade of the deposit including supergene copper enrichment against the abundance of Type 3 inclusions. Although supergene enrichment is unrelated to the formation of Type 3 inclusions, it was reasoned that the total grade of the deposit gave

a better estimate of the original amount of copper in the entire system than the hypogene grade alone. This approach allowed for the presence of possibly high grade hypogene zones which were destroyed during supergene enrichment. The results of this work for 27 deposits are shown on Figure 2a and, although a sizeable scatter is still present, the linearity was considerably improved. This work suggested that a semi-quantitative relationship did exist which might be refined even further.

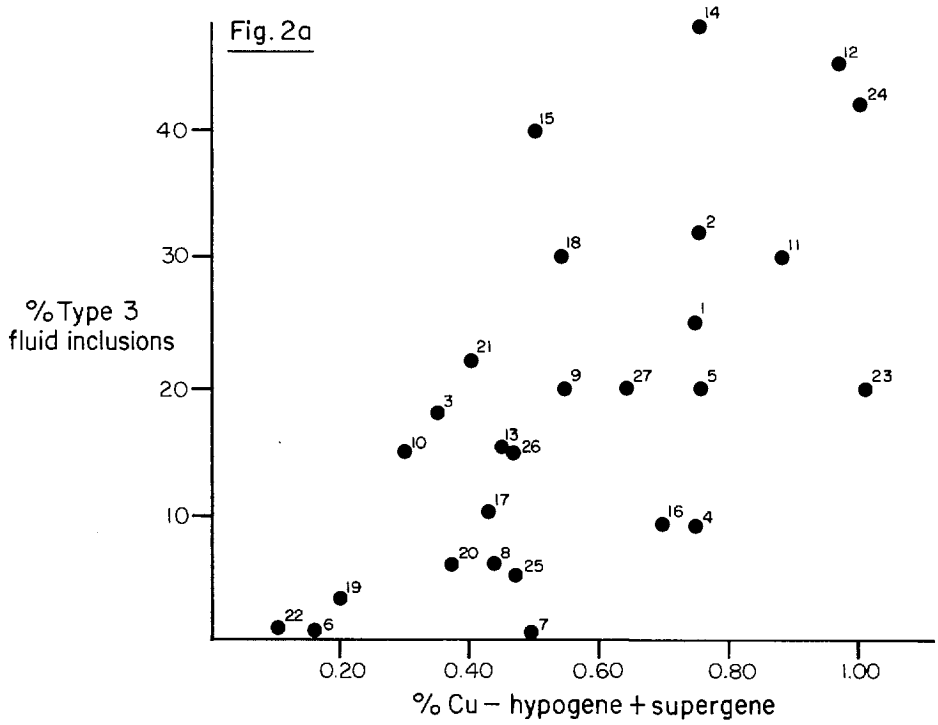
The wide scatter encountered in the first attempt to plot hypogene copper grades against Type 3 fluid inclusions may have resulted from the fact that many of the samples used came from zones of mixed potassic and phyllic alteration. Unknown, but possibly significant, quantities of phyllic alteration and associated abundant Type 1 fluid inclusions may have formed from late thermal collapse of the porphyry copper system. This would have the effect of reducing the relative abundance of Type 3 inclusions by addition of a population of fluid inclusions which were not related in time to ore deposition. To evaluate this possibility an additional graph was constructed which related hypogene copper grade to the abundance of Type 3 inclusions for samples containing only potassic alteration. The results are plotted on Figure 2b. The linearity of the relationship is impressive and allows the grade to be predicted within ±0.15% Cu with an accuracy of 93%. The relationship is even more impressive considering scatter caused by the different cutoffs used to calculate ore reserves and the variable number of thin sections available from the different deposits, and appears to be independent of size or rock type.

I emphasize that Figure 2b was constructed by using average hypogene copper grades for the entire orebody. Although a quantitative relationship between Type 3 fluid inclusions and copper grades is indicated, attempts to apply the relationship to individual assays or drill hole composite assays have met with no significant success. It is always interesting when geologic relationships can be quantified; however, I do not recommend using Figure 2b to predict copper grades. Rather, I would use the relationship qualitatively and expect that increased copper grades should be encountered in areas of more abundant Type 3 fluid inclusions.

COLLECTION OF DATA

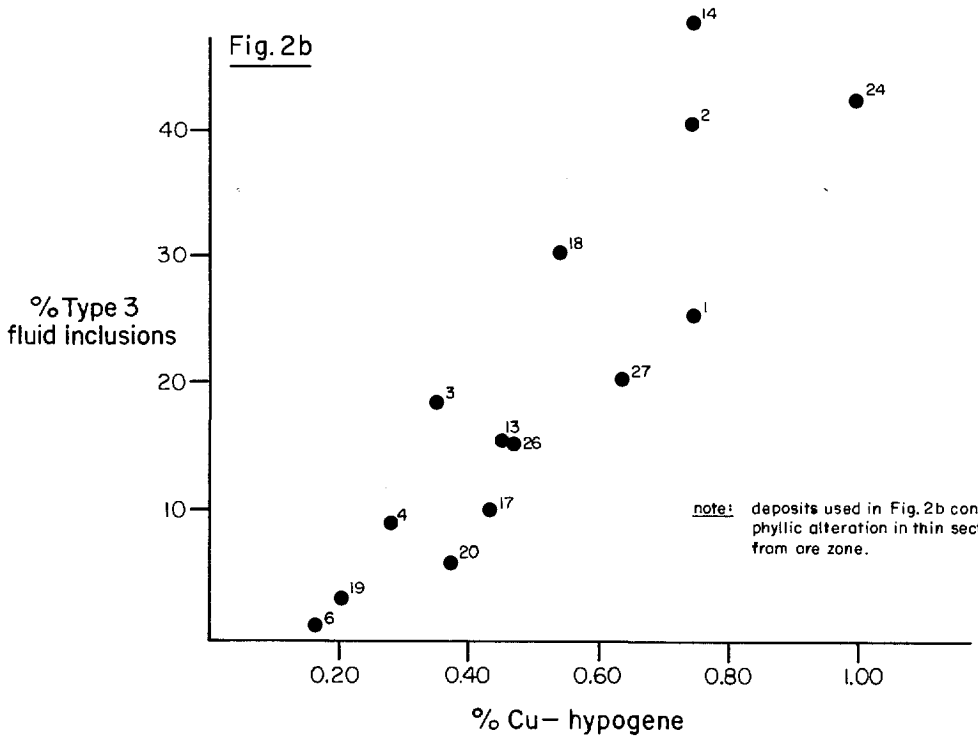
Sampling

Fluid inclusions occur in a variety of different minerals. Quartz is the most suitable mineral for the study of fluid inclusions in porphyry copper deposits due to its abundance, its widespread time-space distribution, its tendency to break easily and heal rapidly (thus trapping more inclusions than other minerals), and its resistance to weathering. The last is particularly important because hypogene fluid distribution patterns are retained during strong supergene alteration or tropical weathering as compared to hypogene alteration and geochemical patterns which are often strongly modified or destroyed. Also, large quartz grains invariably contain statistically more reliable fluid inclusion populations than small grains, particularly the fine-grained quartz in silicified rocks such as jasperoids. Other minerals such as fluorite, calcite, barite, topaz, and adularia may



LIST OF DEPOSITS

1. Aja
2. San Manuel-Kalamazoo
3. Sierrita
4. Silver Bell
5. Sacaton
6. Copper Basin (Bradshaw Mtns.)
7. Ithaca Peak
8. Sunnyside
9. Bisbee
10. San Juan (Safford)
11. Morenci
12. Santa Rita
13. Hillsboro
14. Bingham
15. Yerington
16. La Caridad
17. Lornex
18. Bethlehem
19. Brenda
20. Gibralter
21. Casino
22. Tok
23. Sar Cheshmeh
24. Sapo Alegre (Puerto Rico)
25. Atlas
26. Black Mtn.
27. Marcopper



note: deposits used in Fig. 2b contained no phyllic alteration in thin sections collected from ore zone.

FIGURE-2 RELATION OF TYPE 3 FLUID INCLUSIONS AND COPPER GRADE IN PORPHYRY COPPER DEPOSITS

also contain abundant fluid inclusions, but their distribution and abundance are usually too limited in porphyry copper deposits to permit spatial variations to be studied.

Sampling can be a problem due to the highly variable abundance of fluid inclusions in different ages of quartz in a single thin section and in adjacent rock types. Nash (pers. comm., 1972) comments that his procedures are based more on geology than statistics. At a given location he samples all rocks, all ages of veins, and all alteration assemblages being careful not to miss any part of the geologic record. The number of samples varies, but where the rocks are quartz rich one sample per rock or vein type is sufficient. He initially collects samples a few hundred feet apart and also includes some random samples, resulting in 200-300 samples for each deposit studied in detail.

My approach is also strongly based on the geology; however, I have found that 10-20 samples give a reasonable idea of the types of fluid inclusions present. If significant results are obtained and favorable geological, alteration, or mineralization patterns are present additional samples can be collected. During initial sampling I attempt to avoid quartz veins or fine-grained quartz, unless it is the only quartz available, for reasons discussed below.

Fresh rocks should also be sampled so that background abundances can be determined. Sampling programs should be kept flexible because individual prospects are too variable to permit construction of a rigid sampling approach.

Vertical zoning patterns can be interpreted with a much greater degree of accuracy by sampling intra-mineral rocks such as pebble dikes and intrusive breccias. These rocks may provide samples of deeper fluid inclusion populations which could only be inferred from surface data. Intrusive breccias and tuffs in the Sunnyside area contained angular quartz xenocrysts with Type 3 inclusions, strongly indicating the presence of an underlying brine zone. Intrusive breccias at Summitville contained quartz xenocrysts with abundant Type 2 inclusions, suggesting the presence of an underlying boiling zone. Rocks at the surface were essentially free of fluid inclusions, indicating a location in a zone of condensation which provided no information on either lateral or vertical zoning patterns.

Petrographic techniques

All of my work has been done with a Reichert polarizing microscope with a capability of 1250X magnification using an oil immersion objective. Most studies can be successfully performed in the 500-700X range without the use of immersion oils, which greatly speeds the studies. The studies utilize standard thin sections of the type used in routine petrographic studies. The thickness of these sections (0.03 mm.) results in the destruction of all fluid inclusions that size or larger. However, more than 99% of all fluid inclusions are smaller than 0.003 mm. so that essentially no useful data are lost. The thickness of the cover glass on conventional thin sections is 0.14-0.17 mm. which allows sufficient working room at 1250X to

permit the complete thickness of the section to be examined. Once some finesse has been acquired, a thin section may be checked for fluid inclusions in less time than it takes for a routine mineralogical description.

The more sophisticated equipment including freezing, heating, and crushing stages may also provide useful data; however, the equipment is expensive, its use is time consuming, and utilization will probably not significantly contribute to porphyry copper exploration at the present state of the art. Applications to exploration for other types of deposits probably exist, or will be developed, and the literature should be carefully watched in this regard.

Recording of data

Figure 3 is a typical data sheet which I use during routine studies. It is a Xerox of a portion of a geologic log and permits much data to be accumulated in a minimum amount of space. In addition, the tabular form serves to remind the investigator to check for all the variables to be noted below. The space at the right can be used to describe various aspects of inter and intra-granular variability, additional gas or liquid phases, mixed populations, inclusion shapes, vapor bubble movement, clarity of the quartz, or other notable features. Although there are a lot of columns to be used, I have completed thorough studies on as many as 50 thin sections in a single day. Data in this form can be easily summarized and transferred to maps or cross-sections for three-dimensional studies. The following discussion will discuss procedures to use and pitfalls to avoid when studying fluid inclusions (photomicrographs of various features are included in the Appendix).

1) Total abundance. Fluid inclusions may be initially recognized at low magnification as dark specks which resemble grit left during preparation of the slide. Total abundances must not be estimated at low magnifications because at this scale fluid inclusions can't be distinguished from particulate material which can be very abundant. Most fluid inclusions are so small that two or three may occur stacked above each other in a standard thin section with only one in focus at a time. Thus, when searching for them or estimating abundances one must look vertically within the grain as well as across it.

Total abundances are easily quantified by counting the total number of inclusions per unit area. At high magnifications (300-500X) the abundances are not so great to make actual counting too time consuming. Where abundances are high (more than 75) it is a simple matter to count the number of inclusions in a single quadrant and then multiply by 4 to determine the total. Examples of various abundances are shown on Fig. A-1 and A-2.

The overall abundance of fluid inclusion types gives a semiquantitative idea of the relative amount of hydrothermal fluid which passed through the rock and thus serves as a clue to the position of centers of hydrothermal activity. This is particularly true where the inclusions are of approximately equal sizes. However, fluid inclusions in peripheral zones are occasionally very small and quite abundant, and their importance can be overestimated if allowances aren't made for the variability of total abundance and size.

1.) Type of quartz: magmatic matrix or phenocryst, xenocryst, silicification, vein
2.) Abundance: note size of area
3.) Daughter mineral: give % of total inclusions of all types which contain each mineral
Additional columns for unknown daughter minerals, mineral associations, % gas in each inclusion type, alteration type, size of daughter minerals in addition to general remarks

PROJECT ____________________

FIGURE - 3

Sample number		Rock Type	Type of quartz (1.)	Inclusion size	Abundance (2.)	% Primary	% Type 1	% Type 2	% Type 3	Halite (3.)	Hematite	Opaque	Anhydrite	Sylvite											Remarks

2) Variability of total abundance. Extreme variations in the abundance of fluid inclusions within single quartz grains are readily visible in the peripheral zones of porphyry copper deposits (Fig. A-3). Abundances commonly vary from 0-150 includions/unit area, which makes it difficult to estimate an average abundance. This may appear to contradict earlier statements made regarding the pervasiveness of fluid movement; however, I regard it as a strong indication that the sample was located in an area where the movement of fluid may have been somewhat erratic on a scale of individual grains as might be expected near the margins of porphyry copper systems.

Variations in total abundance within single grains may also be present in the central portions of porphyry copper systems due to strong concentrations of primary inclusions along growth zones. These variations are generally minimized by the pervasive overprint of secondary inclusions.

3) Size of fluid inclusions. This parameter is rather difficult to quantify rapidly so I have used a semi-quantitative classification roughly as follows:

a) small - phases only visible above 700X; inclusions usually less than 1μ dia.

b) medium - phases only visible above 300X; inclusions vary 1-20μ dia.

c) large - phases visible at 120X; inclusions larger than 20μ.

Although it may be useful to separate the sizes according to fluid inclusion type, I have found that Type 2 inclusions are generally the largest. As with abundances, the variation in size is reduced and the overall size of a single inclusion type increases toward the center of porphyry copper systems.

4) Abundance of primary inclusions. Primary inclusions which do not occur along obvious growth zones are sometimes hard to distinguish from pseudosecondary and secondary inclusions. In addition, the tendency for fractures in quartz to heal without any indication of a break can also complicate the situation. Finally, I have seen abundant randomly distributed primary-looking inclusions in the alaskite in the Sunnyside area which are clearly zoned about a Laramide hydrothermal center. The age of the alaskite is Jurassic and the primary-looking inclusions occur in coarse-grained, igneous quartz. Therefore the inclusions are unquestionably secondary, even though they have an unquestionably primary appearance. The importance of the primary appearance in this case may not lie so much in the age of the inclusion as in the fact that the quartz grains have been extensively healed, presumably by the heat and fluids present in the center of the hydrothermal system. Thus, primary-looking inclusions may still provide information as to the location of the center of the system, regardless of the accuracy of the age classification.

5) Type 1 fluid inclusions. Although the absolute abundance of Type 1 fluid inclusions increases toward the center of a porphyry copper system, the relative abundance strongly decreases. Type 1 fluid inclusions may

preserve important information concerning temperature and salinity variations, but this information is generally not available in studies of the type discussed here because heating and cooling stages are required. Rough estimates of temperature may be possible and will be described below. The shapes of Type 1 inclusions are generally irregular and, because they are often the smallest of the three main types, care should be taken not to underestimate their abundance (an example of a Type 1 inclusion is shown in Fig. A-4).

6) Type 2 fluid inclusions. Type 2 inclusions often contain so much gas (+90%) that the small liquid meniscus is difficult to see due to the strong negative relief of the interior portion of the inclusion. This can be partly compensated by using the condensing lens to concentrate the passage of light within the inclusion. Care should be taken not to record a Type 1 inclusion which has leaked as a Type 2 inclusion, although this is probably not a serious source of error during estimation of abundances. It is sometimes difficult to distinguish Type 1 from Type 2 inclusions particularly where an elongate Type 1 inclusion is oriented perpendicular to the slide. This can occasionally be recognized because only one end of the fluid inclusion is in focus at a time. The problem is not usually serious because the different physical state of the material being trapped and the different chemistries of the trapped aqueous solution often result in different shapes of the two inclusion types; Type 2 inclusions are often rather round or in the shape of negative crystals. Generally, the difference in the volume of the gas bubble in Type 1 and Type 2 inclusions is obvious. Because Type 2 inclusions are often much larger than the other two types, care should be taken not to overlook the smaller varieties when estimating abundances (see Fig. A-5).

7) Type 2 daughter minerals. Type 2 daughter minerals, where present, are often rather large in spite of the relatively small volume of the liquid phase. Opaque minerals are generally absent and halite is absent by definition. My impression is that these daughter minerals may often be the same as the adjacent mica and clay minerals which occur as alteration minerals within the enclosing rock. The abundance, size, and description of Type 2 daughter minerals should be recorded.

8) Type 3 fluid inclusions. A Type 3 fluid inclusion contains halite with or without other daughter minerals (see Fig. A-6 and A-7). Many times other daughter minerals which commonly occur with halite will be present, although halite may be absent. Nash and Cunningham (1974) referred to these as Type 1 inclusions; however, such usage tends to complicate the terminology established by Nash and Theodore (1971) and followed by most subsequent papers. My procedure is to record the abundance (in percent) of all Type 3 inclusions and then record the abundance of each daughter mineral. Thus a quartz grain may contain 20% Type 3 inclusions where 15% contain halite, 9% contain hematite, and 4% contain an opaque.

Many quartz grains contain mineral inclusions which are not related to fluid inclusions. Care should be taken not to record these as sites of Type 3 inclusions. Such particulate material may be abundant and can lead to serious errors in fluid inclusion abundance estimates. Extremely large fluid inclusions which have leaked during preparation of the slide can usually be distinguished from the occluded mineral species.

9) Type 3 daughter minerals. The presence of daughter minerals is generally established only at higher magnifications. The high relief, colored, and opaque minerals are readily visible, even in very small inclusions. Many of the low relief anisotropic minerals can be recognized by viewing the slide with crossed nicols and looking for tiny flashes of light as the stage is rotated. The presence of isotropic minerals is not always obvious from their optical characteristics due to interference from the host mineral. Other optical characteristics such as extinction angles are also of limited use. Some of the more diagnostic optical properties of daughter minerals include crystal morphology, color, birefringence, and anisotropism.

Identification of halite is often difficult and, because of its importance to a correct interpretation of porphyry copper fluid zoning, procedures are discussed in somewhat greater detail. The most diagnostic characteristic of halite is its perfect cubic morphology. Although it might be confused with fluorite on the basis of shape, halite has a much lower relief. The low relief of halite can be a source of difficulty when searching for crystals in the smaller fluid inclusions. Thin sections should be viewed at variable light intensities, with and without the condensing lens, to make certain that the low relief and colorless aspects of halite are not so washed out by the intense light as to make the mineral invisible. In addition, because of their nearly identical indices of refraction the contact between halite and quartz is often invisible. Halite-bearing inclusions often tend to occur together in certain areas of single quartz grains so several different portions of the same grain should be examined before recording an abundance estimate.

A list of common daughter minerals is given on Table 2 along with common diagnostic characteristics. Very often an identification is not possible; however, the characteristics of the mineral should be recorded so that its distribution may be determined and information on the compositional zoning of the fluids gained. A very significant breakthrough has been reported recently by Metzger et al (1975) who have shown that scanning electron microscopy can be a powerful tool for the identification of daughter minerals in fluid inclusions. They have succeeded in identifying a number of unknown daughter minerals from Jamestown, Colorado previously described by Nash and Cunningham (1973). It would be useful to have samples of the fluid inclusions so that specimens of these known daughter minerals would be available for comparison with on-going projects.

Additional data which should be routinely recorded include the volume percent of each daughter mineral in the fluid inclusion, the total number of daughter minerals in the inclusions, and any consistent daughter mineral associations. Such information reveals variations in the complexity of the trapped fluid which can be useful.

10) Various liquid-gas species. Several different gas species are occasionally recognized in fluid inclusions. The commonest additional liquid other than the aqueous solution is CO_2. Liquid CO_2 forms at about 25°C (77°F), but commonly evaporates under the microscope due to heat from the substage light. The presence of liquid CO_2 can be recognized as a second rim around the gas bubble and may be observed by either cooling the

section with acetone or cooling the thin sections in an icebox and then observing them as they warm to room temperature. Carbon dioxide is predicted to be most abundant adjacent to or above brine zones, but is occasionally reported in Type 3 inclusions. In addition to CO_2, Roedder (1971) has observed H_2S in the Bingham deposit.

TABLE 2: CHARACTERISTICS OF COMMON DAUGHTER MINERALS IN FLUID INCLUSIONS

Halite:	square cross section; isotropic but may remain a uniform gray under crossed nicols; colorless; index of refraction is very close to quartz.
Sylvite:	rounded-squarish; isotropic but may remain a uniform gray under crossed nicols; colorless to yellow; index of refraction (1.490) is considerably below quartz.
Anhydrite:	tabular-elongate, orthorhombic morphology; anisotropic with moderate birefringence and parallel extinction; colorless.
Calcite:	anhedral-rhombohedral; anisotropic with high birefringence; colorless.
Dawsonite:	sheaves and radial aggregates of hairlike crystals; strongly anisotropic with high birefringence; strong relief; pale green - tan.
Sericite:	elongate, wispy; anisotropic with moderate birefringence; colorless.
Hematite:	occasionally shows hexagonal outline; opaque to red translucence to orange yellow with decreasing thickness.
Sulfides:	opaque grains, sometimes equant.
Magnetite:	opaque; octahedral if you're lucky; occasionally can be moved within an inclusion with a strong magnet.

11) Size of the gas bubble. The size of the gas bubble is a qualitative measure of inclusion trapping temperatures given roughly equal pressures and can thus provide information as to the higher temperature portions of porphyry copper systems. The variations can occasionally be semi-quantified (Cox et al, 1975). Roedder (1968) provides a useful chart for estimating volume and also discusses some of the problems encountered.

Discussion

The distribution of fluid inclusions in porphyry copper alteration zones is summarized on Table 3. Included on Table 3 are order of magnitude estimates of the change for each variable which are often logarithmic as a linear function of distance. Figures 4, 5, and 6 illustrate idealized spatial variations of the more reliable fluid inclusion parameters for different porphyry copper systems. Table 3 and Figures 4-6 represent a composite picture of a typical porphyry copper deposit and, although individual deposits will vary from what is considered typical, the variations will result from differing abundances and not from different zoning patterns.

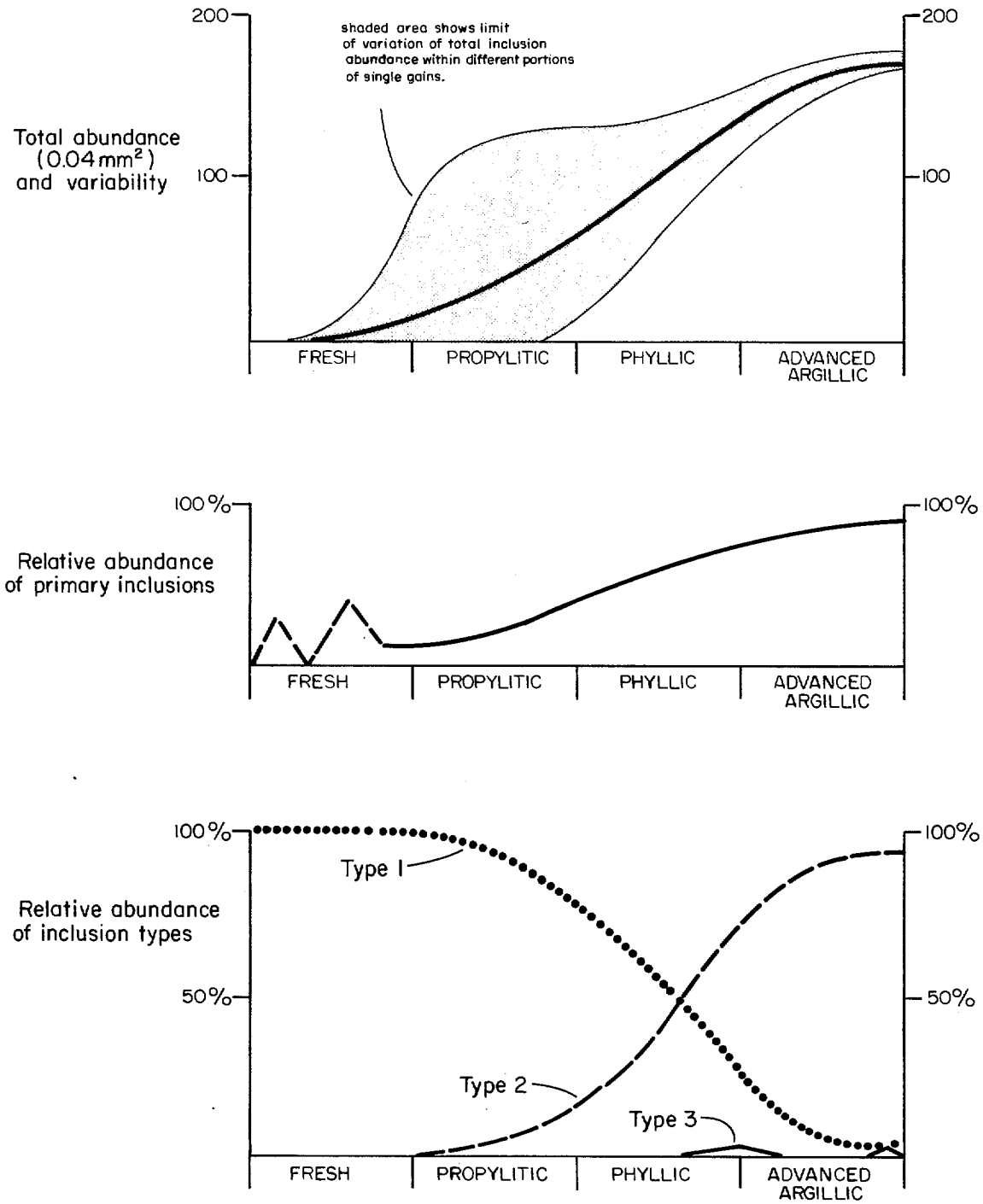


FIGURE-4 DISTRIBUTION OF FLUID INCLUSIONS IN A SHALLOW, LATERALLY ZONED PORPHYRY COPPER SYSTEM

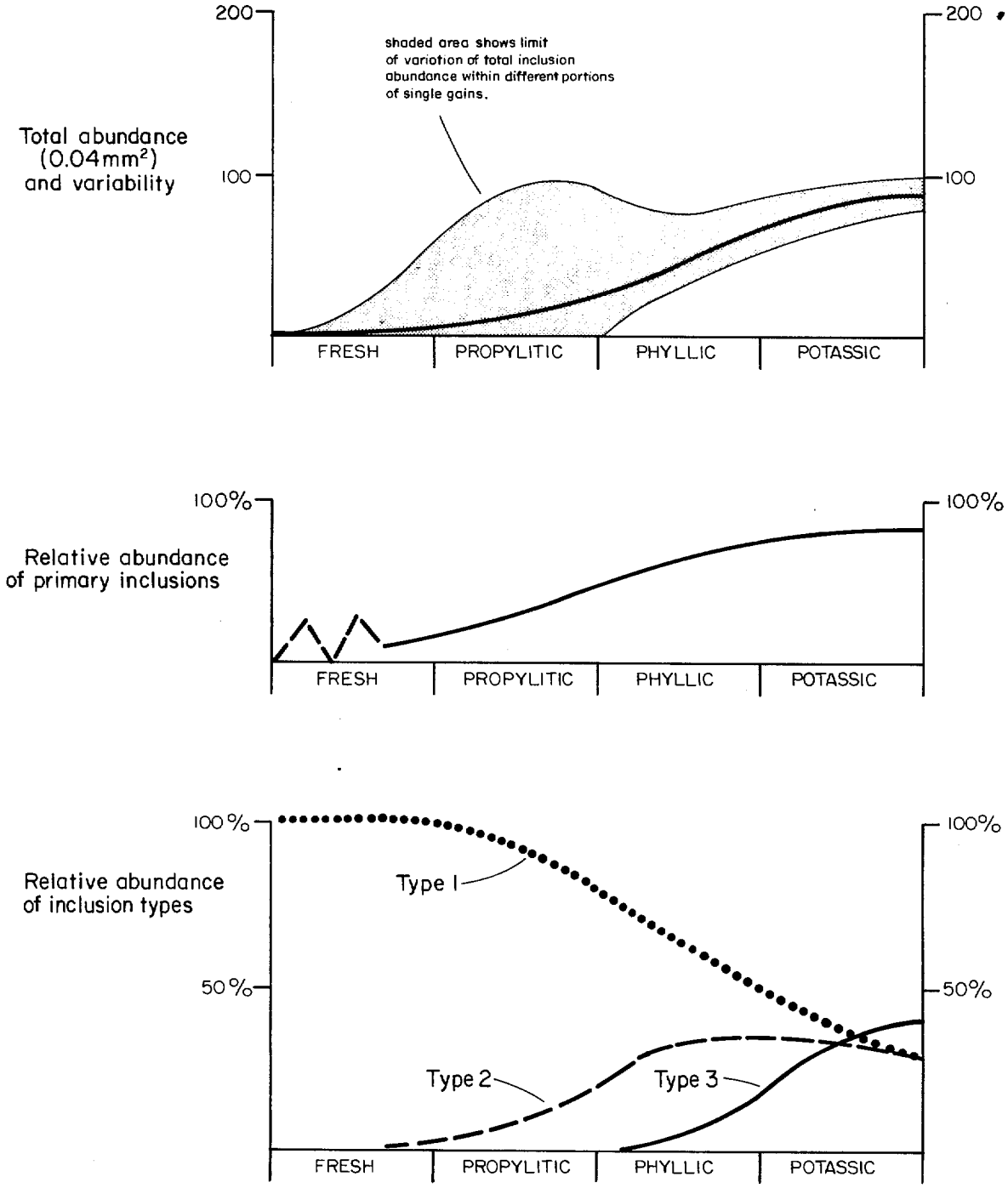


FIGURE-5 DISTRIBUTION OF FLUID INCLUSIONS IN A DEEP, LATERALLY ZONED PORPHYRY COPPER SYSTEM

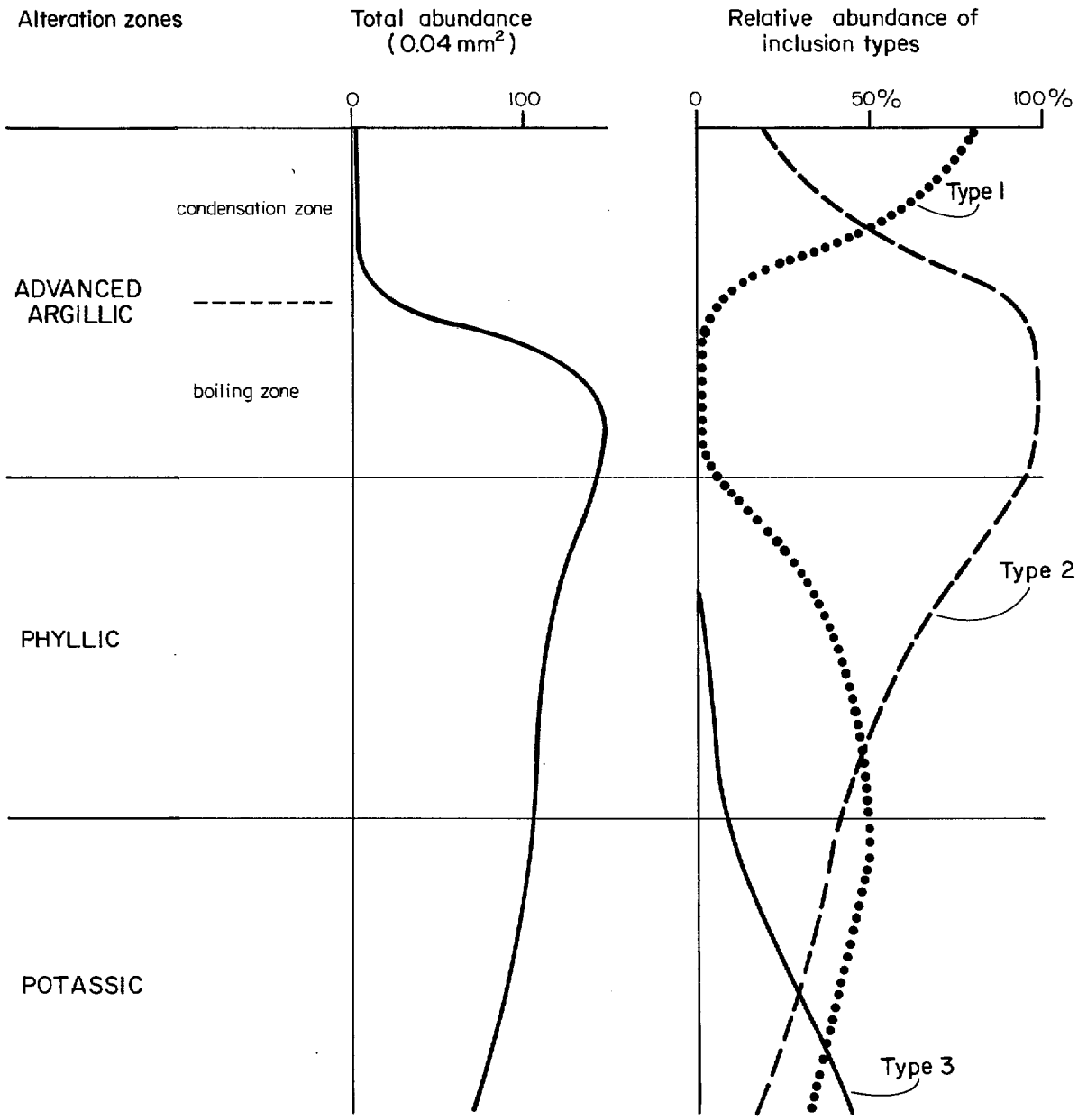


FIGURE-6 DISTRIBUTION OF FLUID INCLUSIONS IN VERTICALLY ZONED PORPHYRY COPPER SYSTEM

TABLE 3: DISTRIBUTION OF FLUID INCLUSIONS IN PORPHYRY COPPER ALTERATION ZONES

CHARACTERISTIC	FRESH	PROPYLITIC	PHYLLIC	ADVANCED ARGILLIC	POTASSIC
1) Total abundance/0.04 mm^2.	2	20	80	120[1)]	100
2) Intragranular variability of total abundance/0.04 mm^2.	0-5	1-130	60-120	80-140	90-110
3) Size of inclusions	small	small-medium	small-large	small-large[1)]	medium-large
4) Abundance of primary inclusions	10%	30%	60%	80%	80%
5) Abundance of Type 1	99	95	55	4[1)]	40
6) Abundance of Type 2	tr	5	40	95[1)]	30
7) Number of Type 2 daughter minerals	—	—	—	1-2	—
8) Abundance of Type 3	—	—	5	tr	30
9) Number of Type 3 daughter minerals	—	—	1-2	1-2	2-5

1) considerable variation in vertically zoned systems

It should be kept in mind that the fluid inclusion distribution patterns seen are, for pre-mineral rocks, a composite of all the hydrothermal events which occurred at that location. The extent to which fluid inclusions from each event are preserved is probably the single most important source of departure from the typical zoning patterns shown in Figures 4-6. The Sunnyside deposit may be an excellent example of this problem. Here an extensive, late, phyllic alteration has thermally collapsed downward on the underlying potassic alteration and higher grade chalcopyrite. Associated Type 1 and 2 fluid inclusions appear to have formed during this event, reducing the relative abundance of Type 3 inclusions. Because of complicating factors such as this it is important that the data be interpreted qualitatively as mentioned earlier.

Without question the most impressive characteristic of fluid inclusions in the central portions of large, ore-bearing porphyry copper systems is their extremely uniform and pervasive distribution down to the scale of individual quartz grains. The distribution is so uniform that it is rarely necessary to check more than one or two areas in a few quartz grains to gain an idea as to the abundance of the various inclusion types. A single quartz grain 2 mm. in diameter will typically contain in excess of 100,000 ? fluid inclusions in the phyllic and potassic alteration zones, illustrating the highly pervasive movement of the hydrothermal fluid from which they were formed. It is important to recognize the presence of these inclusions because they may record the former widespread existence of a hydrothermal fluid in the rock, even though hydrothermal alteration may be absent or

sharply confined to fractures. Petrographic work has clearly shown that fluid inclusions are far more uniformly disseminated through quartz-bearing rocks than either alteration or sulfide minerals. This feature is so characteristic that mixed populations of fluid inclusion types which shouldn't normally occur together probably suggest that the population is coming from an intramineral rock such as a tuff or an intrusive breccia.

Perhaps the greatest single variable between different porphyry copper deposits is the average size of the fluid inclusions. Samples from the Brenda, Lornex, Alwin, and Bethlehem deposits in British Columbia, from the Atlas deposit in the Philippine Islands, and from the alaskite at Silver Bell, Arizona were often so small as to require the use of oil immersion techniques. Whether this is a peculiarity of these deposits or perhaps a depth function is not known, but most other deposits from these same areas contained much larger inclusions.

In many of the deposits studied the fluid inclusion zoning patterns generalized on Table 3 are modified by various geologic features. Thus, any interpretation of fluid inclusion data must be made within the framework of available geologic information. The age of the rock type often has a strong influence on the type of fluid inclusions present even though all rocks present may be pre-ore and occur in the central portion of the mineralized area. This is indicated by data in Table 4 for several porphyry copper deposits and clearly illustrated by Bennett (1975) for the Morenci deposit. The variations are probably due to the fact that the older rocks have been subjected to a greater amount of tectonic activity resulting in a greater degree of fracturing and a more permeable rock. In addition, the older rocks may have been subjected to longer periods of mineralization, an important factor to consider when some of the intrusions may be of intramineral age.

TABLE 4: FLUID INCLUSIONS IN ROCKS OF DIFFERENT AGES WITHIN ORE ZONE

DEPOSIT	% PRIMARY	% TYPES 1	2	3
SACATON				
Laramide qtz. monz. por.	30	85	10	5
Precambrian granite	60	40	40	20
SIERRITA				
Laramide qtz. monz. por.	80	80	10	10
Jurassic qtz. monz.	80	50	10	40
SUNNYSIDE (surface)				
Paleocene quartz feldspar por.	10	70	30	—
Laramide quartz monzonite por.	50	30	65	5
Jurassic alaskite	70	50	35	15

The brittleness of the rock can also be an important factor. In the Sunnyside area the coarse-grained, quartz-rich alaskite (Jurassic) contains a far greater abundance of fluid inclusions than adjacent quartz latite tuffs (Triassic) presumably because the abundance of soft tuffaceous matrix cushioned the contained quartz phenocrysts. Grain size of quartz may exert a strong influence on the abundance of fluid inclusions. Regardless of age

coarse-grained quartz invariably contains far more fluid inclusions than fine-grained quartz. In some cases this is due to the quartz being smaller than the individual inclusions, a common phenomenon in jasperoids. It may also be due to fracturing occurring along grain boundaries rather than through individual grains. Fluid inclusions trapped on intergranular contacts will leak rather easily, leaving no trace of their former presence.

The age of the quartz strongly influences the type and abundance of contained fluid inclusions and, along with rock type, must be carefully evaluated to avoid serious errors. The influence of magmatic quartz of different ages has already been mentioned. The same reasoning also applies to magmatic quartz and accompanying vein quartz, vein quartz of different ages, and recrystallization of older quartz grains (see Fig. A-8 and A-9). Fluid inclusion studies have clearly shown that the composition of the hydrothermal fluid changes during cooling of a porphyry copper system, generally becoming more dilute. I have seen numerous examples where quartz phenocrysts with abundant Type 3 fluid inclusions were cut by vein quartz which contained only rare inclusions, none of which were Type 3. Recrystallization of quartz also tends to destroy preexisting fluid inclusions and can greatly alter abundance estimates if such phenomena are not recognized. I have also observed quartz crystals in strongly mineralized breccia pipes which contained no fluid inclusions, perhaps due to a slow growth rate or formation at a late stage in the hydrothermal event.

Clearly, confusing zoning patterns may arise by failing to recognize different ages of quartz. I have found that the easiest way to treat this problem is to use pre-ore quartz, which, in the case of a mineralizing intrusion, would be either a phenocryst or matrix quartz (where identifiable). Although this does not reveal the time variations in the composition of the hydrothermal fluid, such information is of greater academic than practical interest -- it is more important to identify the location of a brine than it is to identify the point in time when the brine formed. Magmatic or older quartz preserves this information which can be easily sorted out from the many other events which may also be preserved. Once this data is available it is only necessary to be aware of the possible influence of intramineral ages and greatly simplifies the interpretation.

Care should also be exercised not to draw conclusions from data based on a single rock type. Samples from the Monte Cristo stock near Eureka, Nevada contained a variable, but not overly impressive, suite of Type 1 and 2 fluid inclusions. However, G. J. Stathis informs me that significant tonnages of copper mineralization occur in the adjacent sedimentary rocks. Whether Type 3 fluid inclusions are present in or above the ore-bearing sedimentary rocks is not known, although they are present in abundance at Copper Canyon, Nevada as previously discussed. It is perhaps significant that the fluid inclusion populations in the quartz monzonite porphyry at Mission and in the quartz monzonite porphyry stock adjacent to the Imperial area skarns at Silver Bell are unimpressive. Again the information reveals nothing about the potential of the adjacent rocks, but it does strongly indicate that there is no ore in the intrusive rocks <u>even though potassic alteration is well developed.</u>

The barren, unaltered portions of seven productive intrusions were also investigated. Of these the Schultze, Three Peaks, Ruby Star, and Pinos Altos stocks contained only rare, small Type 1 inclusions which showed no consistent variation toward mineralized zones. Background values appeared similar in all stocks with low total abundances, 95-99% Type 1, and only rare Type 3 inclusions. Results from the Yerington stock, the Schieffelin granodiorite (Tombstone), and the Patagonia granodiorite were quite different. Unaltered Schieffelin granodiorite samples from 2 drill holes contained abundant fluid inclusions with up to 25% Type 3 in matrix igneous quartz. Samples of fresh Yerington quartz monzonite generally contained low to moderate abundances of fluid inclusions of which up to 70% were Type 3. Unaltered samples from the northern portion of the Patagonia granodiorite adjacent to the Sunnyside alteration zone contain abundant, large, primary fluid inclusions averaging 20-30% Type 3 in matrix igneous quartz for at least one-half mile beyond the edge of alteration. Samples 2 miles south of the Sunnyside alteration zone contain the normal fluid inclusion background.

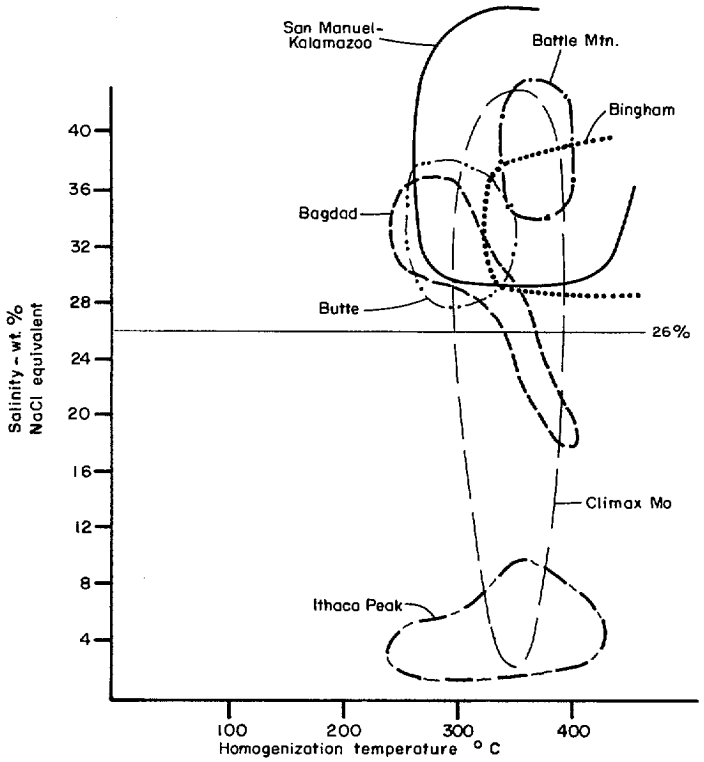
The abundance of Type 3 fluid inclusions in unaltered rock probably indicates that the initial magmatic fluids separating from the rock were highly saline. The inference is that these fluids were probably efficient complexers of base metals and that the presence of Type 3 fluid inclusions is a favorable indication of associated porphyry copper mineralization, particularly within known porphyry copper provinces. The absence of Type 3 inclusions in fresh intrusive rocks is not necessarily an unfavorable feature and these rocks should be explored in the usual way using other criteria.

APPLICATION TO OTHER DEPOSITS

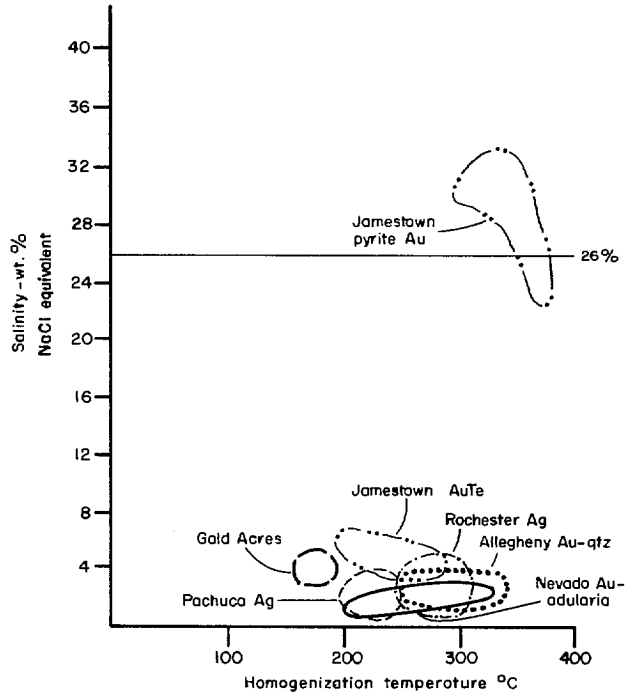
The technique described above is so simple and rapid that possible applications during exploration for other types of deposits must be considered. To illustrate the following discussion I have plotted data from the literature on Figure 7. This shows the relationship between homogenization temperatures and salinity expressed as weight percent equivalent NaCl for fluids existing at the time of ore deposition in a number of different types of deposits. The horizontal line at 26 wt. % NaCl is the point where halite crystals begin to form at room temperature.

It is obvious that the porphyry copper deposits fall well above the 26 wt. % NaCl line, the single exception being the Ithaca Peak deposit. Quantitative data were available for Butte (Roedder, 1971), Bingham (Roedder, 1971), Bagdad (Nash and Cunningham, 1974), Kalamazoo (Davis, 1974), and Copper Canyon (Nash and Theodore, 1971). The position defined by the quantitative studies also appears to be consistent for other porphyry copper deposits due to the presence of visible halite in thin section.

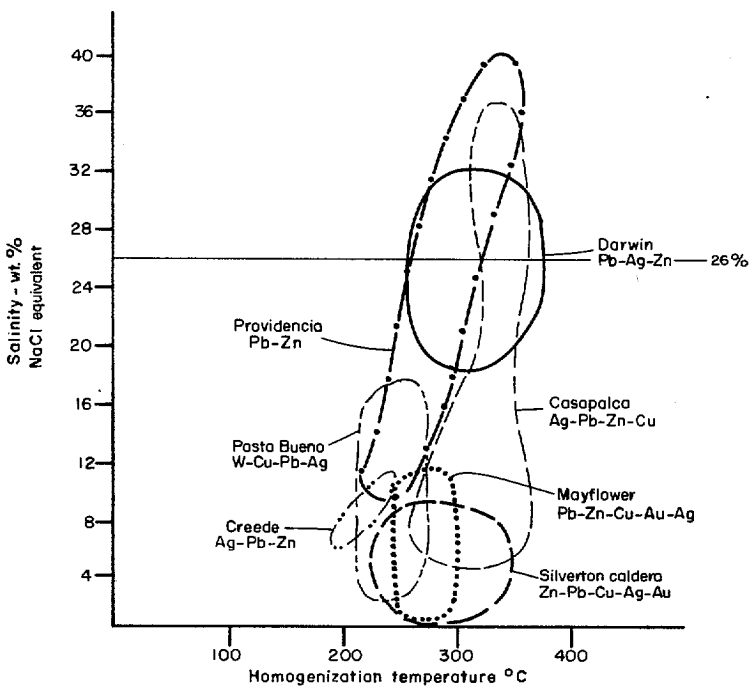
The only porphyry molybdenum deposit studied to date is Climax (Hall et al, 1974). It appears that the majority of the ore fluids there were of moderate salinity and halite is mostly absent. I suspect that other significant variations such as those listed on Table 3 would be present in porphyry molybdenum deposits and would serve as a reasonably accurate guide to the central portion of the hydrothermal system. However, the use of halite as a key daughter mineral may be limited in this type of deposit -- assuming Climax is typical.



Porphyry Cu–Mo deposits



Epithermal Au–Ag deposits



Mesothermal base (precious) metal deposits

References

San Manuel – Davis, 1974
Battle Mtn – Nash & Theodore, 1971
Bingham – Raedder, 1971
Bagdad – Nash & Cunningham, 1974
Butte – Roedder, 1971
Climax – Hall, Friedman & Nash, 1974
Ithaca Peak – Drake, 1972
Darwin – Rye, Hall & Ohmoto, 1974
Casapalca – Rye & Sawkins, 1974
Silverton – Nash, 1975
Pasto Bueno – Landis & Rye, 1974
Creede – Nash, 1972
Mayflower – Nash, 1973
Providencia – Sawkins, 1964
Gold Acres – Nash, 1972
Nevada Au-adularia – Nash, 1972
Allegheny – Coveny & Kelly, 1971
Jamestown – Nash & Cunningham, 1973
Pachuca – Drier, 1976
Rochester – Vikre, 1976

FIGURE–7 TEMPERATURE–SALINITY RELATIONSHIPS FOR CORDILLERAN ORE DEPOSITS

The Sn-W-Ag-Cu deposits of Peru and Bolivia fall both above and below the 26 wt. % NaCl line. In general the periods of Sn deposition (not shown) were marked by higher temperatures and salinities than the periods of W and base metals. The W field overlaps with the field of the mesothermal Pb-Zn-Au-Ag-Cu deposits. Within this field there is a general tendency for the abundance of precious metals to increase with decreasing salinity.

Interestingly, the temperature variations throughout the mesothermal range are rather slight for the region of ore deposition. In all these deposits there are well-developed temperature and salinity variations which can be paragenetically mapped, and in many cases halite-bearing fluid inclusions are present. The major problem is that evidence for pervasive fluid movement is lacking so the vein must be found before the fluid inclusions can be studied. Thus, the technique does not appear to be useful during exploration for either the Sn-W or Pb-Zn-Au-Ag-Cu deposits. Recognition of boiling zones within a vein might be very useful once a productive structure had been located as boiling appears to cause deposition of some metals.

Nash (1972) has shown that the salinities from a number of Au-quartz-adularia vein deposits in Nevada are extremely low. He also found low salinities in the Carlin, Cortez, and Gold Acres disseminated Au deposits. Data from the literature suggest low salinities were also present at Jamestown, Colorado (telluride ores); Homestake, South Dakota; and the Allegheny district, California. Thin section studies also indicate low salinities for the Bodie, Yellowknife (N.W.T.), Tonopah, Hardshell, and Waterloo deposits. Although there appear to be some size and abundance variations, the uniformly low salinities, the fine grain size of the quartz, and the lack of pervasive alteration much beyond the ore would appear to limit the use of fluid inclusion studies during exploration for disseminated precious metal deposits. The early pyritic gold veins at Jamestown, Colorado appear to contain high salinity fluid inclusions, but the fluid appears to have been confined to the vein structures. Work by Drier (1976) suggests some applications may exist for exploration of concealed ore shoots in precious metal vein systems, but his data are not yet available.

Although not shown on Figure 7, data from the literature on the Jerome, Coronation, and Kuroko deposits indicate that ore fluid salinities are below 26 wt. % NaCl. Petrographic work on samples from the Kidd Creek, Millenbach, Vauze, Brunswick 6 and 12, and Caribou deposits reveal no obvious variations adjacent to or within the ore zones. There was some indication in the Brunswick 6 area that certain quartz porphyries contained more fluid inclusions than others, suggesting a possible application during geologic mapping. At the Rammelsberg mine in Germany the kneist, a footwall quartz-sulfide stockwork vein zone similar to the silica dolomite at Mt. Isa, contained only rare, small, Type 1 fluid inclusions. It appears that the close association of Type 3 inclusions and chalcopyrite seen in the porphyry copper deposits is not present in the volcanogenic massive sulfide deposits. In addition, the small size and limited abundance of fluid inclusions would appear to limit the application of the technique during massive sulfide exploration.

The salinity of ore-forming solutions in the Mississippi Valley-type lead-zinc-fluorite deposits lies close to the 26 wt. % NaCl line; however, if this solution is actually a connate brine the halo outside the orebodies is likely to be too large to have any practical uses. The Echo Bay U-Ni-Ag-Cu deposits partly overlap the Mississippi Valley field.

CONCLUSIONS

The porphyry copper deposits are ideally and apparently uniquely suited for exploration-oriented fluid inclusion studies due to the following:

1) the large size of the hydrothermal system relative to ore

2) the presence of well-defined fluid inclusion zoning patterns in, around, and above the ore

3) the pervasiveness of fluid movement at all scales

4) the close spatial relationship of a high salinity fluid and ore, regardless of the strength of the alteration

5) the widespread abundance of relatively coarse-grained quartz, and

6) the retention of hypogene zoning patterns during severe supergene alteration.

Petrographic studies of fluid inclusion zoning should be very useful during the exploration for porphyry copper deposits in a number of different environments. As a general rule I would be reluctant to bottom a hole in abundant Type 3 (halite) fluid inclusions regardless of the depth, capping interpretation, or rock geochemistry. Sizeable areas of Type 3 fluid inclusions should be thoroughly explored to compensate for the tendency to intersect low grade zones in the initial stages of drilling programs. A specific application involves the evaluation of bedrock intersections under post-mineral cover in the Southwestern U.S. Although the discovery of any mineralization would presumably be followed with a diamond drill penetration to sulfides, regardless of the character of the limonite in the capping, the presence of Type 3 inclusions would considerably enhance the potential of the area.

Rotary cuttings of post-mineral alluvium can also be evaluated petrographically. These cuttings may contain fragments eroded from mineralized areas, a fact which can be obscured by iron staining and strong weathering to which the alluvial clasts have often been subjected. This application can be particularly useful for samples collected from valleys adjacent to pediments in the Southwestern U.S.

Vertically zoned porphyry copper systems are well suited to fluid inclusion studies. Deep drilling in the Sunnyside and Charleston areas has demonstrated that the theoretical and experimental models of fluid zoning are quite accurate and that variations in the type and abundance of fluid

inclusions are closely related to hypogene copper ore zones. The application to further exploration at Summitville is obvious.

Deposits which have been subjected to extreme tropical weathering such as in Puerto Rico invariably lose much of their alteration and geochemical expression due to the formation of thick residual soils. However, Cox et al (1975) report that quartz grains collected from the soil overlying the ore zones contain abundant Type 3 fluid inclusions which preserve the original hypogene zoning patterns.

The presence of Type 3 fluid inclusions in deposits associated with weak alteration such as some of the porphyry copper deposits in British Columbia and in the Philippine Is. can be a very useful indication of the proximity to higher grade zones, particularly in areas of extensive post-mineral cover. Fluid inclusion halos at the Cerro Chorcha deposit in Panama were found to extend considerably outside the limits of visible hydrothermal alteration.

Fluid inclusion zoning can be very useful in environments where the copper-bearing ore zones are confined to specific stratigraphic horizons such as the Copper Canyon deposit, Nevada. Saline brines appear to have circulated beyond the ore zone in both lateral and vertical planes and Type 3 inclusions are abundant in overlying sediments.

The presence of abundant Type 3 fluid inclusions in an otherwise barren intrusion may be highly significant. Although the ore may not occur immediately within the brine zone, the presence of Type 3 inclusions indicates that fluids separating from the intrusion were potent ore carriers and must be considered as favorable indications of adjacent copper mineralization. Care should be taken not to attach excessive importance to the presence of the rare Type 3 fluid inclusion which may simply be part of the background population.

Petrographic studies of fluid inclusions are simple, rapid, inexpensive, and easily quantified. This technique provides the geologist with information which is not otherwise available for the evaluation of porphyry copper deposits. The interpretation of this information within the framework of other geologic data should increase the chances of discovery.

REFERENCES

Bennett, K.C., 1975, Geology and origin of the breccias in the Morenci-Metcalf district, Greenlee County, Ariz.: M.S. Thesis, Univ. of Arizona.

Coveny, R.M. and Kelly, W.C., 1971, Dawsonite as a daughter mineral in hydrothermal fluid inclusions: Contr. Mineral. and Petrol., 32, p. 334-342.

Cox, D.P., Gonzalez, I.P., and Nash, J.T., 1975, Geology, geochemistry, and fluid inclusion petrography of the Sapo Alegre porphyry copper prospect and its metavolcanic wallrocks, West-Central Puerto Rico: U.S. Geol. Survey Jour. Research, 3, p. 313-327.

Cunningham, C.G., Jr., 1976, Petrogenesis and postmagmatic geochemistry of the Italian Mountain Intrusive Complex, eastern Elk Mountains, Colo.: Geol. Soc. Amer. Bull., 87, p. 897-908.

Davis, J.D., 1974, Geothermometry, geochemistry, and alteration at the San Manuel porphyry copper orebody, San Manuel, Arizona: Ph.D. Dissertation, Univ. of Arizona.

Drake, W.E., 1972, A study of ore-forming fluids at the Mineral Park porphyry copper deposit, Kingman, Ariz.: Columbia Univ., Ph.D. Thesis, 245 p.

Drier, J.E., 1976, Genesis of the epithermal silver deposits in the Pachuca-Real del Monte district, Hidalgo, Mexico: abstract of talk delivered to Arizona Geol. Society.

Hall, W.E., Friedman, I., and Nash, J.T., 1974, Fluid inclusion and light stable isotope study of the Climax molybdenum deposits, Colorado: Econ. Geol., 69, p. 884-901.

Landis, G.P. and Rye, R.O., 1974, Geologic, fluid inclusion, and stable isotope studies of the Pasto Bueno tungsten-base metal ore deposit, Northern Peru: Econ. Geol., 69, p. 1025-1059.

Metzger, F.W., Nesbitt, B.E., and Kelly, W.C., 1975, Scanning electron microscopy of daughter minerals in fluid inclusions: Geol. Soc. Amer. Abstr. with Programs, 7, p. 1199.

Moore, W.J. and Nash, J.T., 1974, Alteration and fluid inclusion studies of the porphyry copper orebody at Bingham, Utah: Econ. Geol., 69, p. 631-645.

Nash, J.T., 1972, Fluid inclusions as a guide to porphyry-type mineralization: presented at AIME Annual Meeting, San Francisco.

_____1972, Fluid inclusion studies of some gold deposits in Nevada: U.S. Geol. Survey Prof. Paper 800-C, p. C15-C19.

Nash, J.T., 1973, Geochemical studies in the Park City district: I: Ore fluids in the Mayflower mine: Econ. Geol., 68, p. 34-51.

_____1975, Fluid inclusion studies of vein, pipe, and replacement deposits, Northwestern San Juan Mtns., Colo.: Econ. Geol., 70, p. 1448-1462.

_____and Theodore, T.G., 1971, Ore fluids in the porphyry copper deposit at Copper Canyon, Nevada: Econ. Geol., 66, p. 385-399.

_____and Cunningham, C.G., 1973, Fluid-inclusion studies of the fluorspar and gold deposits, Jamestown District, Colo.: Econ. Geol., 68, p. 1247-1262.

_____and Cunningham, C.G., 1974, Fluid inclusion studies of the porphyry copper deposit at Bagdad, Arizona: Jour. Research U.S. Geol. Survey, 2, p. 31-34.

Roedder, E., 1968, Fluid inclusions as samples of ore fluids: in Barnes, H.L., ed., Geochemistry of Hydrothermal Ore Deposits: Holt, Rinehart and Winston, Inc., New York, p. 515-574.

_____1971, Fluid inclusion studies on the porphyry-type ore deposits at Bingham, Utah, Butte, Montana, and Climax, Colorado: Econ. Geol., 66, p. 98-120.

_____1972, Composition of fluid inclusions: U.S. Geol. Survey Prof. Paper 440 - J.J.

Rye, R.O., Hall, W.E., and Ohmoto, H., 1974, Carbon, hydrogen, oxygen, and sulfur isotope study of the Darwin lead-silver-zinc deposit, Southern Calif.: Econ. Geol., 69, p. 468-481.

_____and Sawkins, F.J., 1974, Fluid inclusion and stable isotope studies on the Casapalca Ag-Pb-Zn-Cu deposit, Central Andes, Peru: Econ. Geol., 69, p. 181-205.

Sawkins, F.J., 1964, Lead-zinc deposition in the light of fluid inclusion studies, Providencia mine, Zacatecas, Mexico: Econ. Geol., 59, p. 883-919.

Sourirajan, S. and Kennedy, G.C., 1962, The system H_2O-NaCl at elevated temperatures and pressures: Amer. Jour. Sci., 260, p. 115-141.

Takenouchi, S. and Kennedy, G.C., 1965, The solubility of carbon dioxide in NaCl solutions at high temperatures and pressures: Amer. Jour. Sci., 263, p. 445-454.

Theodore, T.G. and Nash, J.T., 1973, Geochemical and fluid zonation at Copper Canyon, Lander County, Nevada: Econ. Geol., 68, p. 565-570.

Vikre, P.G., 1976, Mesozonal vein deposits and disseminated silver mineralization in the Rochester District, Pershing County, Nevada: unpublished Ph.D. dissertation manuscript.

White, D.E., Muffler, L.J.P., and Truesdell, A.H., 1971, Vapor-dominated hydrothermal systems compared with hot water systems: Econ. Geol., 66, p. 75-97.

APPENDIX: PHOTOMICROGRAPHS OF FLUID INCLUSIONS

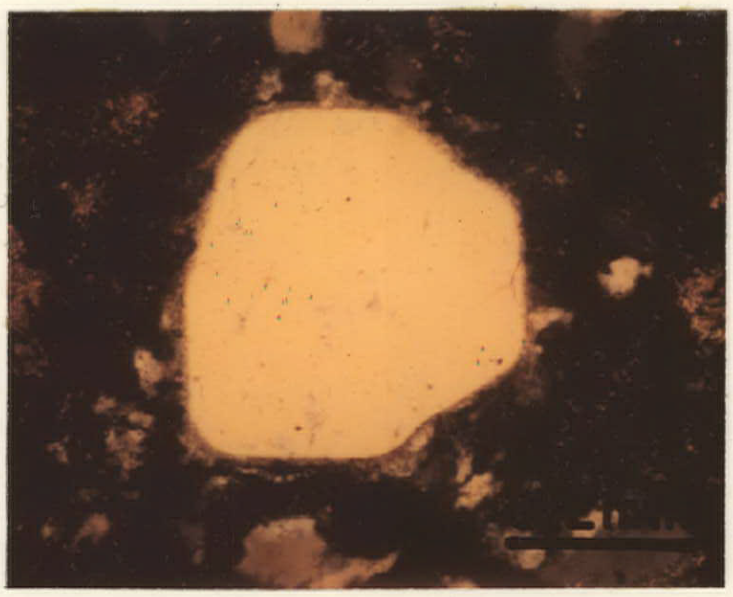


FIGURE A-1: Quartz grain showing very low abundance of fluid inclusions. Sample from unmineralized, but sericitized, quartz feldspar porphyry, Sunnyside area, Patagonia Mtns., Ariz. Polarized light. Bar scale is 0.2 mm.

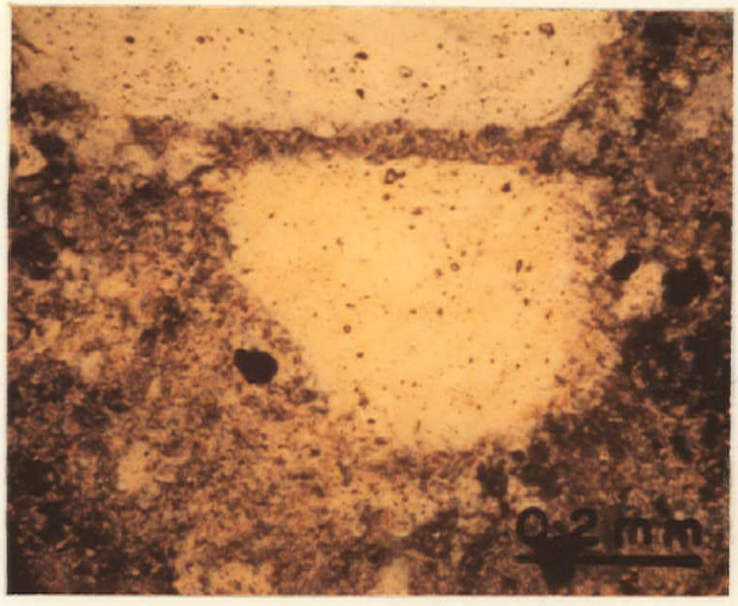


FIGURE A-2: Quartz grains showing uniform, high abundance of fluid inclusions in sericitized quartz feldspar porphyry. Apparent variation of abundance within single quartz grain is caused by presence of several very large inclusions. Same scale as Fig. A-1; the difference in abundance between two samples is obvious. Sample from hole TM-8 at 3410 ft., roughly 1000 ft. above top of chalcopyrite intersection averaging 1200 ft. of 0.25% Cu, Sunnyside area, Patagonia Mtns., Ariz. Polarized light.

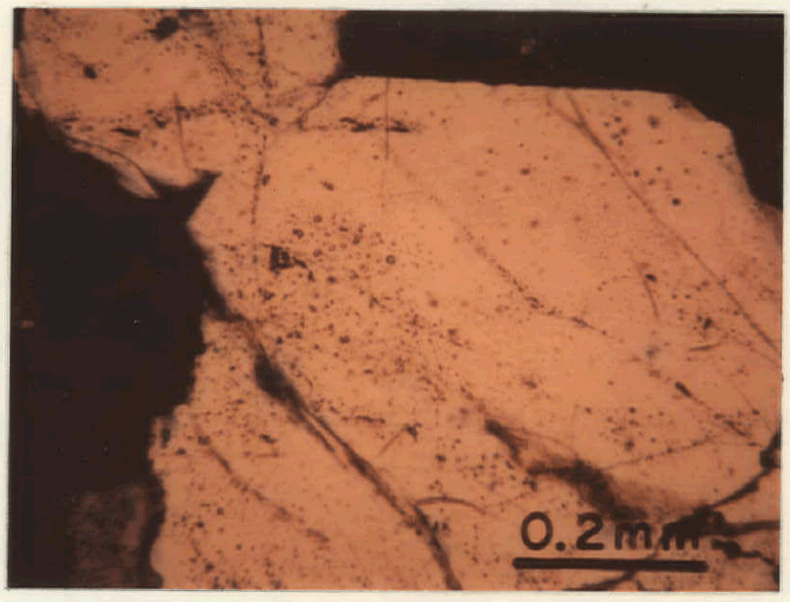


FIGURE A-3: Sample showing strong variation in the total abundance of all fluid inclusion types in quartz. Scale same as Fig. A-1 and A-2. Note strong variation in inclusion sizes and that larger inclusions appear to be primary. Note that inclusions of same size and type appear to occur together. Secondary inclusions are generally small and occur in well-defined fractures of considerable length. Where primary inclusions are absent, the areas between secondary inclusions are nearly devoid of fluid inclusions. Typical of peripheral zone in porphyry copper deposits. Sample is coarse-grained, unmineralized, fresh quartz monzonite collected 2000 ft. southwest of mineralized hill at the Tok prospect, Eastern Alaska. Polarized light.

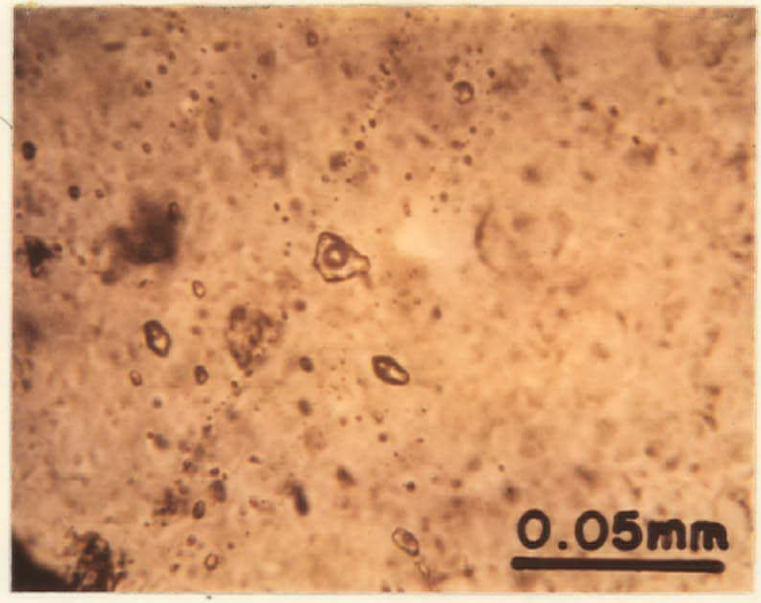


FIGURE A-4: Large, Type 1 fluid inclusions; three large primary inclusions in quartz in center of photograph have 20-30% gas which is close to upper limit of Type 1 inclusions -- probably indicative of high temperature of formation. Smaller inclusion to left of scale has 15% gas bubble. Note swarm of obviously secondary inclusions running NE across photograph, somewhat irregular distribution of inclusions, absence of Type 2 and 3 inclusions -- all suggestive of peripheral zone of porphyry copper deposit. Sample from Precambrian granite, hole SC-8 at 999 ft., Santa Cruz project, Ariz. Plain light.

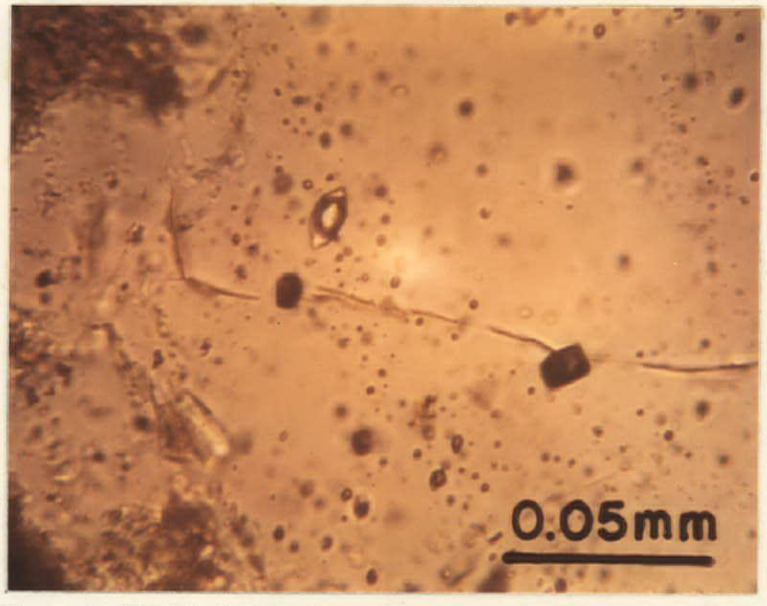


FIGURE A-5: Type 2 fluid inclusion in upper center has 60% gas bubble in a negative crystal. Host mineral is quartz. Distribution of inclusions looks erratic, but many of the fuzzy spots are fluid inclusions which lie above and below the plane of focus. Sample is granitic rock from mineralized zone at the Casino deposit, Yukon Territory. Plain light.

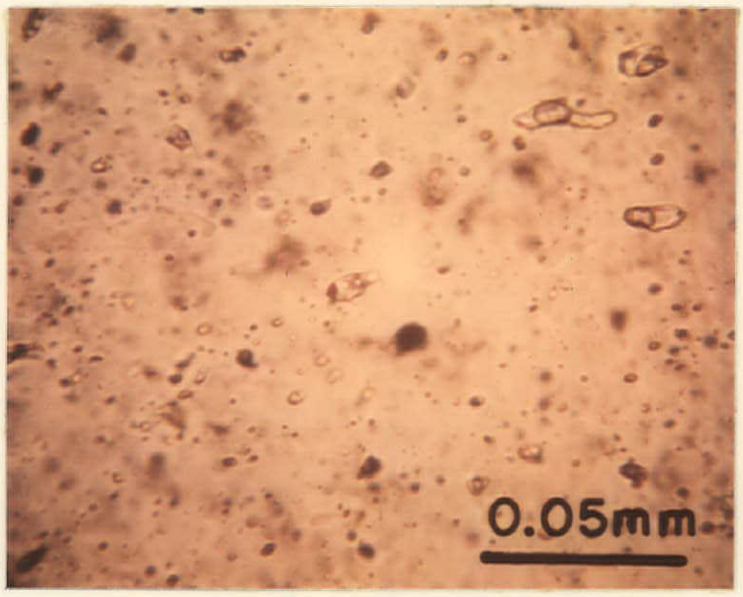


FIGURE A-6: Type 3 fluid inclusion in center of photograph contains, from left to right, a red hematite grain, a small cubic halite crystal, a slightly fuzzy gas bubble; above the gas bubble is a small fuzzy, opaque grain. Note the overall extreme abundance and a very uniform distribution of fluid inclusions. Host mineral is quartz. Sample is Precambrian granite from the 1150 bench in the center of the Sacaton pit, Ariz. Plain light.

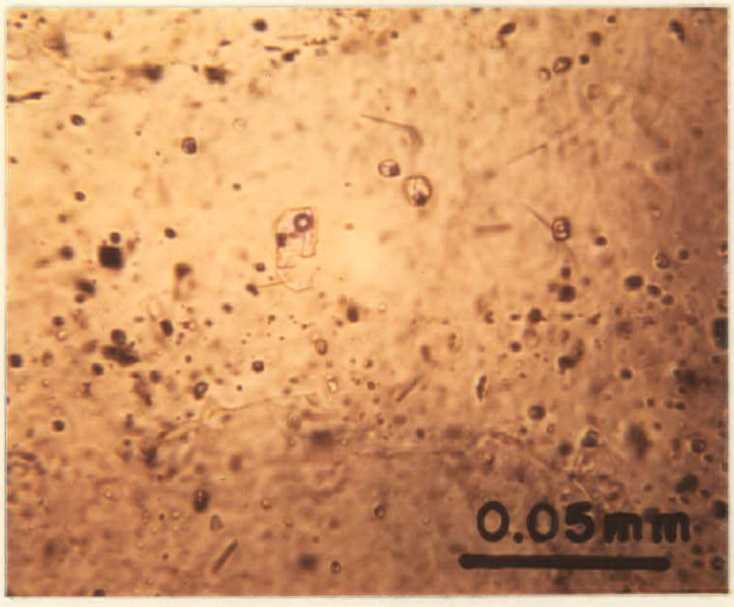


FIGURE A-7: Three, large Type 3 fluid inclusions in upper center. The largest of the three has a squarish shape with a well-defined gas bubble in the NE corner. Along the W side is a slightly fuzzy opaque grain; attached to upper side of opaque is a small, oval, anisotropic unknown daughter mineral. To right of opaque is a large halite crystal. Halite and gas bubbles are also present in the two smaller Type 3 inclusions NE of large inclusion. Note tendency here and in Fig. A-6 for the low relief halite to be partly washed out in the condensed light. Clustering of similar types of inclusions as seen here is common. Sample is quartz monzonite porphyry-granite breccia from 1110 bench in center of Sacaton pit, Ariz. Plain light.

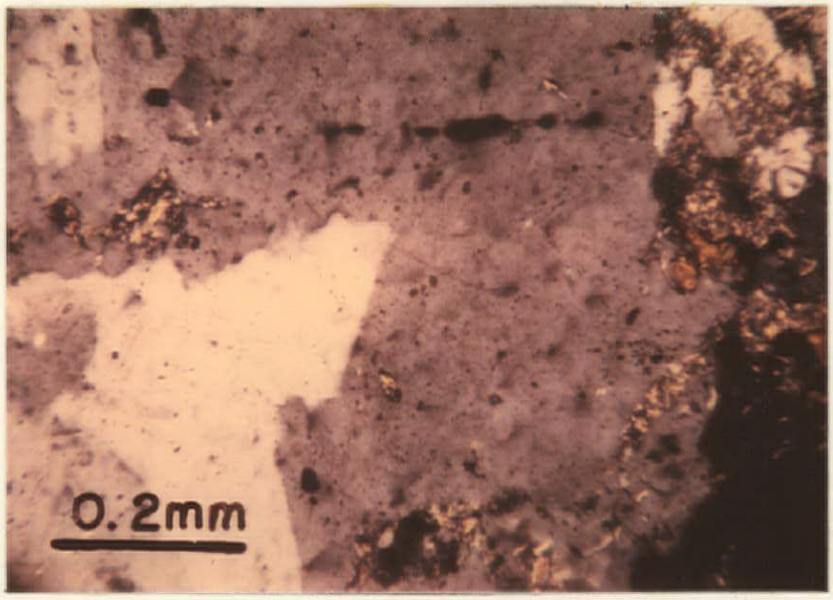


FIGURE A-8: Large quartz grain in Jurassic alaskite from inner portion of phyllic zone on west side of Sunnyside altered area, Patagonia Mtns., Ariz. Light-colored embayment extending to center of photo from lower left is recrystallized portion of an originally homogenous, magmatic quartz grain. Note reduced abundance of fluid inclusions in recrystallized area and see Fig. A-9 for clarification. Polarized light.

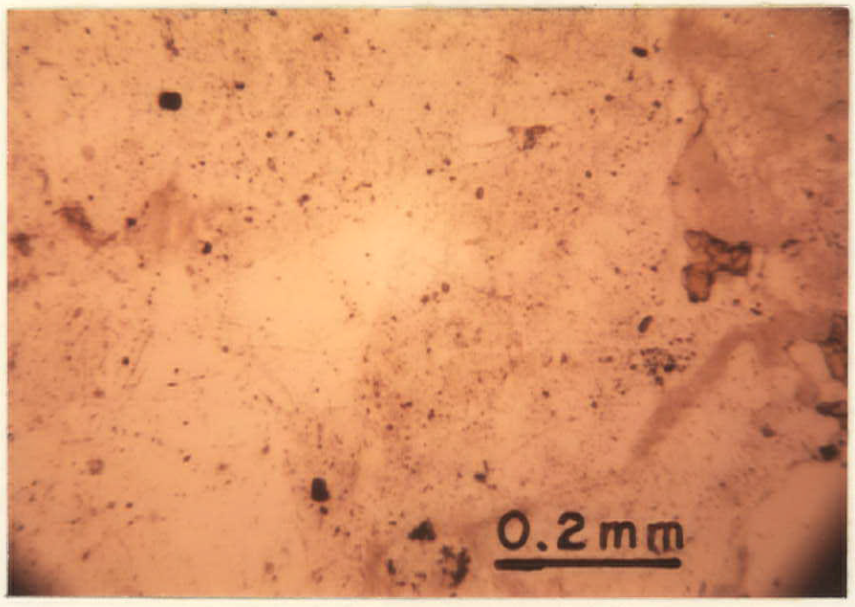


FIGURE A-9: Same photo as Fig. A-8; in plane light. Note obvious reduced abundance of fluid inclusions and near-absence of large inclusions in the recrystallized area. In particular, a linear zone of secondary fluid inclusions with several large types extends NE from center of photo but is terminated at the SW end against the recrystallized area. Presence of some inclusions in recrystallized area indicates recrystallization was intra-mineral. Photo emphasizes importance of knowing relative ages of quartz grains being studied.

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Fluid Inclusions as a Guide to Porphyry Copper Deposits

By

J. Thomas Nash

Open-File Report 76-482

1976

This report is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey standards and nomenclature.

ASARCO
LIBRARY

FLUID INCLUSIONS AS A GUIDE TO PORPHYRY COPPER DEPOSITS

By J. Thomas Nash

Abstract

Fluid-inclusion studies of 36 porphyry copper deposits, mainly in the United States, demonstrate that all but 3 evolved through a hydrothermal stage characterized by very high salinities, generally in excess of about 35 weight percent NaCl equivalent, and boiling temperatures of these fluids ranged from about 250° to 700° C for various stages and deposits. High salinities, shown by halite-bearing inclusions, and boiling, suggested by coexisting gas and liquid-rich inclusions, are considered diagnostic of epizonal intrusions which are the most favorable parents for porphyry copper mineralization. Depth of emplacement of many copper-bearing stocks is deduced from fluid inclusions to have been about 6,000 to 10,000 feet (1,800 to 3,000 metres); fluid pressures during mineralization are interpreted generally to be less than 500 bars.

Moderate-salinity (less than about 12 percent) and moderate-temperature (<350°C) fluids are noted in all porphyry copper deposits and were responsible for the deposition of most copper and molybdenum in deposits such as Bagdad, Esperanza, Mineral Park, Morenci, Ray, Sierrita, in the southwestern United States and several in southern British Columbia. However, with only three exceptions, highly saline fluids apparently were present at an early stage and also deposited metals. The relative amounts and economic importance of copper and molybdenum deposited from high and moderate salinity fluids varies within the porphyry deposit class.

There is compelling geologic and geochemical evidence that chloride ions are important for transport of metals in hydrothermal solutions, but the porphyry coppers stand out as a class associated with fluids of especially high salinity during at least one stage of their formation. Halite cubes in fluid inclusions are an effective although rough indicator of those salinities and can be conveniently monitored during petrographic study of thin sections. It is suggested that fluid inclusions be used to characterize favorable intrusions, metal anomalies, and cap rocks as an additional method of detecting possible disseminated porphyry copper-type metallization. The presence of halite-bearing inclusions, especially coexisting with gas-rich inclusions, is considered a favorable geochemical anomaly in the search for porphyry ore.

INTRODUCTION

Fluid-inclusion studies have added important insight into the genesis of ore deposits, but little effort has been made to apply these techniques and data to mineral exploration. There is compelling experimental and thermodynamic evidence that chloride-bearing hydrothermal fluids are potent solvents for metals through the formation of chloride-metal complex ions (Helgeson, 1964; Holland, 1972; and others); fluid-inclusion data (Roedder, 1967, 1972) has been an important contribution to these geochemical advances. Because fluid inclusions yield the most direct evidence on the salinity of hydrothermal fluids responsible for metallization, and provide a link between the laboratory and the field, they have potential use in exploration. This paper will attempt to summarize the present knowledge of fluids in porphyry copper deposits and outline some practical applications of fluid-inclusion technology to exploration.

At present I know of fluid-inclusion data for 36 porphyry copper deposits (Table 1). The outstanding feature emerging from these studies is the observation of halite-bearing fluid inclusions in all but three porphyry copper deposits studied (Nash, 1971). In samples from many porphyry deposits halite-bearing fluid inclusions coexist with gas-rich type, a relationship interpreted as indicating formation from boiling, very saline fluids. These very saline fluids deposited most of the copper and molybdenum in many deposits, but at others, such as Esperanza, Morenci, and Ray, moderate salinity fluids deposited most of the base metals.

It is concluded that halite-bearing fluid inclusions are a common feature of epizonal intrusions and are especially associated with stocks that generate porphyry copper deposits. Halite-bearing fluid inclusions in igneous or vein quartz, particularly when coexisting with gas-rich inclusions, are deemed a guide to porphyry-type copper mineralization. Fluid inclusions should be considered along with other mineralogical, geochemical, and geophysical evidence in the search for deposits. A more complete description of fluid inclusions from porphyry copper deposits, their temperatures, compositions, and distribution will be published as a chapter in Professional Paper 907, Geology and Resources of Copper Deposits. This preliminary report summarizes part of the complete manuscript that is in press.

Table 1.--Fluid-inclusion data for porphyry copper deposits

[Inclusion types: I, moderate salinity; II, gas-rich; III, halite-bearing; IV, CO_2-rich. Host: PQ, primary quartz, SQ, secondary quartz, including veins; CS, calc-silicate minerals]

Deposit	Inclusion types observed	Host of halite-bearing inclusions	Reference[1]
Arizona:			
Ajo	I, II, III	PQ, SQ	1
Bagdad	I, II, III, IV	PQ, SQ	2
Bisbee	I, III	PQ, SQ	1
Christmas	I, III	PQ, SQ	3
Copper Basin	I, II, III	PQ, SQ	1
Esperanza	I, III	PQ	1, 4
Inspiration	I, II, III	PQ, SQ	3
Mineral Park	I, II, III	PQ, SQ	1, 5
Mission	I, III	SQ, CS	1, 4
Morenci	I, II, III	PQ, SQ	1, 6
Poston Butte (Florence)	I, II, III	PQ, SQ	1
Ray	I, III	PQ, SQ (rare)	1, 7
Sacaton	I. III Type 2 also common	SQ	3
San Manuel	I, II, III, IV	PQ, SQ	1, 7, 8
Sierrita	I, II, III	PQ, SQ	1, 4
Silver Bell	I, II, III	PQ, SQ	1, 4
Twin Buttes	I, III	SQ, CS	3, 4
Nevada:			
Copper Canyon	I, II, III, IV	PQ, SQ, CS	9
Ely	I, II, III	PQ, SQ	1, 10
Yerington	I, II, III, IV	PQ, SQ	1
Other areas:			
Chino, N. Mex.	I, II, III	PQ, SQ	11
Bingham, Utah	I, II, III	PQ, SQ, CS	4, 12
Butte, Mont.	I, II, III, IV	PQ, SQ	4, 13, 14
Catheart Mountain, Maine	I, II, III	PQ, SQ	19
El Salvador, Chile	I, II, III	PQ, SQ	15
Breccia pipes, Chile	I, II, III	SQ	16
La Caridad, Mex.	I, II, III	PQ, SQ	17
Bethlehem, B. C., Canada	I, III	PQ, SQ	1
Victoria, B. C., Canada	I		1
Valley Copper, B. C., Canada	I		1
Helecho, Puerto Rico	I, II, III	PQ, SQ	18
Sapo Alegre, Puerto Rico	I, II, III	PQ, SQ	18
Saindak, Pakistan	I, II, III	PQ, SQ	19
Mt. Fubilan, New Guinea	I, III	SQ	20
Ok Tedi, New Guinea	I, II, III	PQ, SQ	21
Koloula, Guadacanal	I, II, III	PQ, SQ	21

[1]Reference: 1, Observed by J. T. Nash (this report); 2, Nash and Cunningham (1974); 3, D. P. Wheeler (written commun., 1973); 4, Roedder (1971); 5, Drake (1972); 6, Lindgren (1905); 7, Logsdon (1969); 8, J. D. Davis (written commun., 1973); 9, Nash and Theodore (1971); 10, Spencer (1917); 11, D. Norton (oral commun., 1971); 12, Moore and Nash (1974); 13, Meyer and others (1968); 14, Roberts (1973); 15, Gustafson and Hunt (1975); 16, Sillitoe and Sawkins (1971); 17, T. G. Theodore (oral commun., 1974); 18, Observed by D. P. Cox and J. T. Nash; 19, Observed by R. G. Schmidt and J. T. Nash; 20, Bamford (1972); 21, A. R. Chivas and R. W. T. Wilkins (written commun., 1975).

APPLICATIONS TO EXPLORATION

Although there are many unifying similarities between the various disseminated copper deposits, there also are many differences in certain aspects such as goelogic age, wallrock lithology, alteration, and degree of supergene enrichment, factors which complicate assessment of ore targets. In previous sections of this report attention has been drawn repeatedly to the widespread occurrence of high-salinity, halite-bearing fluid inclusions in porphyry copper deposits. Further, there is considerable evidence for the importance of saline liquids in the transport of base metals (Helgeson, 1964, 1969; White, 1968; Holland, 1972) as metal-chlorite complex ions.

The presence of chlorine in intrusive rocks has recently been suggested as a possible prospecting tool (Stollery and others, 1971; Kesler and others, 1973). Microprobe analyses of biotites and amphiboles in intrusive rocks with associated mineralization have shown enrichment in chlorine (Stollery and others, 1971; Parry, 1972). Alternately, whole rocks or minerals may be analyzed for chlorine (Stollery and others, 1971; Haynes and Clark, 1972a, 1972b). Though the findings of these studies are in basic agreement with those presented in this report, the methods used are rather expensive, time consuming, or nonspecific. Fluid-inclusion petrography employing conventional thin sections (Nash and Theodore, 1971; Moore and Nash, 1974) is a preferable method because it yields more information at less cost, and is readily combined with other desirable petrographic studies.

Sampling and petrographic techniques

The approach I have used in reconnaissance studies of fluid inclusions is subjective, yet seems to produce plausible results. An important part of these studies is the collection of representative samples; here one must use guides such as structure, alteration, and sulfide mineralogy. Grid sampling is not recommended. Many students of fluid inclusions tend to collect vuggy, well-formed vein materials known to contain the largest, best-preserved inclusions. Such samples are commonly late-stage, however, and may not be representative of the most economically important stages of metallization and alteration. To avoid such sample bias, an effective technique is to sample quartz-bearing pre-ore rocks and to study secondary inclusions on fractures through quartz clasts or quartz phenocrysts. Such samples provide a record of changes in fluids introduced during multiple periods of fracturing, an advantage for exploration that outweighs the disadvantage of not knowing exact age relations. The sequence of fluids can best be determined from vein samples whose relative ages are established by structural and paragenetic criteria.

Three types of sample preparation may be used: thin section, polished thin section, or grains in immersion oil. Although the latter is cheapest it has the great disadvantage of conveying little or no textural information, and for that reason I have rarely used it. Conventional thin sections are highly advantageous: minerals are identified readily, textural relations are preserved, optical quality of inclusions in most minerals is very good even for those of one micron diameter, and the preparations are made at low cost. Thin sections may be prepared with or without coverglasses, but one must be able to focus into the thin rock slice with a 100X immersion objective (focal distance generally 0.09 mm). Doubly polished sections cut to a

thickness which allows adequate light transmission are required for heating and freezing stage study and are superior for petrography of larger inclusions and for minerals with high indices of refraction. Structural and textural relations should be determined in the field or with a binocular microscope.

Individual fluid inclusions are generally visible at 100 to 200X, although at such magnification they commonly look like "foreign matter." Depending upon size and morphology, the inclusions may be clear or dark from internal reflection. For study of typical rocks from porphyry copper deposits a good quality 100X oil immersion objective and substage condenser are virtually indispensable for proper resolution of vapor bubbles and daughter minerals. At magnifications of about 1,000X one focuses inside crystals and can resolve thousands of inclusions. Proper use of focused condensed light is required to illuminate the interior of inclusions. During petrographic study observations should be made of types of inclusions present, their textural occurrence (on fractures, isolated, healed or recrystallized, necked down, and so forth), identity and size of daughter minerals, phase proportions, and relative abundance of inclusion types; total abundance should be estimated. This estimate is best made by reference to type samples and is recorded in a relative sense (high, moderate, and low).

Identification of favorable intrusive bodies

Many petrologic features have been considered in attempts to characterize intrusives favorable for porphyry copper deposits (Stringham, 1966; Lowell and Guilbert, 1970). I believe that fluid inclusion types and abundance should be considered also. Evidence given previously suggests that favorable intrusive rocks should contain halite-bearing and probably gas-rich inclusions. Such inclusions appear to characterize epizonal intrusions, many of which have generated ore deposits. Abundance of these inclusions correlates with intensity of fracturing, water and salt content, and other unspecified physical conditions, all of which are favorable for metallization. Post-ore intrusions commonly can be discerned by a low abundance of inclusions, but not by inclusion types alone. Likewise, feeder-dikes and very shallow intrusives can often be discerned by their low fluid-inclusion content.

The fluid-inclusion criteria obviously should not be the only criteria used to evaluate the mineral potential of intrusive bodies because many metal- and sulfide-poor epizonal intrusions studied by the author contain halite-bearing and gas-rich inclusions similar in appearance to those in fertile intrusions. Other features, easily noted while making the fluid-inclusion examination, should also be present, such as recrystallization, added K-feldspar or biotite, secondary biotite replacing amphibole, and sulfide minerals replacing magnetite.

Characterizing hydrothermal systems

An important application of fluid-inclusion petrography is to aid in establishing the character of metal anomalies. Knowledge of fluid character should help the explorationist discriminate between types of hydrothermal systems and thereby increase his confidence that he has found a system that has a potential for extensive disseminated mineralization, rather than a small epithermal system. Vein and replacement base- and precious-metal deposits of the "mesothermal" and "epithermal" type tend to form from moderate-salinity fluids (Roedder, 1963; Nash, 1972, 1973). As outlined here, the porphyry copper deposits appear to stand out as a class associated with highly saline and commonly, boiling fluids. Hence, efforts should be made to characterize the hydrothermal system which caused the metal anomaly by looking for signs of high salinity (halite-bearing inclusions) and boiling (gas-rich inclusions).

Studies of high-temperature halite-bearing and gas-rich inclusions in altered porphyry bodies in four precious metal mining districts demonstrate specific application of this technique. Fluid-inclusion studies of pyritized, potassic altered zones of intrusive bodies in the northwest San Juan Mountains, Colorado, San Miguel Mountains, Colorado, Park City district, Utah, and Goldfield district, Nevada, suggest the need to reevaluate each of these areas for potential disseminated sulfide mineralization at depth. Base- and precious-metal ores in these districts were deposited from low- to moderate-salinity (<10 weight percent NaCl) moderate-temperature (<320°C) fluids (Nash, 1973, 1975). In three of these districts the observed zone of high-salinity fluids underlies the known precious-metal ore; it formed earlier than the precious-metal ore but during the same period of metallization. Potassic alteration in the deeper zones is not obviously different in the field.

Gossans and leached outcrops

Fluid inclusions in silicified leached capping and gossans provide an important record of depositional conditions which is of great value to explorationists. Evidence from many districts indicates that fluid inclusions in quartz survive in excellent condition the leaching which destroys other primary minerals. Fluid inclusions in these surface samples allow a good estimate of thermal and compositional history during primary mineralization, and there is no confusion with supergene processes because such low-temperature conditions leave only liquid-filled inclusions with no gas bubble.

Silicified caprock above the Bagdad, Bisbee (Lavender pit), Copper Canyon, Ely, Mineral Park, and Ray deposits all contain distinctive inclusions identical to those in the underlying orebody. Samples of caprock from Bagdad and Mineral Park contain few halite-bearing inclusions, just as do ore veins in those deposits (Nash and Cunningham, 1974), but the samples from Copper Canyon and Ely contain abundant halite-bearing and gas-rich inclusions indicating the former presence of hot, highly saline, boiling fluids. Silicified capping above the Ray deposit contains only moderate salinity, moderate temperature (about 300°C) inclusions like those in ore veins. Leached, oxidized capping derived from the "older porphyry" in the Lavender pit contains abundant halite-bearing inclusions but no gas-rich type. Caprock above the La Caridad deposit, Mexico, contains prominent halite-bearing inclusions indicative of potent, hot solutions (T. G. Theodore, oral commun., 1974).

Laterite and soil

Fluid inclusions in quartz survive even severe weathering in the tropics as shown by studies of deposits in Puerto Rico (Cox and others, 1975). Hence, inclusions can be examined in quartz in residual soils or laterite to determine the presence of hydrothermal alteration. For these studies soil samples are washed and coarsely sieved to remove clays, and the residual grains cast in epoxy prior to making thin sections. By study of the residual quartz grains it is possible to distinguish quartz phenocrysts from hydrothermal and supergene quartz on the basis of fluid inclusion types and abundance. Phenocrysts contain the most abundant inclusions and gas fractions are generally high; supergene quartz contains only liquid-filled inclusions with no vapor bubble. Hydrothermal activity is clearly indicated by appropriate fluid inclusions, even in samples in which weathering destroys all textural and mineralogical evidence of hydrothermal alteration.

References cited

Bamford, R. W., 1972, The Mount Fubilan (OK Tedi) porphyry copper deposit, Territory of Papua and New Guinea: Econ. Geology, v. 67, p. 1019-1033.

Cox, D. P., Perez Gonzales, I., and Nash, J. T., 1975, Geology, geochemistry, and fluid-inclusion petrography of the Sapo Alegre porphyry copper prospect and its metavolcanic wall rocks, West-Central Puerto Rico: U.S. Geol. Survey Jour. Research, v. 3, no. 3, p. 313-327.

Drake, W. E., 1972, A study of ore forming fluids of the Mineral Park porphyry copper deposit, Kingman, Arizona: Columbia Univ. Ph.D. thesis, 245 p.

Gustafson, L. B., and Hunt, J. P., 1975, The porphyry copper deposit at El Salvador, Chile: Econ. Geology, v. 70, p. 857-912.

Haynes, S. J., and Clark, A. H., 1972a, A rapid method for the determination of chlorine in silicate rocks using ion-selective electrodes: Econ. Geology, v. 67, p. 378-382.

_____1972b, Distribution of chlorine and fluorine in granitoid rocks and associated ore deposits, northern Chile [abs.]: Econ. Geology, v. 67, p. 1005.

Helgeson, H. C., 1964, Complexing and hydrothermal ore deposition: New York, The Macmillan Co., 128 p.

_____1969, Thermodynamics of hydrothermal systems at elevated temperatures and pressures: Am. Jour. Sci., v. 267, p. 729-804.

Holland, H. D., 1972, Granites, solutions, and base metal deposits: Econ. Geology, v. 67, p. 281-301.

Kesler, S. E., Van Loon, J. C., and Moore, C. M., 1973, Evaluation of ore potential of granodioritic rocks using water-extractable chloride and fluoride: Canadian Inst. Mining and Metallurgy Bull., v. 66, no. 730, p. 56-60.

Lindgren, Waldemar, 1905, The copper deposits of the Clifton-Morenci district, Arizona: U.S. Geol. Survey Prof. Paper 43, 375 p.

Logsdon, M. J., 1969, A fluid inclusion study of the porphyry copper deposits at Ray and San Manuel, Arizona [abs.], in Edwin Roedder, ed., Fluid inclusion research--Proceedings of COFFI, 1969: p. 20 [1972].

Lowell, J. D., and Guilbert, J. M., 1970, Lateral and vertical alteration-mineralization zoning in porphyry ore deposits: Econ. Geology, v. 65, p. 373-408.

Meyer, Charles, Shea, E. P., Goddard, C. C., Jr., and others, 1968, Ore deposits at Butte, Montana, in J. D. Ridge, ed., Ore deposits of the United States, 1933-1967 (Graton-Sales Volume), v. 2: New York, Am. Inst. Mining, Metallurgy and Petroleum Engineers, p. 1373-1416.

Moore, W. J., and Nash, J. T., 1974, Alteration and fluid inclusion studies of the porphyry copper orebody at Bingham, Utah: Econ. Geology, v. 69, no. 5, p. 631-645.

Nash, J. T., 1971, Fluid inclusions as a guide to porphyry-type mineralization: Econ. Geology, v. 66, p. 1268.

_____1972, Fluid inclusion studies of some gold deposits in Nevada: U.S. Geol. Survey Prof. Paper 800-C, p. C15-C19.

_____1973, Geochemical studies in the Park City district, Utah--I, Ore fluids in the Mayflower mine: Econ. Geology, v. 68, p. 34-51.

_____1975, Fluid inclusion studies of vein, pipe, and replacement deposits, northwestern San Juan Mountains, Colorado: Econ. Geology, v. 70, p. 1448-1462.

Nash, J. T., and Cunningham, C. G., Jr., 1974, Fluid-inclusion studies of the porphyry copper deposit at Bagdad, Ariz.: Jour. Research, v. 2, no. 1, p. 31-34.

Nash, J. T., and Theodore, T. G., 1971, Ore fluids in a porphyry copper deposit at Copper Canyon, Nevada: Econ. Geology, v. 66, p. 385-399.

Parry, W. T., 1972, Chlorine in biotite from Basin and Range plutons, Econ. Geology, v. 67, p. 972-975.

Roberts, S. A., 1973, Pervasive early alteration in the Butte district, Montana, in Society of Economic Geologists, Butte field meeting Guidebook, Butte, Mont., Aug. 18-21, 1973: Butte, Mont., Anaconda Co., Photoreproduction Dept., p. HH1-HH8.

Roedder, E., 1963, Studies of fluid inclusions II--Freezing data and their interpretation: Econ. Geology, v. 58, p. 167-211.

_____1967, Fluid inclusions as samples of ore fluids, in H. L. Barnes, ed., Geochemistry of hydrothermal ore deposits: New York, Holt, Rinehart, and Winston, Inc., p. 515-574.

_____1972, Composition of fluid inclusions, in Michael Fleischer, tech. ed., Data of geochemistry [6th ed.]: U.S. Geol. Survey Prof. Paper 440-JJ, 164 p.

Sillitoe, R. H., and Sawkins, F. J., 1971, Geologic, mineralogic, and fluid inclusion studies relating to the origin of copper-bearing tourmaline breccia pipes, Chile: Econ. Geology, v. 66, p. 1028-1041.

Spencer, A. C., 1917, The geology and ore deposits of Ely, Nevada: U.S. Geol. Survey Prof. Paper 96, 189 p.

Stollery, G., Borcsik, M., and Holland, H. D., 1971, Chlorine in intrusives--A possible prospecting tool: Econ. Geology, v. 66, p. 361-367.

Stringham, Bronson, 1966, Igneous rock types and host rocks associated with porphyry copper deposits, in Geology of the porphyry copper deposits, southwestern North America: Tucson, Arizona Univ. Press, p. 35-40.

White, D. E., 1968, Environments of generation of some base-metal ore deposits: Econ. Geology, v. 63, p. 301-335.

ASARCO 1975 Exploration Meeting

FLUID INCLUSIONS AS GUIDES TO PORPHYRY COPPER DEPOSITS

Frederick T. Graybeal

Fluid inclusions are tiny drops of liquid found in a variety of minerals which represent samples of the fluid present in the rock at the time of entrapment. These inclusions are easily identified under the microscope and can be classified as follows:

1) gas-poor: liquid with a small gas bubble
2) gas-rich: liquid with a large gas bubble
3) saline: liquid, a small gas bubble, and one or more solid phases such as halite, hematite, and anhydrite.

Sparse published data reveal that spatial variations of different types of fluid inclusions are closely related to zones of ore-grade mineralization at the Battle Mtn., Bingham, and San Manuel-Kalamazoo porphyry copper deposits. These data have been supplemented with a study of roughly 600 samples from 40 porphyry copper orebodies and sub-marginal prospects in the Western Cordillera of North America, the Philippine Is., and Iran. The results indicate that saline and gas-rich types are abundant within and above the ore zones as compared to gas-poor, dilute types which are relatively more abundant in peripheral or sub-marginal zones. This distribution is consistent with known formational processes in porphyry copper deposits and allows the existence of concealed mineralization to be predicted. Variations of fluid inclusion zones appear primarily related to base metal mineralization rather than to alteration and are unaffected by supergene processes.

Quartz is the most suitable mineral for the study of fluid inclusions in porphyry copper deposits due to its abundance, widespread distribution, brittle nature, and resistance to weathering. Inclusions are best studied in standard thin sections at 1000-1200x magnification using an oil immersion objective, although in many deposits they are sufficiently large to be identified at 250-500x. These studies are inexpensive, rapid, easily quantified, and can be performed with a standard petrographic microscope. The results must be carefully interpreted within the overall geologic framework because such factors as grain size, paragenesis, and age of the host rock may exert a strong control on the type and abundance of fluid inclusions present, even within the ore zones.

Porphyry copper systems are ideally suited to fluid inclusion studies because of their large size relative to the ore zone, the pervasiveness of alteration and mineralization, and the presence of well-defined zoning patterns. These studies should be particularly useful during exploration of poorly-exposed deposits and for rapid evaluation of vertical zoning patterns above deep-lying mineralization. A brief review of the literature and available samples indicates that this technique is less applicable to exploration for other types of ore deposits.

FLUID INCLUSIONS AS GUIDES TO PORPHYRY COPPER DEPOSITS

INTRODUCTION

1) Complex studies in the literature

2) Practical value first noted by Nash & Theodore (1971), emphasized by Nash (1972)

3) Nash found:
   a) chemical variations in ore fluid with systematic relation to ore
   b) evidence concerning distribution of chemical variations is preserved in fluid inclusions
   c) evidence is easily recognized using standard petrographic techniques

4) Tucson office has used technique since 1972 on certain projects
   a) CONOCO only company who may be using technique
   b) recent paper by Cunningham in Denver reemphasized Nash findings
   c) people know about technique; don't know how useful it is until you use it

TYPES OF FLUID INCLUSIONS

1) Fluid inclusions are tiny drops of liquid which become trapped on the surfaces of growing crystals or in later fractures
   a) they do not generally leak
   b) represent sample of fluid present in rock at time of entrapment

2) Classification important for mapping
   a) According to age or occurrence - SLIDE 1
      1) primary - trapped during growth of mineral; distribution random or in growth zones
      2) pseudosecondary - trapped in fracture during growth
      3) secondary - trapped along fracture plane after growth of mineral was complete
      4) SLIDE 2 - no inclusions (TM-8, Sunnyside)
      5) SLIDE 3 - primary inclusions (TM-8, Sunnyside)
      6) SLIDE 4 - primary & secondary incl. (Sacaton)

   b) According to composition - SLIDE 5
      1) Type 1 - liquid and small bubble
         a) bubble forms by contraction of fluid during cooling; smaller bubble = lower temp.
         b) represent low salinity liquids
         c) relative abundance greatest in peripheral zones
      2) Type 2 - liquid and large gas bubble
         a) bubble forms greater than 50% of inclusion
         b) represents a gas, indicates boiling conditions
         c) relative abundance greatest in and above ore zones

3) Type 3 - liquid, a small gas bubble, and one or more daughter minerals
   a) minerals are halite, opaque, hematite, anhydrite, numerous unknowns
   b) minerals form if liquid becomes saturated with various components during cooling
   c) many subdivisions of Type 3 are possible, but in present context a Type 3 always contains halite
      1) presence of halite at room temp. means NaCl = +26% wt. %
      2) increased size of halite cubes means increased salinity.
   d) Type 3 is most abundant in chalcopyrite zone
4) SLIDE 6 - Type 1 (Santa Cruz)
5) SLIDE 7 - Type 2 (Casino)
6) SLIDE 8 - Type 3 (Sacaton)
7) SLIDE 9 - Type 3, larger halite (Sacaton)

DISTRIBUTION OF FLUID INCLUSIONS IN PORPHYRY COPPERS

1) Discussion of Table - SLIDE 10
   a) tabulation represents averages for ore zones, based on 3-10 thin sections
   b) abundances similar within a single ore zone
   c) abundances similar between different ore zones
      1) compare average values with Iran and Panama
      2) note Type 2 and Type 3
   d) note difference between ore, submarginal, barren
   e) note that the effects are pervasive; every quartz grain in a given zone has similar population

2) Similar fluid inclusion populations are independent of:
   a) rock type: qtz. diorite (Philippines) - granite porphyry (Caridad)
   b) age of deposit: Jurassic - Pliocene
   c) metallogenetic province
   d) alteration type or strength

3) Similar populations are dependent on the presence of chalcopyrite
   a) due to formational process which operates in all porphyry copper deposits and which is related to ore deposition
      1) result is close spatial relationship between Type 2 and 3 inclusions and chalcopyrite
      2) an understanding of this process will enable the geologist to interpret his data with a high degree of accuracy

THE PROCESS

1) Presence of closely coexisting gas-rich (Type 2) and gas-poor (Type 1 and/or 3) is strong evidence for boiling
   a) boiling is common in porphyry copper deposits; boiling point depends on temperature, pressure, composition

2) Effect of boiling - SLIDE 11
   a) develops 2 coexisting phases - liquid and gas
   b) gas is NaCl-poor; liquid is NaCl-rich
      1) continued boiling removes H_2O and enriches liquid in NaCl
   c) data show that NaCl-rich fluids (brine) are intimately associated with chalcopyrite ore
   d) this empirical relationship suggests that if we can predict the location of the brine we will find increased amounts of chalcopyrite

3) Boiling can be easily recognized in thin section
   a) gas is light and rises to upper portions of the system, above the relatively heavier brine
   b) thus, chalcopyrite should be found below boiling zones and within brine zones

SPATIAL DISTRIBUTION OF FLUID INCLUSIONS

1) Averages indicate a close association of Type 2 and Type 3 inclusions with porphyry Cu ore. What is the detailed picture?

2) Lateral variations
   a) Copper Canyon, Battle Mtn. dist., Nev. - SLIDE 12
      1) high salinity fluids (Type 3 inclusions) are centered on east ore body; in both sedimentary and igneous rocks
         a) not limited to intrusion, not symmetrical about intrusion
      2) Type 3 inclusions more specific than pyrite, and rock geochemistry (latter leads into intrusion)
      3) Theodore & Nash conclude that distribution of Type 3 inclusions was better ore guide than pyrite or rock geochemistry

   b) Bingham district, Utah - SLIDE 13
      1) high salinity inclusions follow the copper ore zone (Type 3 = +40%)
      2) Type 1 inclusions relatively more abundant in peripheral areas
         a) absolute abundance Type 1 greatest in ore
      3) Type 2 most abundant on edge of ore, erratic

   c) Kalamazoo, Ariz. - SLIDE 14
      1) shows abundance of fluid inclusions in (tilted) vertical drill hole in Precambrian qmz
      2) abundance of Type 2 and Type 3 inclusions increase adjacent to and in ore zone
         a) halo is limited; 500 ft. - Type 3, 1000 ft. - Type 2, but this section is in the western or deepest portions of orebody
      3) total abundance of inclusions increases inward
      4) abundance of primary inclusions increases inward
      5) alteration forms wider halo, but Type 2 & 3 inclusions tell us we are close and demonstrate close association with ore

d) El Tiro area, Silver Bell district, Ariz. - SLIDE 15
   1) Types 2 and 3 most abundant in ore zone
      a) types 2 and 3 are more uniformly present in ore zone than primary alteration or mineralization
   2) total abundance of all types highest in alaskite adjacent to ore
   3) average size increases rapidly toward ore

e) general comments - SLIDE 16
   1) similar lateral variations at Sierrita, Sacaton
   2) Casino - abundance of Type 2 suggests deep chalcopyrite ore not yet found
   3) Cerro Chorcha - Type 2 and 3 abundant cover large area, looks favorable in comparison to known ore deposits
   4) submarginal types have only rare Type 3 even though some have pervasive phyllic and potassic alteration

3) Vertical variations - NO DATA IN LITERATURE
   a) Charleston district, Tombstone Hills, Arizona
      1) surface sampling - SLIDE 17
         a) Type 2 inclusions restricted to zone of pervasive alteration
         b) no Type 3 inclusions anywhere on surface (mapping by J.R.King)
      2) drill holes - SLIDE 18
         a) CHS-1: continuous Type 3 at 1400 ft.; potassic alteration at 2200 ft.; +0.13% Cu at 2500 ft.
         b) CHS-2: rare Type 2, no Type 3 to 3400 ft.
      3) CHS-1 clearly demonstrates presence of saline brine under a zone of abundant Type 2 inclusions (hole collared before inclusion work)
         a) fluid inclusion zoning conforms well to predicted behavior
         b) within Type 2 zone is found potassic alteration cpy mineraliz. — in a district where neither were previously known to occur

   b) Sunnyside area, Patagonia Mtns., Ariz. - SLIDE 19
      1) hole in quartz feldspar porphyry, intensely altered throughout
      2) Type 2 rare at surface, relative abundance high at 1500 ft.
      3) Type 3 rare 1800-3600 ft., becomes abundant below 3600 ft.
         a) clear zoning of an upper boiling zone underlain by a denser brine with associated potassic alteration and chalcopyrite (1200 ft. of 0.25% Cu)
         b) pattern similar to Tombstone, emphasizes similar process (also Red Mtn., Ariz.)
      4) additional complexities involve copper zones near surface, but absence of Type 3 inclusions suggested deep potential still present
         a) we are currently exploring higher grade, more shallow portions of the deep zone; shallow zones are small
      5) Type 2 very small, nearly absent at surface in qtz feld por
         a) adjacent tuffs contained 2 types of qtz xenocrysts, well-mixed
            1) no fluid inclusions
            2) large Type 2 with rare Type 3
         b) evidence from many other deposits indicates uniform populations in the same sample

1) suggestion was strong that tuff provided a sample of preexisting deep, concealed mineralization
2) mixed populations seen in intrusive breccias at Summitville

c) Vertical fluid zoning suggests dense brines underlie boiling zones; most brines exceed 26 wt. % NaCl
   1) empirical relationships indicate brine will contain significant interval of +0.20% Cu as cpy
   2) data suggest that +0.20% Cu will be encountered within 2000 ft. of the top of a zone of continuous Type 3 inclusions; within 500 ft. of abundant Type 3 (+10%)
   3) understanding of process of brine formation and recognition of close empirical relationship between brine and chalcopyrite combine to give us a powerful tool for evaluation of vertical zoning targets during exploration
   4) can't predict actual grade, length, or depth of mineraliz., but the mere ability to predict its presence is of considerable importance to exploration.

SUMMARY OF FLUID INCLUSION RELATIONSHIPS TO PORPHYRY COPPER ORE

1) Review table - SLIDE 20
   a) variations listed are only constant for same age quartz
   b) ore means primary chalcopyrite
   c) variations are easily quantified
   d) not all variations diagnostic in a single deposit, listed in approximate order of importance.

DATA COLLECTION

1) Quartz is the most suitable host mineral because it is widespread, abundant, brittle, and doesn't weather.

2) Sampling approach
   a) Nash samples all rocks, veins; 200-300 samples/deposit
   b) My sampling approach is designed around major problems:
      1) abundance - need more samples where qtz is rare
      2) grain size - fine-grained quartz often not useable
      3) age - types of fluid inclusions can vary according to age of quartz:
         a) primary quartz in rocks of different age - SLIDE 21
         b) primary/vein quartz - SLIDES 22 & 23 (TR-10, Sunnyside)
         c) primary/recrystallized qtz - SLIDES 24 & 25 (alaskite, Sunnyside)
      4) in a qtz-rich environment 10-20 samples may be sufficient for a first pass; fresh rocks should also be sampled
      5) be careful to interpret within geologic framework

3) Petrographic technique - easy, fast, inexpensive
   a) standard petrographic microscope, standard thin section
   b) need 1000-1200x oil immersion; most work at 500x (w/o oils)

c) fluid inclusion data can be read more easily than mineralogy & textures
d) details of technique are best reserved for a text or actual time at the microscope.

APPLICATION TO OTHER DEPOSITS

1) Explanation of temperature - salinity - SLIDE 26
   a) note 26 wt. % NaCl equivalent - above which halite becomes visible at room temperature
   b) plots represent region of ore deposition only

2) Porphyry Cu
   a) Battle Mtn., Kalamazoo, Bagdad, Butte, Bingham
      1) note Ithaca Peak
   b) position consistent for other deposits due to visible halite

3) Climax Mo
   a) ore-forming fluids generally less than 26% NaCl

4) Pb-Zn-Au-Ag-Cu
   a) Providencia, Darwin, Casapalca, Mayflower, Creede, Gilman, Andean Sn-W
      1) limestone replacement generally at higher salinity than veins
   b) Type 3 inclusions usually rare, occur from top to bottom of veins
      1) Type 3 inclusions without halite are abundant
   c) problem is that to study fluid inclusions you must first find the vein or replacement
   d) conclude technique not too useful for this type because of lack of pervasive fluid movement, lack of quartz, and erratic spatial distribution of inclusions

5) Gold deposits (includes Ag)
   a) Carlin, Cortez, Gold Acres, Aurora, Manhattan (Nevada); Jamestown, Colo., Alleghany, Calif. (probably Yellowknife, Bodie, Waterloo, Hardshell, Tonopah)
      1) uniformly low salinities in all deposits; abundance often low
      2) Jamestown pyritic Au veins center on 26% NaCl
   b) some size and abundance variations, but low salinities, fine-grain size of quartz, and lack of pervasive alteration much beyond ore may limit the method
      1) useful for pyritic Au at Leadville(?)

6) Volcanogenic massive sulfide (and variants)
   a) Jerome, Coronation, Kuroko
      1) salinities generally low; pervasive halos appear to be lacking
      2) petrographic work on Kidd Creek, Millenbach, Vauze, and Caribou reveal no clear variations adjacent to ore or associations within ore
         a) Brunswick 6 & 12 show more abundant inclusions in qtz por schist (crystal tuff) adjacent to ore
         b) Rammelsberg has only rare, small inclusions in the kneist (similar to silica-dolomite at Mt. Isa)
         c) technique limited by low salinities, rare inclusions, lack of pervasive effects outside ore

7) Miss Valley
   a) samples in literature come from ore
   b) if connate brines are the ore-forming fluid then the halo may involve tens of thousands of cubic miles - a somewhat unmanageable size

CONCLUSION

1) Porphyry Cu deposits are ideally (and uniquely) suited for exploration-oriented fluid inclusion studies due to the following characteristics:
   a) large size of the entire system relative to ore
   b) presence of well-defined fluid zoning patterns geometrically equilibrated within and outside of ore
   c) rapid changes in fluid inclusion zones which are easy to recognize
   d) pervasiveness of fluid movement at both large and small scales (down to scale of single grains)
      1) inclusions are not confined to hard to find veins or concealed beds
   e) close spatial relationship of a high-salinity fluid and ore; regardless of alteration strength
   f) abundance of quartz
   g) retention of hypogene zoning patterns during severe supergene alteration
   h) simple formational model which allows location of high-salinity fluid and chalcopyrite to be predicted

2) Useful for evaluation of lateral zoning in poorly exposed deposits; deposits associated with weak alteration; deposits with unreactive wallrock
   a) Philippine Is., W. Canada, Alaska, Central America
      1) studies at Cerro Chorcha suggest ore zone much larger than area of CuOx
      2) lateral zoning in barren plutons with Type 3 in matrix quartz may also be useful

3) Useful for evaluation of vertically zoned porphyry Cu systems
   a) involve deep targets - words management doesn't like to hear
   b) Ariz., Nevada, San Juan (Colorado), NW Wyoming, Mexico, Panama
   c) evaluation of deep hole relative to bottoming can be rapidly made
      1) Type 2 extend 2500 ft. above ore (or more)
      2) continuous Type 3 extend up to 2500 ft. above ore; only abundant (+5%) within 300-1000 ft. of ore; only +10% in ore (based on 3 deep holes)
      3) never bottom a hole in continuous Type 3

4) Probably useful in S. America also but problem there is that the deposits are so big that finding the ore is easier than finding the money to develop it.
   a) might be useful for evaluating large pyritic zones in volcanic rocks which have been noted by J. H. Courtright

5) Technique is not a panacea but it can be extremely useful during porphyry Cu exploration

a) I would recommend that every office involved with porphyry Cu exploration be equipped with a good petrographic microscope ($2500 range)
   1) it will pay for itself in consultants' fees after 100-200 thin sections
b) it will require a geologist who is familiar with rock and alteration petrography - or who is willing to learn. I think the necessary talent is already available within the company; possibly interested parties could assemble over a microscope if supervisors think technique could be useful to them.

ASARCO

Southwestern Exploration Division

May 17, 1982

To: F. R. Koutz
H. G. Kreis
G. J. Stathis

From: J. D. Sell

Fluid Inclusion Studies

Attached is a copy of Mr. Graybeal's letter on the subject, along with a copy of Ballantyne's data.

I suggest that Koutz secure the samples of the Ventura area, and Kreis secure the samples from Santa Cruz and Florence Pediment. I will take care of Superior East. Please have the samples (4 to 6 sample sites, several from each site) submitted to Kreis by June 4 so that he can package them and send them off as a group for slide preparation. *

Later, when the slides are returned and all of us (or 3 out of 4) are available I will ask Vikre to return to Tucson for a few days to instruct all of us in the procedures. Stathis can then work the Florence Pediment slides.

FTG mentioned by phone that if the fluid inclusion microscope has been moved prior to this group being ready, then we will set up an arrangement to go to Reno for the course.

This is not a rush job for the results, but all should be ready in time.

James D. Sell

JDS/cg

Attachments

cc: PGVikre (w/o attach.)

* See list by HGK attached. (June 7, 1982)

Systematics of Stretching of Fluid Inclusions I: Fluorite & Sphalerite at 1 Atmosphere confining Pressure, by
R J Bodnar & P M Bethke
Econ Geol Vol 79, No. 1, p. 141-161

~~48" fluorite lamps~~

ASARCO

Exploration Department
R. L. Brown
Director of Exploration

May 11, 1982

Mr. J. D. Sell
Manager, Southwestern Exploration Division
Tucson Office

Fluid Inclusion Studies

Dear Mr. Sell:

Although it may not be clear to everybody, the fluid inclusion microscope was purchased for use as an exploration tool. To date, it has been largely used by Mr. Vikre to unravel complex assemblages at Buckskin and to provide a clearer understanding of selected precious metal environments including Summitville (with application to Goldfield) and the Comstock Lode. I have a verbal understanding with Mr. Vikre that the fluid inclusion equipment will be moved to Reno once the office is firmly in place and Mr. Vikre indicated this would be early Fall.

Before this equipment disappears from Tucson I would like to see Tucson Office staff become more familiar with its use. I had previously discussed this subject briefly with Mr. Payne, but I did not push - now I'm pushing. As with any new tool, only use will breed familiarity and I would suggest the following topics be assigned subject to revision by you:

Sell - thermal zoning patterns at Superior E.
Kreis - " " " " Santa Cruz
Stathis - " " " " Florence Pediment
Koutz - " " " " Ventura (reasonably familiar already).

The thermal zoning studies I have in mind are of the type done by Ballantyne at North Silver Bell which rather nicely pointed the way to the center of the hydrothermal system from a distance of about 2 miles. I recall that he used 3 or 4 sample sites with a few slabs from each site. Studies of this type are simple, quick, and do not rely on time-consuming concurrent mineral paragenesis studies. Data are interpreted on histograms. Mr. Kreis has a copy of the Ballantyne data which were originally given at the S.E.G. Spring Symposium on Porphyry Copper Deposits held in Tucson a few years ago.

RECEIVED
MAY 17 1982
S. W. U. S. EXPL. DIV.

ASARCO Incorporated 120 Broadway New York, N.Y. 10271 (212) 669-1000
Telex: ITT 420585 RCA 232378 WUI 62522 Cables: MINEDEPART Telegrams: WU 1-25991

The studies would involve 1) selection of samples to be doubly polished, 2) sending of samples for preparation, 3) heating the samples, and 4) plotting of data. I suspect Mr. Vikre could provide the necessary instructions for #1 and #2 in about 10 minutes and for #3 in an hour. My guess is that the time involved would be a day or less per man for the heating work and not more than 2 days total including a brief report. The work could be done at some time when the geologist is in the office for other reasons so this work should not interfere with their field plans.

This type of fluid inclusion work can be extremely useful in the definition of the center of a hydrothermal system and, unlike geochemical sampling of weathered material, the results are not influenced by supergene effects. Hopefully, use of the heating stage for a brief study will convince the skeptics.

Very truly yours,

F. T. Graybeal

F. T. Graybeal

cc: WLKurtz
PGVikre

HGK

THERMAL GRADIENTS IN THE NORTH SILVER BELL ALTERATION HALO

by

Geoffrey H. Ballantyne

Introduction

A fluid inclusion study has been undertaken with the object of determining thermal gradients across the North Silver Bell alteration halo. Independent temperature data are needed in order to evaluate the temperature dependence of subtle mineralogic changes being documented at Silver Bell and other porphyry copper deposits.

The approach taken in this study differs from that of other fluid inclusion studies in that it was deliberately restricted to secondary inclusions in the quartz-phenocrysts of a pre-mineral host rock. Such inclusions may be expected to record much or all of the thermal history of the system, and particular filling temperatures can not be assigned any chronological significance. However, for the present purpose, there are important advantages to the method. The samples are uniform and there is no sampling bias so that the data are amenable to statistical analysis. Most importantly, the fluid inclusion temperature data have an immediate relevance to pervasive the alteration which occurs in the same samples.

Geologic Setting

The samples studied are all from a pre-mineral rhyodacite porphyry which outcrops on the eastern flank of the North Silver Bell system, and is continuously exposed from near the center of the system to beyond the limits of obvious hydrothermal alteration.

The rhyodacite porphyry has a distinctly tuffaceous appearance but has been shown to be a large sill injected between Paleozoic sediments

and Cretaceous volcanics and vocaniclastic sediments (Watson, 1964). Radiometric dates are not available for the rhyodacite but geologic evidence suggests a Cretaceous age of more than 70 million years.

Mineralization and alteration in the Silver Bell district are spatially related to monzonite and quartz monzonite intrusions dated at 63 to 67 million years (Damon et al., 1964). In the North Silver Bell area quartz monzonite occurs either as an irregular stock, or a closely-spaced swarm of wide dikes, and intrudes the rhyodacite porphyry directly.

The occurrence of a single rather uniform rock type encompassing all of the alteration zones in the North Silver Bell area is an especially favorable circumstance for the study of thermal and alteration gradients.

Sample Locations

The samples are from an east-west traverse approximately normal to alteration assemblage boundaries. The following table summarizes the sample locations relative to each other and to the alteration zones.

Sample #	Distance from SB-4	Position Relative to Alteration Zones
SB-4	0	Near center of secondary biotite zone
SB-6	953 meters	Outer edge of secondary biotite zone
SB-11	1410 meters	Center of chlorite-epidote zone
SB-22	2507 meters	Within outer chlorite-calcite zone

Description of the Fluid Inclusions and the Quartz Host

The rhyodacite prophyry contains abundant quartz phenocrysts up to 5mm in diameter. The phenocrysts are extensively embayed and rounded but most are equidimensional and they probably originally crystallized as bypyramids. The phenocrysts contain rare large primary fluid inclusions and very abundant smaller secondary inclusions.

The primary inclusions occupy negative crystal-shaped vacuoles with maximum dimensions of about 40 microns. They are somewhat less than half filled by a prominent, dark-colored bubble which does not disappear on heating to 440°C. The bubbles appear to consist of two or more phases concentrically arranged. The primary inclusions are inferred to have been trapped during growth of the quartz phenocrysts prior to emplacement of the rhyodacite.

The secondary inclusions occur on through-going fractures which terminate either at the crystal margin or in other fractures. For this reason they are thought to be true secondary inclusions which formed subsequent to complete crystalization of the quartz grains. They probably represent trapped samples of a hydrothermal fluid which circulated through the rhyodacite during a period of intense hydrothermal activity which followed emplacement of the quartz monzonite intrusions.

Two types of secondary inclusions were observed, both consisting of a clear non-viscous vapor bubble in a clear liquid. In almost all of the inclusions the vapor bubble occupies approximately 25 to 40 percent of the vacuole. Rare inclusions in which the vapor bubble occupies 80 percent or more of the vacuole were observed only in sample SB-11 where they occur in close association with the more common liquid-dominated inclusions. No daughter minerals were observed in the inclusions in any of the samples.

The secondary inclusions vary in shape and size from smooth elliptical inclusions up to 5 microns long, to irregular planar features with maximum dimensions of up to 20 microns.

Homogenization Temperatures

Homogenization temperatures for sixty four inclusions are listed

in Table 1. Three further inclusions in sample SB-4 had not homogenized by 440°C, the maximum temperature obtained to date on the heating stage. As indicated in Table 1, duplicate filling temperature determinations were made for most samples, and the second determination for most samples agreed with the first to within 1°C. The biggest disparity recorded was 6°C. This indicates that no serious leakage occurred during heating of the inclusions and that precise filling temperatures could be determined despite the small size of the inclusions. Filling temperatures for a small number of inclusions in which the vapor bubble did not reappear on cooling are not presented. All the filling temperatures presented are for homogenization in the liquid phase. The last disappearance of the liquid in the few inclusions which homogenised in the vapor phase could not be accurately discerned.

Discussion of the significance of the homogenization temperatures is deferred until after the following section in which pressure corrections are considered.

Depth of Cover and Pressure Corrections

The coexistence of inclusions which homogenize in the liquid phase and inclusions which homogenize in the vapor phase, in sample SB-11, indicates that some of the fluids trapped in this sample were boiling. That is, the vapor pressure of the fluids exceeded the fluid pressure. Since the vapor pressure of aqueous solutions of various salinities is known as a function of temperature, the fluid pressure at the time of entrapment of these inclusions can be calculated.

If it is assumed that the fluid pressure at the time of entrapment was due to a column of fluid of appropriate density, in an open system of fractures, in the overlying rocks, an estimate of the thick-

TABLE 1

HOMOGENIZATION TEMPERATURES (°C)--NORTH SILVER BELL

SB-4	SB-6	SB-11	SB-22
405, 410	336, 337	340, 341	278, NR
400, 400	300, 302	324, 320	270, NR
370, 368	274, 275	320, 320	247, 245
360, 365	265, 264	314, 317	246, NR
360, 364	264, NR	305, 305	240, 237
348, 348	260, 258	304, 304	239, 239
345, 340	254, 254	300, 302	228, 233
342, 342	252, 250	295, 294	205, NR
330, 327	243, 243	290, 290	190, 190
290, 291	243, 243	265, 266	184, 185
285, 285	241, 241	255, 258	170, NR
250, 250	237, 237	250, 250	165, 168
230, 230	235, 236		133, 128
230, NR	233, 234		
223, 224	233, 233		
	232, 232		
	226, 226		
	224, 224		
	215, 214		
	212, 212		
Mean* 318	Mean 248	Mean 297	Mean 214
S. Dev.* 62.3	S. Dev. 29.1	S. Dev. 27.7	S. Dev. 42.8
Range* 184	Range 125	Range 91	Range 147

* Since three sample from SB-4 did not monogenize at 440°C the mean, standard deviation and range are all minimum values.

** NR indicates that the filling determination was not repeated.

ness of this rock cover can be made. Haas (1971) presents depth solutions for such a model.

Since the inclusions studied are too small to allow salinity determinations a precise depth estimate for sample SB-11 is not possible. However, for any assumed range of salinities a depth range can be calculated. The mean filling temperature for inclusions in sample SB-11 is 297°C. For salinities equivalent to 0 and 25 weight percent NaCl a depth range of 1250 to 750 meters is indicated by Haas' curves. Sample SB-11 is from near the center of the chlorite-epidote zone. It is probable that salinities at this point in the hydrothermal system were less than 5%. The 1250 meter estimate is a maximum depth estimate for several reasons. If the vein system were less than completely open so that pressures approaches lithostatic levels or if salinities were significantly greater than 0% the pressure gradients would be higher and a thinner cover would be indicated.

Another implication of the depth estimate for sample SB-11 is that if similar estimates of the stratigraphic cover are made for this sample and for the sample from the biotite zone, a marked increase in salinity and/or an increase in pressure above hydrostatic levels would be required to suppress boiling of the higher temperature fluids present in the biotite zone. Indeed, an increase in salinity alone is insufficient and either a larger hydrostatic head or pressures exceeding hydrostatic levels are necessary in the biotite zone.

Homogenous single phase fluids trapped at pressures above their boiling curves do not separate into liquid and vapor bubbles until they cool below the two phase curve. Consequently temperatures obtained by noting the point of disappearance of vapor bubbles must be corrected

LEAVE 4/10" SPACE BETWEEN TEMP SCALE & FIRST HISTOGRAM.

DELETE 4/10" OF SPACE

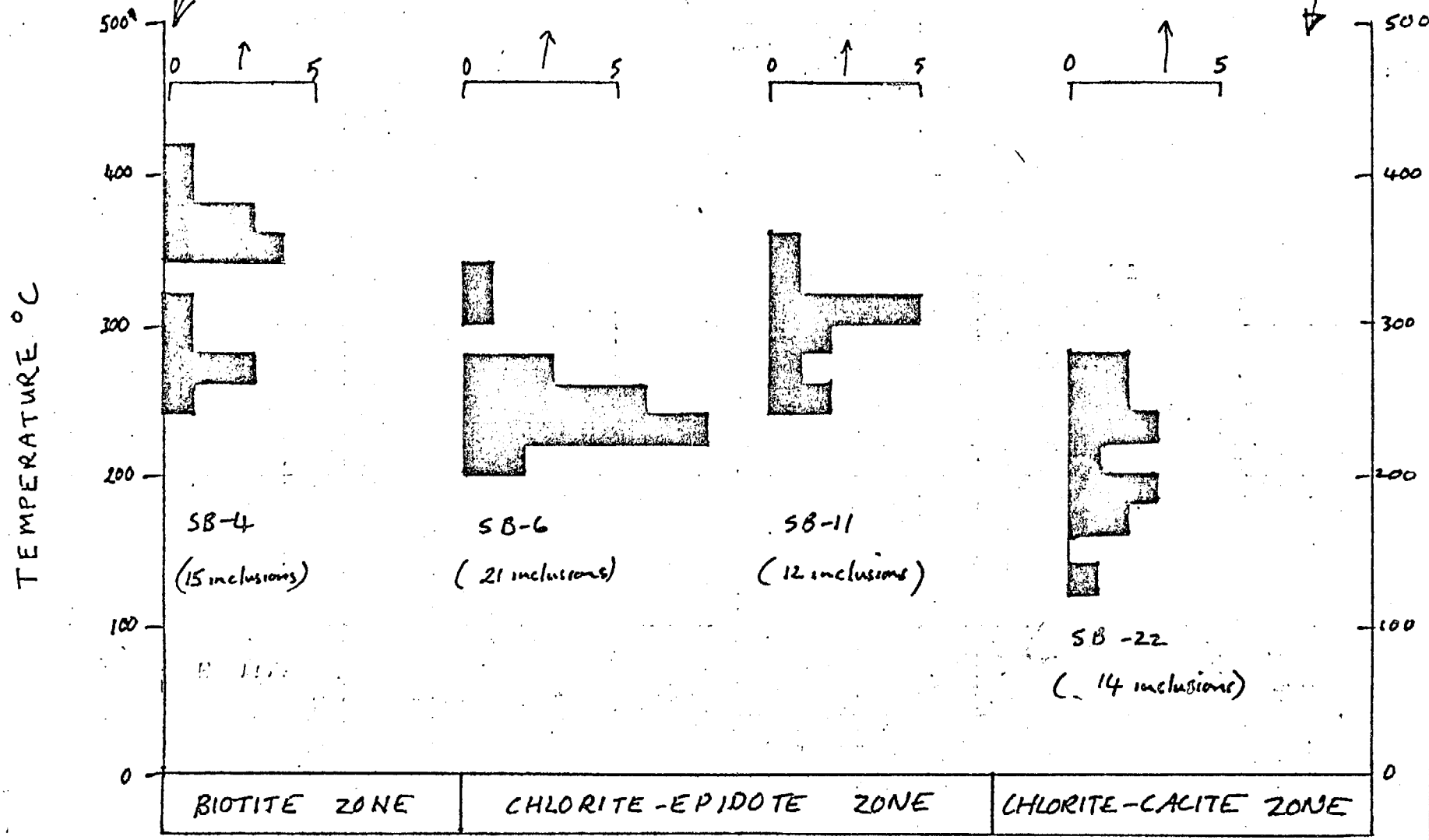


FIGURE 1. HISTOGRAMS OF HOMOGENIZATION TEMPERATURES - NORTH SILVER BELL

upwards to account for any cooling that occurred prior to the fluid reaching the two phase curve. The homogenization temperatures for sample SB-11 do not require any correction since this sample apparently lay close to the boiling curve. Assuming the cover for the other samples to be approximately the same as for sample SB-11, and any possible salinity conditions, the curves of Potter (1977) indicate that maximum pressure corrections of less than 10°C would be required.

Interpretation of the Filling Temperatures

The filling temperatures may be most readily evaluated by reference to Figure 1 on which they are presented in the form of frequency histograms for each sample. Two features are immediately apparent from this figure. First, the fracturing and healing of the quartz phenocrysts occurred over a considerable temperature range in each sample, and, second, the trapping temperatures were generally highest in the center of the biotite zone and decreased outwards.

The occurrence of a range of filling temperatures in each sample is to be expected. Unlike primary inclusions in crystals deposited in veins or vugs during a limited time period, the secondary inclusions in these phenocrysts probably trapped fluids throughout much of the life of the hydrothermal system. Indeed fluids should have been trapped throughout the time period during which the rocks were being actively fractured and were subjected to fluids with high enough temperatures and silica activities for the fractures to heal.

The maximum filling temperature for each sample may reasonably be interpreted as the temperature maximum reached at each sample site during convective cooling of the causative intrusion. The outward decrease of these maixma accords well with the assumption that the

quartz monzonites were indeed the principal heat source for the system.

The minimum filling temperatures also decrease outwards. This result is not necessarily expectable since all parts of the system have cooled to ambient temperatures and kinetic limitations on the trapping mechanism might be expected to be the same throughout the system. A possible explanation is that trapping proceeded to lower temperatures on the periphery of the system because the fluids there had a high degree of silica supersaturation inherited from higher temperature conditions, whereas initially silica-rich solutions may long since have been diluted by the time the center of the deposit cooled to such low temperatures. Another explanation is suggested by the overall distribution of filling temperatures for each sample. The most common filling temperatures are seen to occur at intermediate temperatures in the thermal history of each sample. This suggests that a period of most intense fracturing occurred at a time when a thermal gradient was established across the alteration halo. If, as seems possible, fracturing ceased before complete cooling of the system, fractures in the central areas may have been completely healed before temperatures reached levels below which entrapment was not kinetically feasible.

Thermal Gradients

Thermal gradients may be calculated from the homogenization temperatures. The maximum, minimum, and mean filling temperatures for each sample are plotted versus distance from sample SB-4 on Figure 2. Least squares regression indicates that the maximum filling temperatures, interpreted as temperature maxima for each sample site, decrease outward at the rate of 62°C per kilometer. This is a minimum gradient since

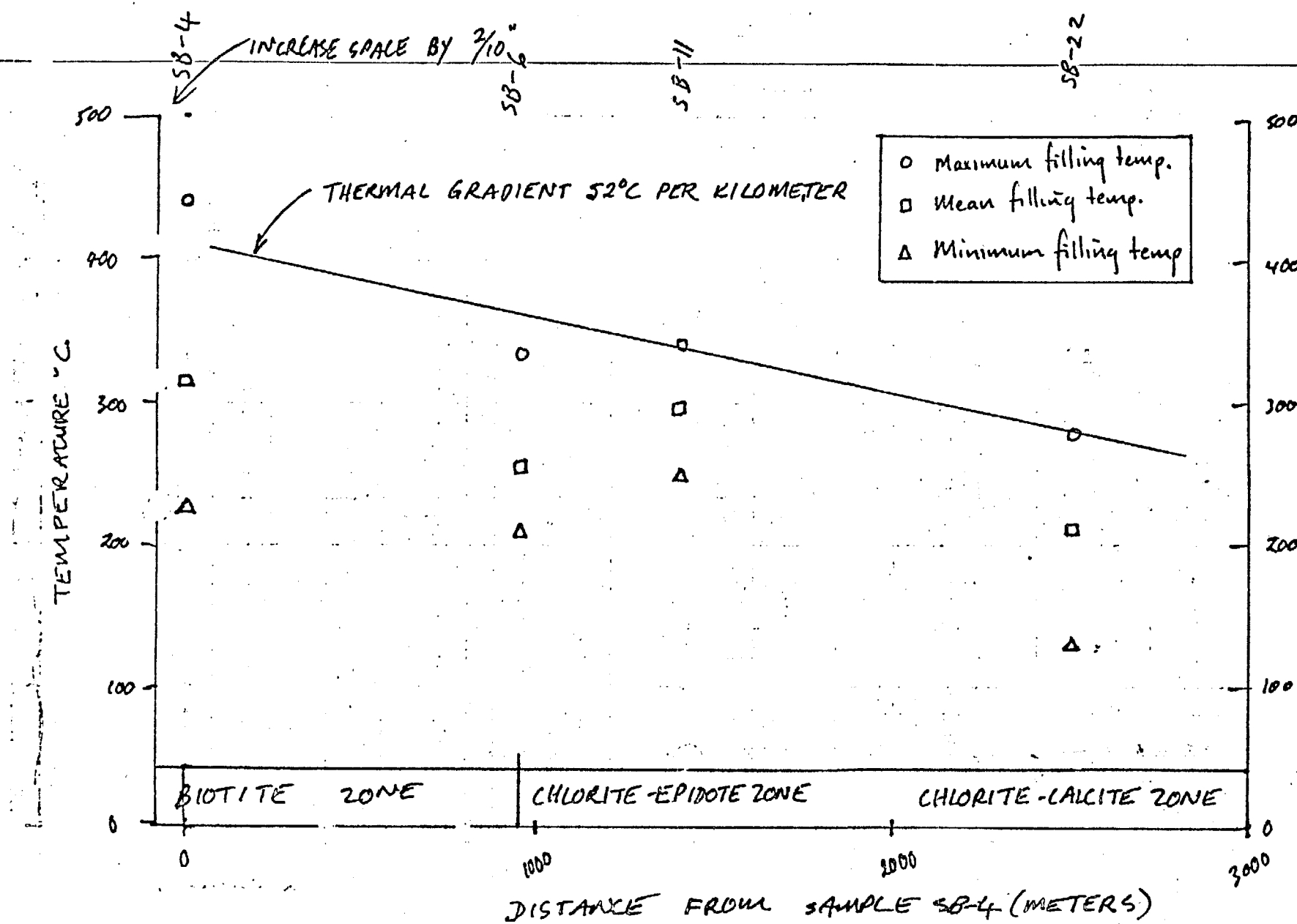
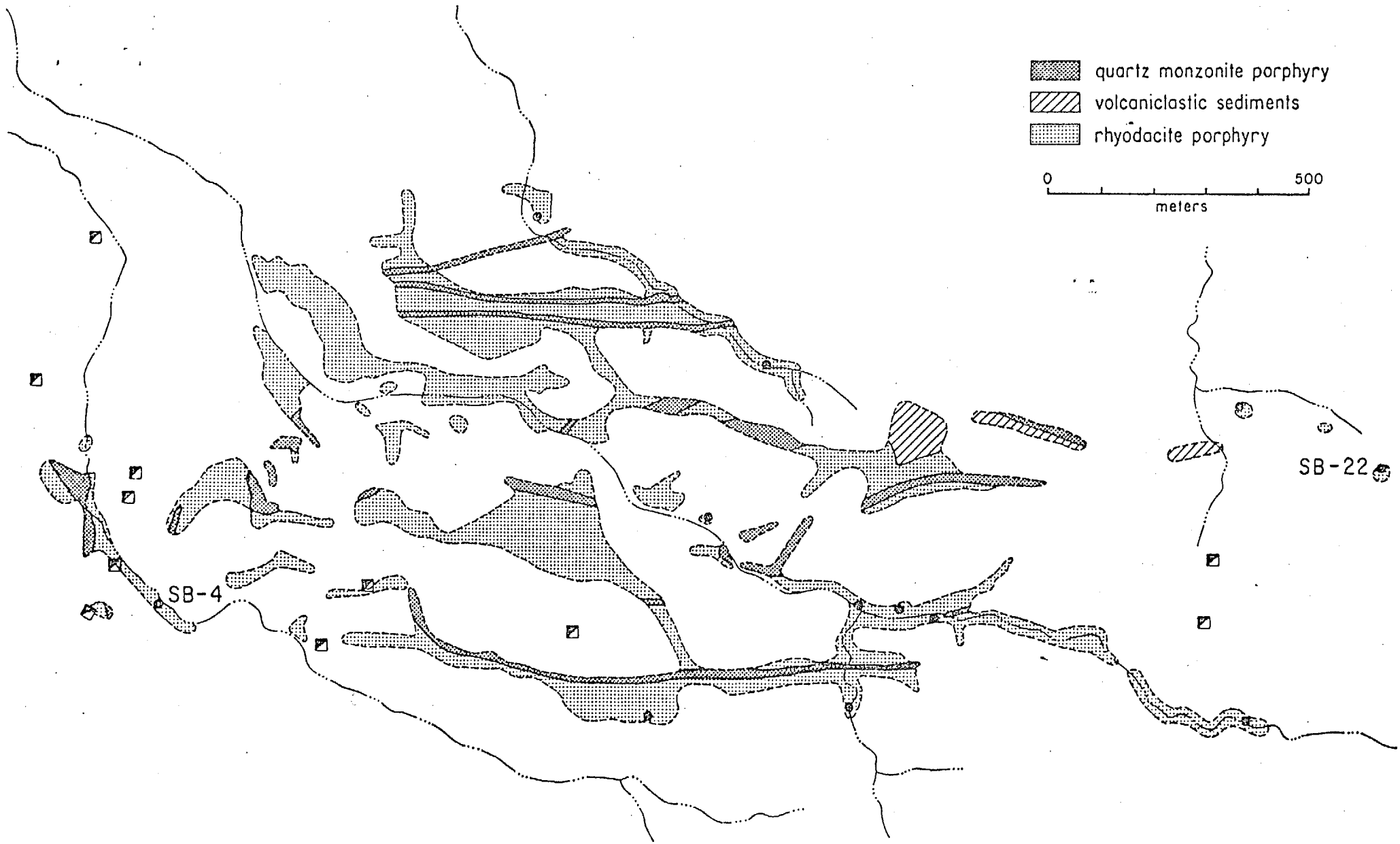


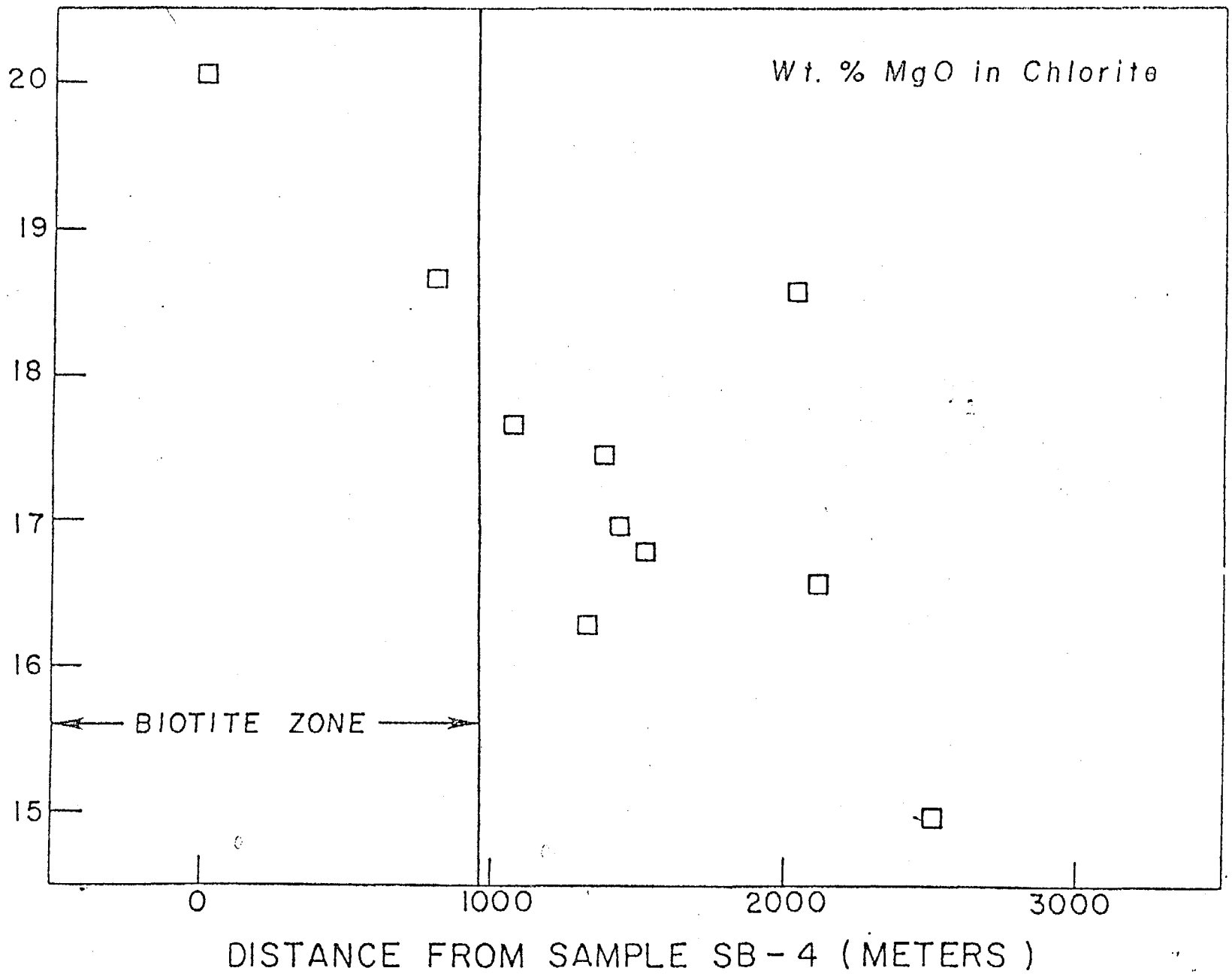
FIGURE 2. FILLING TEMPERATURES ~~VERSUS~~ PLOTTED VERSUS DISTANCE

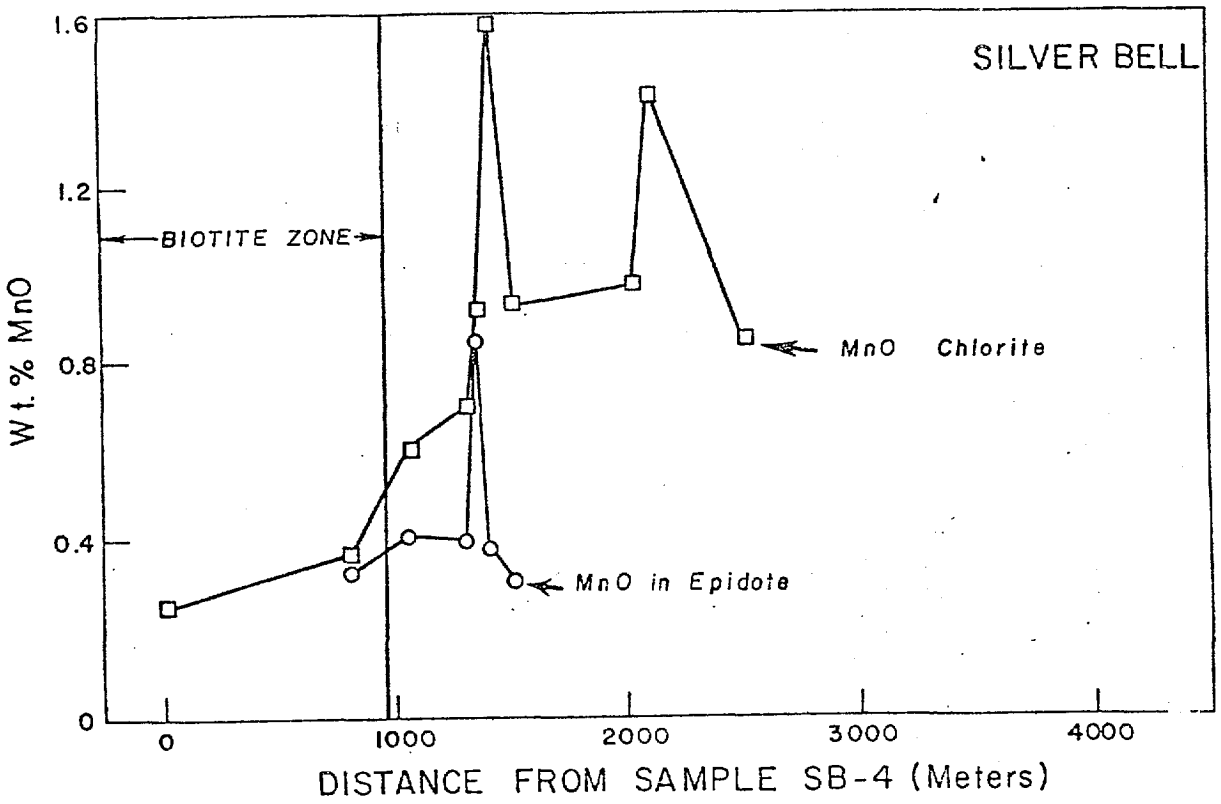
three inclusions in sample SB-4 did not homogenize, and the maximum temperature (440°C) obtained during the heating run has been assigned as the maximum filling temperature for that sample. The minimum filling temperatures decrease at the rate of 34°C per kilometer. Neither of these figures is, of course, a true thermal gradient as there is no indication that the maximum or minimum temperatures at each site occurred simultaneously. The mean filling temperatures decrease outwards at the rate of 37°C per kilometer and this may be a good approximation of the thermal gradient integrated over the life of the system.

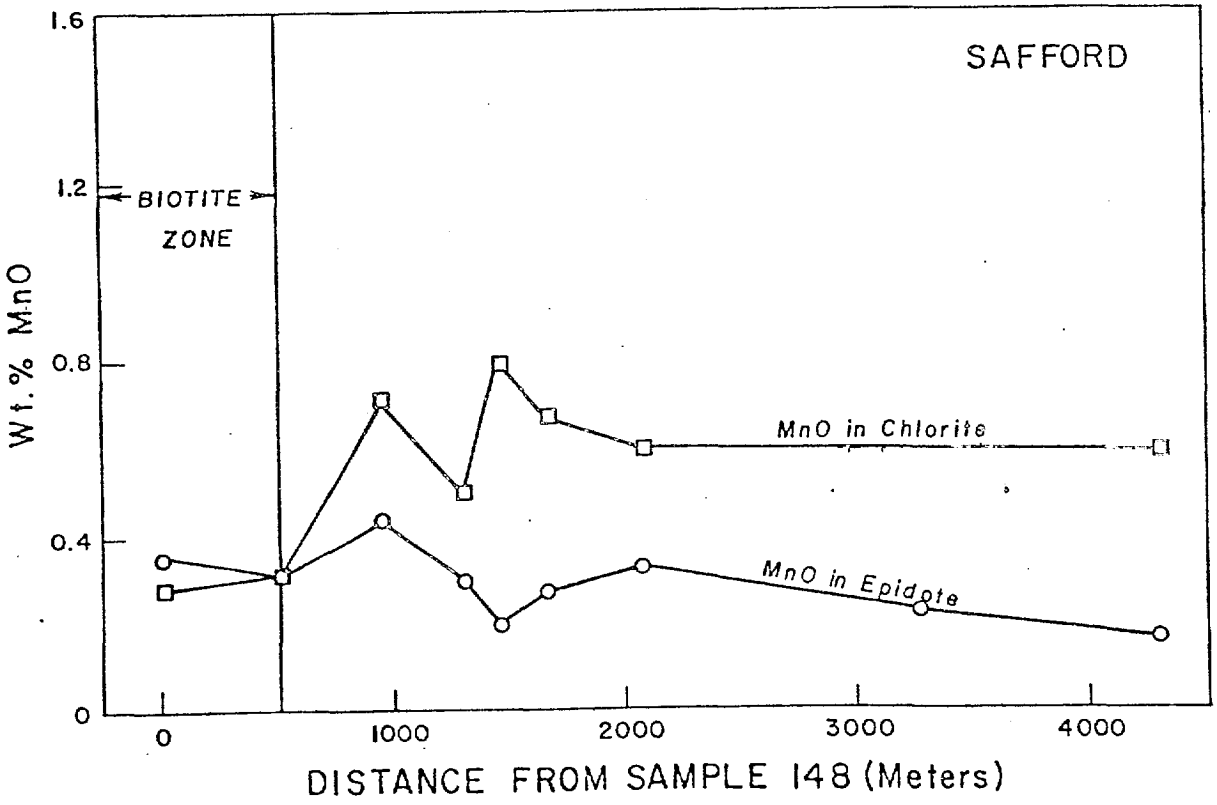
These thermal gradients may be compared with those predicted by the convective cooling model of Cathles (1977). The most closely analogous model presented by Cathles is for a 1.4 kilometer wide intrusion, emplaced at a depth of 2.3 kilometers, in rocks with a permeability of .25 millidarcies. Lateral thermal gradients at a depth of two kilometers (just below the top of the intrusion) and for the one kilometer interval from 300 to 1300 meters from the pluton, range from 200 to 60°C per kilometer as the pluton cools. The temperature maxima decrease outward at the range of 160°C per kilometer. Significantly none of Cathles' model configurations disperses heat sufficiently effectively that temperatures rise above 100°C at a distance of 2.5 kilometers from the pluton, whereas the sample 2.5 kilometers from the center of the North Silver Bell system records temperatures of up to 278°C. This suggests that the dikes of quartz monzonite which project outwards through the propylitic zone at North Silver Bell (and possibly underlying intrusive rock) have dispersed the thermal anomaly and given rise to more subdued thermal gradients than indicated by Cathles' cooling model.

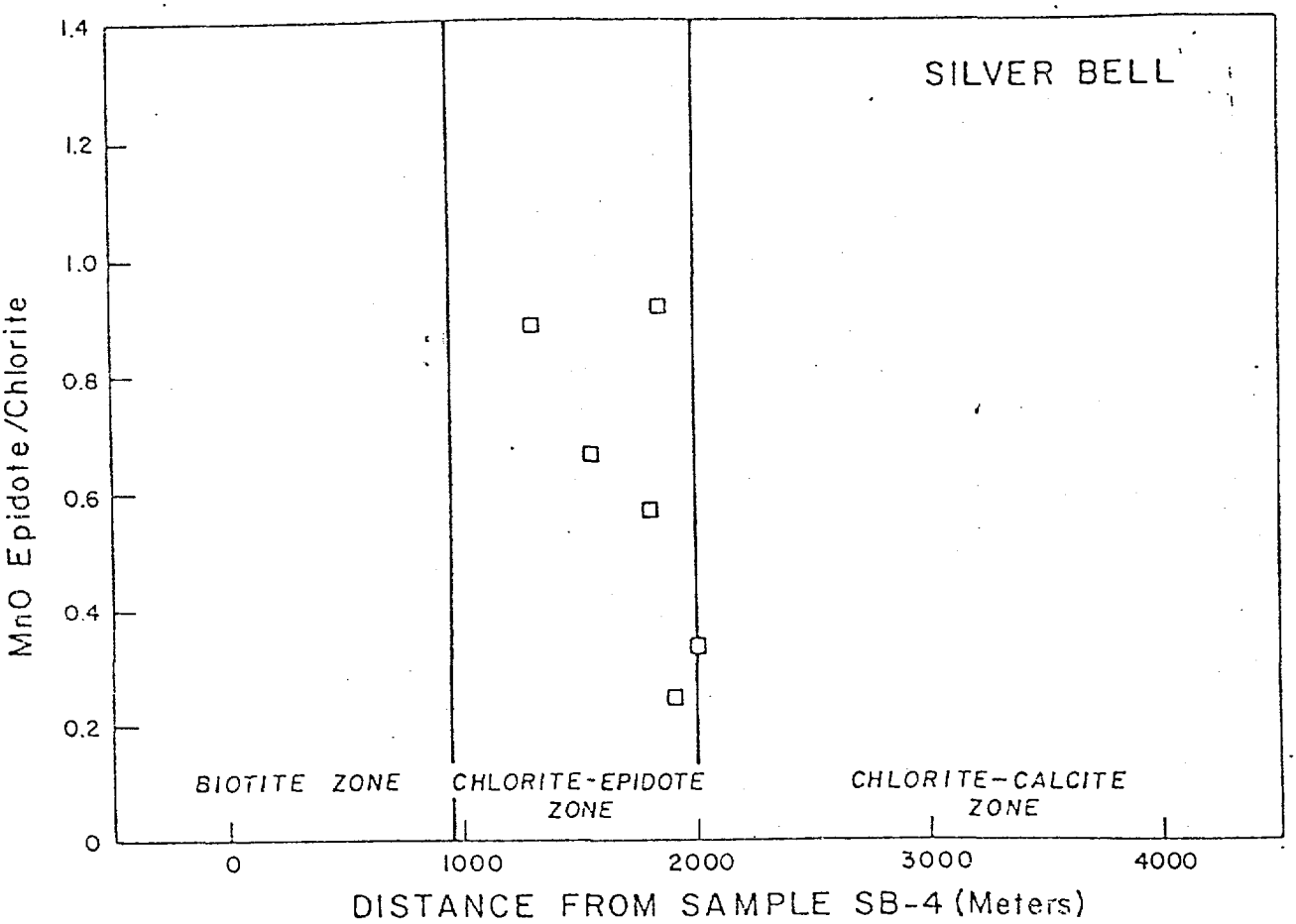
The static model of Haas (1971), in which the hydrothermal fluid is everywhere on the boiling curve, indicates a maximum possible vertical thermal gradient of 200°C per kilometer for the first kilometer from the surface, and drastically decreasing gradients at depth. Cathles' convective model indicates vertical thermal gradients generally equal to or less than horizontal gradients in areas adjacent to (but not above), plutons. Consequently it is considered likely that in the propylitic zone temperatures will vary at similar rates in the horizontal and vertical directions and mineralogic changes will vary accordingly.

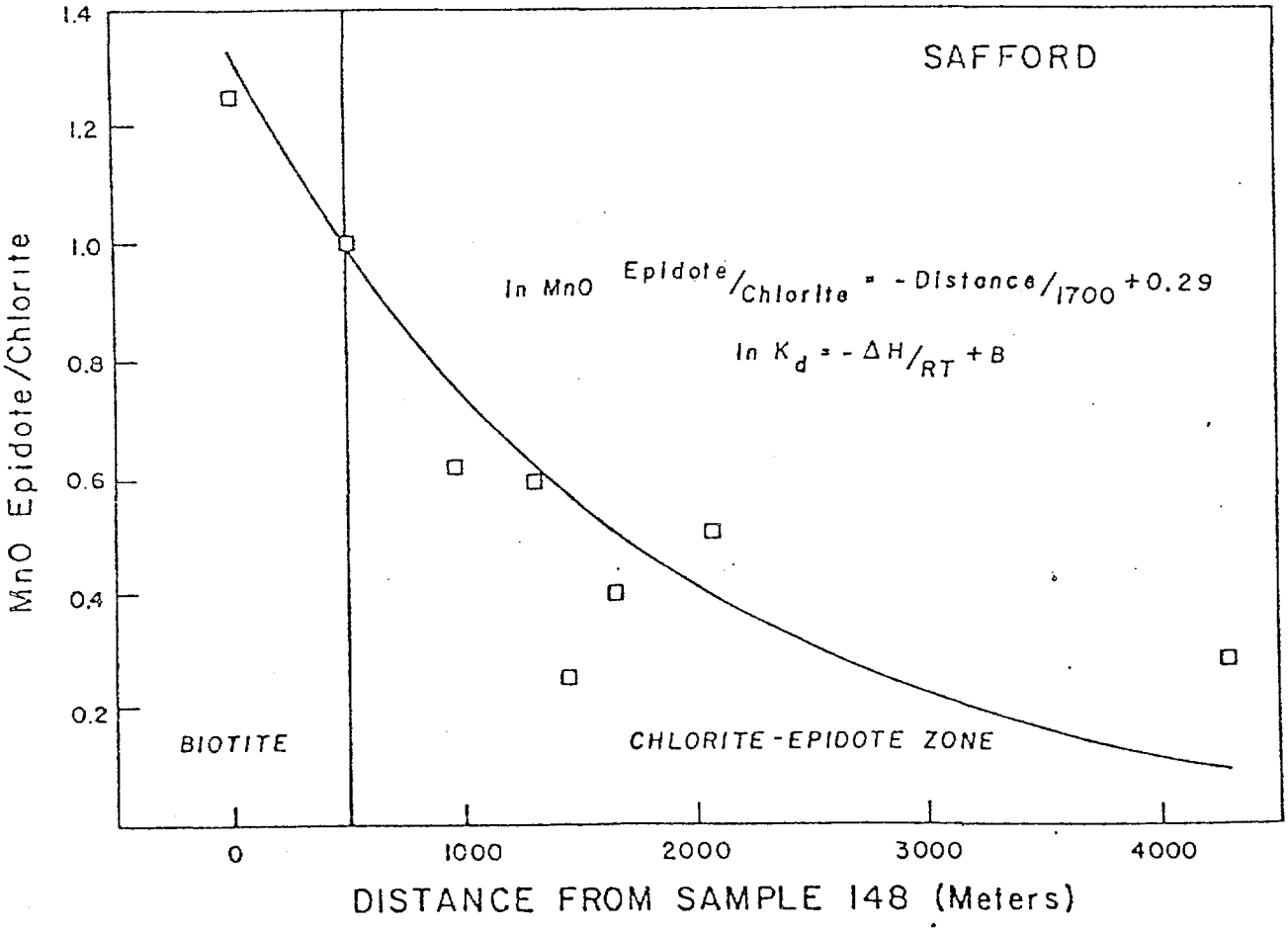

quartz monzonite porphyry
volcaniclastic sediments
rhyodacite porphyry
0
500
meters
SB-4
SB-22


Wt. % MgO in Chlorite
20
19
18
17
16
15
BIOTITE ZONE
0
1000
2000
3000
DISTANCE FROM SAMPLE SB-4 (METERS)


SILVER BELL
BIOTITE ZONE
MnO Chlorite
MnO in Epidote
Wt. % MnO
1.6
1.2
0.8
0.4
0
0
1000
2000
3000
4000
DISTANCE FROM SAMPLE SB-4 (Meters)


SAFFORD
BIOTITE ZONE
MnO in Chlorite
MnO in Epidote
Wt. % MnO
1.6
1.2
0.8
0.4
0
0
1000
2000
3000
4000
DISTANCE FROM SAMPLE 148 (Meters)


SILVER BELL
MnO Epidote/Chlorite
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
BIOTITE ZONE
CHLORITE-EPIDOTE ZONE
CHLORITE-CALCITE ZONE
0
1000
2000
3000
4000
DISTANCE FROM SAMPLE SB-4 (Meters)


SAFFORD
MnO Epidote/Chlorite
1.4
1.2
1.0
0.8
0.6
0.4
0.2
ln MnO Epidote/Chlorite = - Distance/1700 + 0.29
ln Kd = - ΔH/RT + B
BIOTITE
CHLORITE-EPIDOTE ZONE
0
1000
2000
3000
4000
DISTANCE FROM SAMPLE 148 (Meters)

ASARCO

Southwestern Exploration Division

June 7, 1982

To: H. G. Kreis

From: J. D. Sell

Fluid Inclusion Study Samples
Superior East, EA-0010
Pinal County, Arizona

I submit the following numbered samples for preparation of double polished sections for fluid inclusion heating stage studies.

2-4229	10-3990
2W-4300	10-4272
3A-4699	11-4283
3A-4805	11-4503
8-4064	13-3552
8-4151	13-3950
9-4055	14-4147
9-4428	14-4262
9-4856	14-5170
	14-5735

James D. Sell

JDS/cg

ASARCO

Exploration Department
Southwestern United States Division

June 7, 1982

Rudolf Von Huene
Thin Section Laboratory
1555 East Walnut Street
Pasadena, CA 91106

Dear Sir:

Please prepare double polished thin sections (100 to 150 micron thickness, removable from slide) of each of the following:

2-4229	14-5170	FP-4 2567	SC-51 1634
2W-4300	14-5735	FP-4 2793	SC-59 2927
3A-4699	PB-12 650	FP-5 1785	SC-59 3272
3A-4805	PB-17 977	FP-5 1857	CG-118 1183
8-4064	PB-20 390	SC-2 2661	CG-118 1976
8-4151	PB-25 1206	SC-2 2705	CG-118 2369
9-4055	PB-26 1421	SC-12 1415	CG-118 2907
9-4428	PB-28 924	SC-12 1724	V-371249
9-4856	PB-30 1468	SC-12 1901	V-371319
10-3990	PB-31 802	SC-13 1674	V-371615
10-4272	PB-33 1768	SC-13 1855	V-38815
11-4283	FP-1 2540	SC-20 1358	V-382055
11-4503	FP-1 2542	SC-20 1533	V-382598
13-3552	FP-2 666	SC-20 1908	V-385455
13-3950	FP-2 970	SC-20 2218	TR-17-1474
14-4147	FP-3 2967	SC-25 1682	TR-17-2241
14-4262	FP-3 3177	SC-51 1162	TR-17-3827

Sincerely yours,

Henry G. Kreis

Henry G. Kreis

HGK/cg

cc: JDSell
FRKoutz
GJStathis

ASARCO Incorporated P. O. Box 5747 Tucson, Az 85703
1150 North 7th Avenue (602) 792-3010

higher grade Cu zones and gradual increasing Mo values with depth are similar to those in TM-8 and should be useful guides during subsequent drilling.

Higher grade copper zones

Two zones of anomalously high grade copper were intersected in TR-10 and are listed in Table 1.

TABLE 1: Significant assay results in TR-10

interval	length	% Cu	% MoS_2	oz. Au	oz. Ag
110-160[1)]	50 ft.	0.63			0.13
3860-4210[2)]	350 ft.	0.57	0.033	0.004	0.14

1) cutoff at 0.40% Cu
2) cutoff at 0.50% Cu

The interval from 110-160 ft. is predominantly chalcocite and its association with mixed leached zones is a strong indication of a supergene origin.

The interval from 3860-4210 ft. is essentially all chalcopyrite. Much of the disseminated chalcopyrite in this zone averages 0.04-0.06 mm in diameter and is therefore difficult to recognize in hand specimen. However, check assays by different laboratories of selected intervals confirm the Cu content. The absence of associated potassic alteration, which is the normal situation in the high-grade portion of the chalcopyrite zone, is significant as will be noted below. In all other respects the zone is typical of higher-grade primary Cu zones in porphyry copper deposits and, except for grade, it is identical to the deep chalcopyrite zone in TM-8.

FLUID INCLUSION DATA

Fluid inclusions were studied petrographically in fourteen thin sections. Comparisons between the upper and lower portions of the hole are difficult due to the absence of quartz grains of demonstrably similar age. I have tentatively assumed that the quartz xenocrysts in the intrusive breccia are of an age similar to the quartz phenocrysts in the underlying quartz feldspar porphyry. Somewhat uniform populations of fluid inclusions in different quartz xenocrysts suggest that significant vertical mixing of different populations has not occurred and thus the data should be useful for comparing superimposed hydrothermal events.

Fluids evolving from the quartz feldspar porphyry were boiling and moving upward through the intrusive breccia and other wall rocks. This resulted in the formation of a dense, saline brine below about 2500 ft.

The top of the zone of boiling appears to lie at about 1100 ft. above which a reduction in vapor occurred due to possible mixing with dilute, cooler groundwater. The pattern of boiling in the rocks above the quartz feldspar porphyry was apparently more irregular than in TM-8 presumably due to channeling of the fluids.

The overall distribution of types of fluid inclusions in TR-10 is remarkably similar to TM-8. The possibly greater depth to the top of the boiling zone in TM-8 may indicate easier access of the fluids to the surface due either to a lighter lithostatic load or more permeable channelways, or both. An abrupt drop in the salinity and abundance of the fluid inclusions occurs at about 5200 ft. indicating the presence of a later unrecognized intrusion, the top of a second, deeper boiling zone, or bottoming of the hydrothermal system.

DISCUSSION

The close association of advanced argillic alteration, the enargite zone, the Pb-Zn zone, and the zone of strongest boiling are strong indications of a genetic relationship, similar to that seen in TM-8. The significance of the lower Pb and Zn content of TR-10 as compared to TM-8 is not presently understood. The presence of diverse rock types in TR-10 may have caused some channeling of fluids and may be partly responsible for the strong variations in Pb and Zn mineralization. The presence of a well-developed advanced argillic alteration assemblage in pre-diatreme rocks contrasts sharply with its near-absence in rocks within the diatreme, particularly the quartz feldspar porphyry, a relationship which exists throughout the Sunnyside area.

The abrupt appearance of quartz veins in TR-10 is closely related to a zone of abundant pyrite veins and the high grade chalcopyrite intersection. Similar relationships were not observed in TM-8. As presently known, the veins are restricted to the quartz feldspar porphyry. They may represent slight collapse of the system due either to withdrawal of magma at depth, or to removal of material during alteration. Either interpretation is consistent with their somewhat intermediate position in the paragenetic sequence.

Another point of general discussion concerns the well-documented collapse of the phyllic zone into the underlying potassic zone. The documentation is seen both in the vein-like zones of quartz-sericite which cut matrix hydrothermal orthoclase and in the late rims of covellite on chalcopyrite. The presence of a collapsed phyllic zone may explain the lack of coincidence of the high grade portion of the chalcopyrite zone and the phyllic-potassic interface. Thus the present position of the high grade zone, centered at about 4100 ft., may represent the former position of the top of the potassic alteration zone. The extent of collapse could be 500 ft. or more.

Our approach to exploration of the Sunnyside area to date has involved locating the phyllic-potassic alteration interface for higher grade copper mineralization. Assuming collapse has occurred, we may have to alter this

concept in that the higher grade zones may occur within the phyllic zone. Thus, deep drilling for the potassic-phyllic interface may be unnecessary, and ore grade mineralization may be encountered at depths above what might be predicted from a knowledge of potassic zone geometry.

Figure 2 is a correlation of significant data between TR-10 and TM-8. The flat-lying enargite-covellite zone occurs near the top of the zone of saline fluid inclusions. The configuration of the chalcopyrite zone may be influenced by the shape of the quartz feldspar porphyry. The deep, +0.25 % Cu, chalcopyrite zones in both holes appear closely related to both the potassic zone and the zone of +50 ppm Mo. The very similar characteristics of the two deep chalcopyrite intersections indicate that the 0.57% Cu intercept in TR-10 and the 0.56% Cu intercept in TM-8 are unrelated.

Further exploration

The presence of Pb and Zn halos above the higher grade primary Cu mineralization should be a useful exploration guide, although correlations between the amount of Pb-Zn and depth to or amount of Cu are not clear. Gradually increasing amounts of Mo also appear to be a favorable guide. Molybdenite is always most abundant where chalcopyrite is most abundant.

The good correlation of higher grade chalcopyrite with sulfide and quartz veins and vugs indicates that structural features should be carefully logged. In particular, the greatest percentage of vein pyrite occurs in a 1000 ft. thick zone immediately above the high grade chalcopyrite zone. A similar pattern also occurs in TM-8, although it is not nearly as well defined.

I suspect that continuous higher grade boiling zones such as those encountered in TM-8 will be absent outside the diatreme, possibly excepting well-developed breccias. This would probably be due to the presence of structurally variable rocks which would channel hydrothermal solutions causing boiling zones to be spatially separated.

The correlation of well-developed advanced argillic alteration and deep-lying high grade copper mineralization in TR-10 may be important. Similar well-developed advanced argillic alteration has recently been recognized at the surface in a discontinuous northwesterly-striking zone which overlies TR-10 and which is coincident with the stronger portions of the Mo rock chip anomaly.

In summary, the following criteria are presently considered to be most important as surface exploration guides to deep chalcopyrite mineralization:

1) anomalous amounts of Mo

2) well-developed advanced argillic alteration

3) intersecting pre-ore structures

4) the presence of mixed saline and gas-rich fluid inclusions is suspected but not yet clearly established.

The following criteria are considered to be most important as drill hole exploration guides to deep chalcopyrite mineralization (listed in order of increasing proximity to ore-grade Cu):

1) mixed gas-rich and saline fluid inclusions which become larger, more abundant, and more saline with increasing depth

2) anomalous amounts of Pb and Zn

3) increasing amounts of Mo

4) increasing abundance of stockwork pyrite and quartz veins.

Application of the above criteria indicates that further exploration of the deep chalcopyrite zone in TR-10 should initially be confined to the area west of the diatreme between TR-10 and the BX breccia (SU drill holes).

F. T. Graybeal

F. T. Graybeal

FTG:lb
Attachs.