Fluid Inclusion Studies on the Porphyry-Type Ore Deposits at Bingham, Utah, Butte, Montana, and Climax, Colorado

EDWIN ROEDDER

Abstract

Data are given on the composition, temperature, pressure, and density of the hydrothermal fluids present in the central Cu-Mo core of the deposit at Bingham, Utah, and in its related but not necessarily coeval peripheral Pb-Zn deposits. These data are based on a study of primary and secondary fluid inclusions in transparent ore and gangue minerals that included the use of freezing, heating, and crushing microscope stages.

The composition of the hydrothermal fluids at various stages in the mineralization and repeated later fracturing and rehealing ranged from nearly fresh water to water containing more than 60 weight percent salts in solution—virtually a hydrothermal fluid melt—in some quartz-molybdenite-chalcopyrite veins from the core. Most of these salts have crystallized out as daughter minerals on cooling, forming major amounts of halite and sylvite and minor amounts of anhydrite(?), hematite(?) and several unidentified phases. These highly saline fluids occur only in the core. Some of them have apparently boiled, forming bubbles of a relatively low density CO₂-rich “steam” containing only a few percent NaCl. These low-density fluids have also been trapped as inclusions. The fluids that formed the peripheral deposits had low salinities, and some of these also have apparently boiled. A few were very high in hydrogen sulfide.

Inclusions from a quartz pod and in the quartz-molybdenite-chalcopyrite veins from the core yield the highest temperatures, 640°–725° C; most inclusions from the core homogenize at temperatures above 400° C. Samples from the peripheral deposits were uniformly lower, in the range 295°–330° C.

The abundant evidence of intermittent boiling of these solutions is important because it places limits on the pressure at the time of trapping; it results in there being little or no need for a pressure correction to the homogenization temperatures, and it indicates that the pressure has varied with time. Although some of the homogenization temperatures are very high, the high salinity causes the vapor pressures at homogenization to be relatively low, from about 80 to a maximum of about 1,100 atmospheres.

The density of the hydrothermal fluids is of great concern in any consideration of flow patterns, and particularly in the inevitable mixing with possibly heated ground waters. Steam inclusions from the core had gross densities of 0.3 to 0.1 g·cm⁻³, but many of the highly saline inclusions in the core contain fluids whose density at trapping was as high as 1.3 g·cm⁻³. The fluids trapped in inclusions in the peripheral deposits had densities of 0.75–0.95 g·cm⁻³, well below that of the surrounding cold ground water. Hydraulic pressure gradients from these density differences, and the vapor pressures involved, must also have varied with time in any given location, particularly when boiling occurred, and thus the circulation patterns could have been very complex. The more highly saline fluids are believed to be of truly magmatic origin, and not merely heated ground water from the area at the time of the intrusion.

The great abundance throughout the core of planes of secondary inclusions in which individual planes are uniform but adjacent planes have widely varying composition, density, and homogenization temperature, is evidence of thorough and repeated fracturing of these rocks under hydrothermal conditions.

Inclusions were also examined in some samples from Butte, Montana, Climax, Colorado, and several Arizona porphyry copper deposits. The ranges of temperature, composition, and density found were similar but smaller than at Bingham. This might be simply a result of insufficient sampling.

1 Publication authorized by the Director, U. S. Geological Survey.
Introduction

This report is, in effect, only a reconnaissance, begun some years ago, of a much larger investigation that would require many man years to complete. Consequently, the data are fragmentary at best but may still be useful to others who are planning similar studies or who wish to apply the results in other ways. A very few of the results given here were published earlier (Roedder, 1963), and others were given in two abstracts (E. Roedder, in U. S. Geol. Survey, 1965, p. A156; Roedder and Creel, 1966). Most of the work has dealt with the porphyry Cu-Mo deposit at Bingham, Utah, in the core of the Bingham district (hereafter called “core”), and its peripheral Pb-Zn deposits, but a few results are given from studies of other similar deposits. Descriptions of the samples examined that were found to be useful, and details on locality, mineralogy, and source are given in the Appendix. The geology of the Bingham area has been summarized (Peters et al., 1966; Rubbright and Hart, 1968) and will not be reviewed here.

Doubly polished plates about 1 mm thick were cut from many of the samples, and in addition, loose crystals and clear cleavage fragments were examined in oils. After detailed microscopy, freezing determinations were made of selected parts of the plates, followed by homogenization studies on some of these same inclusions.

Data from General Microscopy

Origin of the Inclusions

Most of the samples obtained were not particularly suitable for inclusion studies and hence are not listed in the Appendix. Some had only a very few or very tiny inclusions with very irregular, jagged walls, making observations difficult. Many samples contained so many planes of small secondary inclusions that any larger primary inclusions, if recognized at all, had significant if not large probabilities of having been opened and the contents replaced by later fluids. The great abundance of planes of secondary inclusions is merely the microscopic equivalent of the extensive fracturing so apparent in the field at Bingham and other porphyry copper deposits. It thus provides evidence that these ores were thoroughly and repeatedly fractured on a microscopic scale under hydrothermal conditions, and any subsequent precipitation on exposure to weathering conditions (from the hydration of anhydrite or other reaction having a large volume change), as has been suggested by others, must have been superimposed on this earlier fracturing.

*The words “core” and “peripheral” are used here as spatial terms, and do not imply sequential formation from the same fluids.

Fig. 1. Photomicrograph of the two most common types of secondary inclusions at Bingham, from a 5-10-cm quartz-molybdenite vein in the pit. On the left are four healed fractures, now outlined by trains of fluid inclusions, and a recent fracture that has not healed (almost vertical through center of photograph). When recognizable as discrete planes of inclusions (as opposed to Fig. 13), all such healed fractures usually contain inclusions of two types, A or B, and any given fracture contains only one type. All three fractures marked A consist solely of A-type inclusions, and fracture B consists solely of B-type inclusions. Type A contains saturated liquid (l), a small vapor bubble (v), a red or opaque daughter mineral, presumably hematite ( specularite, s), and a large crystal of halite (x). Many of the larger ones also contain a small birefringent crystal, possibly anhydrite (b), and other phases. Type B usually contains a small opaque grain, presumably hematite ( speculaire, s), low-salinity liquid (l) and a large bubble of compressed gas (v). The composition of type B is as expected if it represents the dense steam phase from the boiling of fluid of the gross composition of type A (see text). Sample ER 63-209.

As the composition of the individual inclusions among any given fracture is uniform, in contrast to the grossly different compositions of inclusions along adjacent fractures (Fig. 1), it is evident that these materials have been repeatedly fractured and re-healed in the presence of fluid phases that differed from time to time. In many of the samples of quartz from the core, recognition of these differences in composition for different planes of inclusions is possible in rather sparse clear areas in the crystals containing few inclusion (Figs. 1-25). The bulk of such quartz is so crisscrossed with planes of inclusions that co-genetic inclusions cannot be recognized with certainty (Fig. 13). Even the euohedral crystals projecting into vugs have many planes of secondary inclusions, which may have formed by any of several processes (Roedder, 1967a, p. 523), but these relatively rare vug minerals still provided most of the recognizable primary inclusions in both the core and the satilite deposits.

In addition to the problem of too many planes of inclusions and the probable reopening of earlier inclusions by later fractures, the normal recrystallization and slow movement of secondary inclusions
away from their original planar array (Roedder, 1970a) adds considerable ambiguity to any assignment of cogenetic origin. In the core, in particular, the long duration of the high-temperature stage was such that many apparently secondary inclusions appear to be randomly distributed and hence look “primary” (Fig. 25). Although other varieties occur less commonly, most of the inclusions from the core fall into two categories, dense and highly saline (type A), and tenuous, with low salinity (type B, Fig. 1). Of these two main types, only type A occurs as possibly primary inclusions, in vein quartz, in addition to abundant occurrence as secondary or pseudosecondary inclusions. Type B inclusions are in almost all cases demonstrably secondary (or pseudosecondary).

**Bubble Movement in a Thermal Gradient**

The direction of movement of the bubble when an inclusion is subjected to a thermal gradient from a minute electrically heated hot-wire probe or simply from asymmetric microscope illumination (Roedder, 1965) permits a simple four-fold categorization of inclusions that was found to be useful on many of these samples. The categories are based on bubbles that move **up** the gradient, those that move **down**, those that oscillate, and those that do not move at all in a gradient, but yet are not constrained from movement by the walls. Although the categorization is based on as yet unknown and probably minor chemical variables, it is still useful as an empirical tool, because demonstrably cogenetic inclusions always fall in the same category.

**Identification of Daughter Minerals**

Daughter minerals, formed in the inclusions after trapping, are common in inclusions from the core. Their identification is seldom certain, particularly for a single grain (Roedder, 1971), and most of the phases present in these inclusions remain unidentified. However, as these daughter crystals have grown from the fluid on cooling after trapping, their identification gives important data on the composition of the ore-forming fluids.

The largest and most common by far is halite. It is generally present as a sharp cubic crystal, but some crystals are rounded. The identification as NaCl is based on several properties. It is isotropic and colorless, and its temperature coefficient of solubility is small (as determined both on heating and freezing). On freezing it reacts with the solution to form crystals of the birefringent dihydrate NaCl·2H₂O; on warming these melt incongruently to solution and halite, mostly just below the incongruent melting point for the pure compound, +0.15°C. This melting is sluggish, however, as the crystals can be held above their melting point for many minutes, to temperatures as high as +14°C. Where necking down has occurred in an inclusion in quartz containing a cube of halite, it is sometimes in close contact with the quartz walls instead of the solution. When this occurs the interface essentially vanishes, because there is no difference in index of refraction for NaCl and the fast ray of quartz (both have n = 1.544; Fig. 23).

Sylvite (KCl) was identified with less certainty. It is also isotropic and colorless and usually rounded, although sharp octahedra may form on cooling from homogenization. Sylvite has an appreciably lower index (n = 1.490) than halite and shows no reaction with water on cooling. Sylvite has a much higher temperature coefficient of solubility than halite; hence, it dissolves completely at relatively low temperatures (usually 60°–80°C, but occasionally as high as 108°C (Figs. 2 and 4)).

Hematite (specularite) was tentatively identified on the basis of its color (yellow or orange-yellow in plates about 1 μm thick, bright red when 5–10 μm thick, and opaque in thicker or more equant grains), extremely high index of refraction, thin flat hexagonal crystal habit (Figs. 6 and 7), and high birefringence and parallel extinction for some positions (but isotropic when viewed normal to the hexagonal plate). Measurements of the volume percent of hematite varied widely, as might be expected from the difficulties of measurement alone, but most yielded calculated inclusion fluid compositions with <1 wt percent Fe₂O₃.

The various other birefringent phases can only be tentatively identified at this time. Elongate or rectangular prisms with parallel extinction and moderate birefringence (Figs. 2, 8, 9) are believed to be anhydrite (about 1 percent by weight). Some of the tiny highly birefringent, more equant grains (Figs. 2, 4) could be rhombohedral carbonates, but in view of the wide range of rare and unusual daughter minerals that have been identified in inclusions from other types of deposits, particularly as noted in the extensive Russian literature (cited by Roedder, 1971), there are many other possibilities. It is also important to note that as these daughter minerals cannot generally be moved relative to the host quartz, they can be examined for birefringence only at the positions of extinction for the host. Thus some of the apparently isotropic grains in the examples photographed may actually be birefringent.

Although many of the daughter minerals remain unidentified, experience has shown that most inclusions form only a single crystal of each daughter mineral phase, and hence where there are 10 daughter crystals, as in Figure 2, presumably there are 10 different phases. Most inclusions do not permit ade-
quate visibility of all their contents, and so the actual number may be even greater. Phases with very low solubility are most likely to occur as multiple crystals, if any do (Roedder, 1970a), yet I have not recognized with certainty more than one hematite flake in any inclusion. On the other hand, there is much evidence of metastability in these inclusions, as found, because of lack of nucleation of daughter minerals, particularly of the phases of smaller volume and in the smaller inclusions. Most very small inclusions (<10 μm) of type A (Fig. 11) contain only vapor, liquid, and halite as recognizable phases.

The minute opaque phases in these inclusions (other than coarser hematite crystals) may include a variety of oxide or sulfide ore minerals, but they have not yet been identified even tentatively, due mainly to the problems of mechanical handling. All have been checked for magnetic properties, by moving a strong magnet beside the microscope objective, but none has moved, so they cannot be magnetite or even magnetic pyrrhotite. Not infrequently a square outline is seen, so some of the grains may be (or may have been) pyrite.

**Distribution of Daughter Minerals**

Outside the central copper-molybdenum core of the deposit, the abundance and volume of daughter minerals in the inclusions declines drastically. One of the major exceptions is the occurrence of relatively large opaque mineral grains in inclusions in a sphalerite from the Lark mine (ER 63-228). Many of these daughter minerals amounted to several volume percent of the inclusions, but such measurements may seriously overestimate the volume (Roedder, 1960, p. 227). Other exceptions include small strongly birefringent grains in some samples, such as a quartz from the U. S. mine (ER 63-214). Halite is missing from all inclusions in the peripheral deposits, except for the H₂S-bearing inclusions described later. One other exception is notable, namely the Ophir Hill mine, 21 kilometers southwest of the center of the pit, although this is not "peripheral" to Bingham in the normal sense (see Appendix, sample ER 63-236).

**Occurrence of Liquid H₂S**

The most unusual inclusions found contained actual liquid H₂S. This has been reported only once before, in marbles of the Grenville series (Harrington, 1905). A sample of coarse bluish marble from the U. S. mine at Lark (ER 63-232) that partially envelops one Pb-Zn ore shoot (Rubbright and Hart, 1968, p. 899) gives a strong odor of H₂S on scratching. Sections cut from it are rich in apparently secondary, ordinary inclusions of halite plus solution plus vapor, but most are optically too poor to study effectively. In addition however, a few small primary (?) inclusions contain H₂S. The best inclusions of this type that were found are shown in Figures 15 and 16. The liquid H₂S appears as an annular ring around the bubbles, which, incidentally, are surprisingly large for this sample location. The liquid differs only slightly in index of refraction from that of the water solution, so its presence is indicated only by a faint "second meniscus" (Fig. 15). This meniscus is generally not as readily visible as shown in the photomicrographs, as the contrast of these prints has been increased.¹ The H₂S was recognized on the basis of its index of refraction, its phase relations, its expansion to gas on crushing, and, of course, its odor. The index of refraction of liquid H₂S is 1.374, and that of liquid H₂O is 1.333, but the second fluid in these inclusions is very slightly lower in index than the water. As many of the inclusions with H₂S in this sample show 10–15 volume percent of isotropic cubes in the water solution, presumably NaCl, the index is higher than for pure water. NaCl alone will increase it to 1.378 at 18° C, and other salts can raise it further.

On heating, the liquid H₂S in six of these inclusions simply disappeared at 97 ± 1° C, apparently by merging with the gas phase. In another (inclusion C in Fig. 15), the liquid H₂S evaporated into the bubble, the last disappearing at 64 ± 1° C. (The nature of the material precluded attempts at actual homogenization of the inclusions at much higher temperatures.) As the critical point for H₂S is at 100.4° C and 89 atm, these data are at least compatible with the second liquid being liquid H₂S. The relative volumes of the phases in these inclusions can only be estimated rather crudely, but several yielded 12 volume percent liquid H₂S and about 30 volume percent vapor. The amounts of H₂S in the aqueous phase are probably insignificant compared with that as liquid H₂S (Selleck et al., 1952).

Several inclusions in this sample are even more complex, in that they contain three immiscible liquids, plus vapor. The best two of these are illustrated in Figure 16, but other, less photogenic ones were found. These inclusions are similar to those in Figure 15, except that within the annular ring of liquid H₂S is a small spherical droplet of another liquid. Apparently the lowest surface energy state is for this new liquid to be in contact only with the liquid H₂S. At first I thought it might be a globule of liquid CO₂, as it disappears on gentle warming (and even with heating from intense microscope illumina-

¹ A colleague, when looking through the microscope at some of the inclusions shown in Figure 15, with optimum illumination, was still not certain that he did indeed see the faint meniscus.

² In some of these, necking down of the calcite has yielded inclusions almost filled with halite.
tion), but liquid H₂S is miscible with liquid CO₂ (Francis, 1954) and has an index of refraction of only 1.17 at 24°C (Quinn and Jones, 1936), whereas this globule has an index *above* that of the surrounding liquid H₂S. Another possibility is an organic fluid of low molecular weight (and hence readily volatile). However, Francis (1954) reports that liquid H₂S is miscible with all liquid hydrocarbons (and hence, by inference, with gaseous ones when they are liquefied). On further heating, the liquid H₂S in these inclusions evaporates into the vapor bubble.

Another sample of fetid calcite, from the same area but much higher in elevation (actually from the surface—ER 63-212), showed similar inclusions but were too difficult to work with effectively. Still another sample (ER 63-216), of quartz from the U. S. mine, contains a few inclusions that appear similar, but give no odor of H₂S.

**Data from Crushing**

The crushing stage (Roedder, 1970b) permits a determination of the presence of compressed, non-condensable gases in inclusions and crude estimates of their concentration. Highly compressed gas was found to be present in many samples, but the very

---

**Inclusions from Bingham**

All are of polished plates of quartz, and are taken in transmitted plain light, except as indicated. See Appendix for sample details.

Figs. 2 and 3. Multiphase presumably pseudosecondary type A inclusion containing at least 10 daughter crystals, photographed at two levels of focus. There are two opaque crystals (O), a large cube of halite (H), two strongly birefringent crystals (B) (a plate or rod on the left in Fig. 3 and two small equant crystals on the right), sylvinite (Sy), and four smaller apparently isotropic ones (I). Additional phases are vapor (V) interstitial liquid (L), and two small isotropic crystals not visible in either photograph. On heating, several of the smaller isotropic crystals dissolve in the range 63-92°C, but the sylvinite dissolved at 108°C. ER 63-209A.

Figs. 4 and 5. Similar to the above, from same sample. Taken with partially crossed polars to show a cluster and four small individual, highly birefringent crystals (B), 3 opaque grains (O), large halite crystal (H), sylvinite (Sy) and another apparently isotropic crystal (I). Behavior on heating very similar to above.

Figs. 6 and 7. Multiphase primary or pseudosecondary inclusions showing red, hexagonal tablets, probably halite (spherical, S), opaque grains (O), and several other birefringent and isotropic daughter minerals. In Fig. 7 the large cube (H) is halite, and the smaller grain (Sy) is sylvinite. ER 63-211A.

Fig. 8. Multiphase inclusion showing halite (H), sylvinite (Sy), and several birefringent (B) and opaque (O) daughter crystals. The sylvinite crystal dissolves at about 70°C, at which temperature the halite crystal is only slightly more rounded. ER 61-40.

Fig. 9. Multiphase primary inclusion showing halite (H), sylvinite (Sy), a red flake, probably hematite (specularite, S) and two birefringent crystals (B). The rodlike birefringent crystal is believed to be anhydrite, on the basis of its optical properties. ER 63-211-2.

Fig. 10. Multiphase primary inclusion in the process of losing a small rodlike birefringent daughter mineral (at top) by necking down. A large halite crystal is out of focus. ER 63-211.

Fig. 11. Probably pseudosecondary, essentially vapor-filled, type B inclusion showing very large vapor bubble and small fillet of liquid (at top). Inclusions of this type must have originally trapped fairly low-density steam. ER 63-211-2.

---

**Fig. 12.** Primary two-phase inclusion (liquid (L) plus vapor (V)) in zoned spherelite from the Lark mine. This inclusion appears typical for the peripheral Pb-Zn deposits. Homogenization temperature 305°C; freezing temperature -13.7°C. ER 63-228.

**Fig. 13.** White quartz from vein with molybdenite showing typical high concentration of inclusions, making unambiguous assignments of origin or co-geneticity of any given inclusions impossible. Most of the inclusions in this field are type A (Fig. 1), plus a smaller number of type B. ER 63-209A.

**Fig. 14.** Serial photographs of a sample during homogenization run, taken at the temperatures indicated. Only two of these inclusions (arrows) were optically adequate for photography. Each has a bubble and an opaque crystal at room temperature. Heating to 355°C caused the bubbles to decrease in volume appreciably. Heating to 475°C caused further decrease and a visible decrease in contrast between vapor and liquid, indicating a decrease in the differences in index of refraction. The bubble in the upper inclusion has moved, presumably in response to temperature gradients in the heating stage. At 395°C the bubbles are even less distinct. Between 595°C and 655°C (about 645°C) the upper inclusion is homogenized in the liquid phase, but the lower inclusion required 725°C for it to homogenize, also in the liquid phase. In both, the meniscus between liquid and vapor was very faint near homogenization. Neither opaque daughter mineral dissolved during the run.

**Fig. 15.** Possibly primary inclusions containing liquid water (w), vapor (v), and another faintly visible immiscible liquid (L) believed to be liquefied H₂S. All are in calcite (c) from the U. S. mine at Lark. ER 63-232.

**Fig. 16.** Possibly primary inclusions containing *three* immiscible liquids plus vapor, from same calcite (c) sample as Fig. 15. Photo A shows an inclusion of NaCl-saturated solution (b) and vapor (v) with a large halite crystal (x). Surrounding the vapor bubble is an asymmetric ring of an immiscible liquid (l₁) believed to be H₂S, and a smaller spherical globule of another unknown immiscible liquid (l₂), which stays embedded in the thickest part of the ring of liquid H₂S. Minor thermal gradients cause the annular ring to rotate relative to the bubble (see inset, where (l₂) is on top). A small opaque grain (z) is visible in A but frequently is hidden from sight. Slight warming causes liquid (l₂) to disappear (into the vapor bubble?), yielding a symmetrical annular ring of liquid H₂S (B). Another similar inclusion is shown in C.
EDWIN ROEDDER

high concentration of tiny inclusions in most samples made it difficult to recognize which types of inclusions produced the gas. Crushing very tiny fragments containing only a few isolated inclusions of type B or of type A (Fig 1), showed that type B contained large amounts of gas, whereas type A contained relatively small amounts. If type B inclusions represent the dense steam from the boiling of type A fluids, it is to be expected that gases such as CO₂ would have partitioned preferentially into the vapor phase. The common occurrence of CO₂ in inclusions from many other environments, the presence of silicified limestones at Bingham, and the identification of presumed carbon dioxide hydrate in such type B inclusions in the freezing work (detailed in the next section), all suggest that this evolved gas is largely CO₂, but actual proof is lacking. Those inclusions containing liquid H₂S described above evolve the expected large quantities of gas on crushing, but the gases evolved on crushing the other samples cannot be H₂S, as there is no odor of H₂S on crushing, and the human nose is an exceedingly sensitive detector for H₂S (<10⁻¹⁸ grams).

Only a very few inclusions from the peripheral deposits were tested on the crushing stage; most show some evolution of gas, but in smaller amounts. The vapor bubbles in one sample of quartz from the Lark mine (ER 63-230) expanded to about double their original diameter, corresponding to an eightfold volume expansion. If this is all from the gases in the bubble alone, with no evolution from the liquid, a pressure of roughly eight atmospheres must be present in these bubbles at room temperatures.

Data from Freezing

Those inclusions that were most optically suitable were examined on the freezing stage (Roedder, 1962) to determine the freezing temperature and hence the approximate salinity (from the depression of the freezing point). Freezing temperatures on a total of 387 inclusions from samples from the Bingham district, including four from the core, are summarized in Figure 30 (bottom).

Two types of data are not plotted on Figure 30. First, all freezing data on multiphase inclusions with halite daughter crystals are excluded, as the phase changes on freezing such highly saline fluids are generally complex and not readily amenable to interpretation because of the unknown compositional variables. Freezing of such inclusions is useful for distinguishing halite from sylvite daughter crystals, but for little else.

Second, I have excluded those inclusions that yielded metastable (superheated) ice, at negative pressures (Roedder, 1967b), because these values will yield erroneous salinities. Very few such inclusions were found, presumably because most of the inclusions contain bubbles that are too large in volume percent to be eliminated on freezing. Of this small number, only five showed metastable ice above 0°C, the highest being at +3.5°C.

The plot of all 387 inclusions from all Bingham samples (Fig. 30, bottom) appears to show an almost meaningless random distribution, with a concentration of values around -2°C to -4°C. This apparent randomness disappears, however, when more limited groups of samples are considered. Thus when a series of 110 inclusions in zoned crystals of sphalerite and quartz from vugs in one stope is examined (Fig. 30, middle), the total spread is almost as great, but the range for the inclusions in sphalerite includes appreciably lower temperatures (and hence higher salinities) than that for the quartz crystals in the same vugs. In these samples the quartz and sphalerite were only partly contemporaneous. There is some evidence that the spread of values might actually be smaller, because the only recognizably primary inclusions in this group all had freezing temperatures lower than -6.0°C.

Forty-three inclusions were examined from quartz crystals in vugs in galena from another stope (sample ER 63-230). Two of these inclusions that were believed, on textural grounds, to be primary yielded freezing temperatures of -19.5°C; the other 41, all possibly or probably secondary, had freezing temperatures spread out from -10.6°C to -4.0°C, plus one at -1.4°C. Other samples showed similar and even narrower ranges for specific groups of inclusions preselected on the basis of apparent volume percent gas, or bubble movement, where primary vs secondary origin could not be determined.

The secondary inclusions in quartz phenocrysts from a quartz latite porphyry dike in the pit, sample ER 63-207 (Fig 30, top), could be placed in four categories by microscopy, the three shown in Figure 30 and a fourth, containing NaCl cubes, that is not plotted. The difference between the estimates of 20 and 25 volume percent gas for two of the types is not reproducible, but even though very few such inclusions were studied, the gross differences and tight grouping of the freezing temperatures (and hence salinities) of these two are significant. Thus, liquids of three different gross salinities were present at different times during the fracturing and healing of these phenocrysts: approximately 40 percent salt (yielding inclusions with halite daughter crystals), approximately 20 percent salt (yielding freezing temperatures of -15°C, and approximately 3 percent salt (yielding -1.6 to -2°C).

The fourth type of inclusion, with 70 to 90 percent gas (type B), deserves some special comment.
This is one of the most common types of inclusion in most samples from the core and presumably represents the trapping of steam bubbles (Fig. 1) from the boiling of the more saline brines represented by type A. All inclusions of this type that were studied on the freezing stage yielded similar modest freezing temperatures, generally in the range −1° to −3° C, and rarely below −4° C, corresponding to 6–7 percent salt at most. However, the inclusions of this type that were run are probably not all valid samples of the steam phase. If the data on the pure system NaCl·H₂O (Sourirajan and Kennedy, 1962) can be applied here, one can see that at temperatures of 400°–700° C (the probable maximum range, as discussed in a later section), this amount of salt can easily be dissolved in steam even at fairly low pressures. However, the liquid phase in equilibrium with such steam is much richer in salt, so even if only a small amount of liquid is trapped with the steam, the relative concentrations and densities are such that the liquid formed on cooling would be larger in volume and more concentrated in salt than that from the condensation of the pure steam phase. It would hence be desirable to freeze those type B inclusions containing the minimum amount of the liquid at room temperature, but these are the very ones least likely to be suitable for freezing, because of problems of total reflection that cause poor visibility of the thin layers of fluid. Some were well below 5 percent liquid, but never adequately visible for freezing. Those with considerably more liquid frequently contained a saturated solution (Figs. 25 and 26).

Another feature of the type B inclusions is important. In those in which the visibility was best, the temperature of melting of the last ice crystal, although plotted on Figure 30 as a “freezing temperature,” was not exactly that. Vague, faintly visible masses of unknown, isotropic material seemed to persist up to temperatures slightly above 0° C. In view of the large quantities of gas evolved from such inclusions on crushing, these vague masses are probably the carbon dioxide hydrate CO₂·5½ H₂O, which is cubic, has an index of refraction near that of water, and is stable to about these temperatures (Roedder, 1963, p. 188). However, no liquid CO₂ was recognized in any Bingham district inclusion, either at room temperature or on freezing.

Data from Homogenization

Method and Equipment

Following the freezing runs, homogenization temperatures were determined on many of the same inclusions. Although only eight samples were actually heated (four from the core and four from the peripheral deposits), numerous other samples appeared to have comparable inclusions. All determinations below 360° C were made on a Leitz model 350 heating stage. The effects of temperature gradients in this stage were minimized by essentially levelling off the temperature after each increment and by the use of organic melting-point standards sealed in capillary tubes placed on the stage with the sample chips. Strong oblique illumination from above or below the stage, using a flexible fiber optics illuminator (½” × 24”), help to reveal the bubble in those inclusions where the rather low condenser aperture afforded by the heating stage design made it otherwise impossible to see into the inclusion (this is merely an adaptation of a procedure first proposed by Ingerson, 1947; Fig. 24). Following the homogenization determinations, each inclusion was checked for leakage by either a repeat run or by remeasuring the size of the bubble at room temperature, or both. The total error in such homogenization measurements is probably less than ±10° C in most, if not all, these runs.

Homogenization temperatures higher than 360° C cannot be run on this stage. For these a high-temperature stage was used (Richter and Abell, 1953). In this stage, the position, shape, and thickness of the sample can have major effects on the accuracy of the determinations. Heat flow out of the Pt·Pt/10 percent Rh thermocouple leads and their insulation, and other problems, made it essential to calibrate the thermocouple actually in the stage during the run. For calibration, I used the sudden coalescence into a sphere of minute cleavage slivers of very pure Te (m.p. 449.5° C) and Sb (m.p. 630.5° C),* sealed in individual evacuated fused silica capillaries placed on the stage with the samples. These calibration tubes are made as follows: pull a capillary of about 0.5 mm OD from a fused silica tube of about 5 mm OD; seal off the capillary end; drop into the wide end a fragment of the standard element of suitable size and shape; vibrate the tube to move the fragment to the closed end; attach hose and evacuate; wrap closed end with wet asbestos; seal off quickly with an oxy-hydrogen microflame, as close to end as possible. If the capillary is thin, and the flame small, it is possible to make calibration tubes as short as 5–7 mm without melting the sliver. After sealing thus, another fragment of the same element may be similarly sealed into the next part of capillary. Only one element is loaded into the capillary pulled from a given tube. (This is because the fragments used weigh only about a microgram, so there would be a serious hazard of significant eutectic lowering of the melting point from an almost invisible grain of another substance.) Sublimation of the elements in these tubes takes place during the runs, particularly the longer, more careful runs, the new crystals growing on the cooler parts. If the tubes are too long, these cooler parts can be out of the field of view, and if the entire crystal transfers, that calibration point is lost. Hence short tubes are desirable. This sublimation frequently moves part of the substance to the top of the capillary, immediately above, indicating an unknown but finite vertical temperature gradient in the stage. Most disconcerting, however, is that the original crystal (on the

* Obtained from Amer. Smelting and Refining Co.
bottom) melts at an apparent temperature (based on standard tables for EMF of the thermocouple) that may be 25° C or even more below that at which the sublimed crystals on the upper wall melt, just 0.3 mm above, indicating very serious vertical temperature gradients. (As the elements used are 99.99 and 99.999+ percent pure, the previous sublimation should have had no measurable effect.) For such reasons the temperatures higher than 360° C reported here should be considered to be accurate to perhaps ±25° C. The errors are probably largest at the highest temperatures, but the error in relative temperatures between simultaneously-run inclusions is probably much smaller. A few high temperature runs were made on a Leitz model 1350 stage, but these could only be considered to be corroborative, because of difficulties of control and calibration.

Results—Samples from Peripheral Deposits

Very few heating stage runs were made on materials from outside the core, but the data at hand are believed to be probably representative. Fourteen primary inclusions in sphalerite from the surface over the U. S. mine (ER 63-212) all homogenized at 294°–298° C, and three primary inclusions in sphalerite from deep in the Lark mine (ER 63-228) homogenized at 304°, 307° and 309° C (Fig. 12). It is important to note that although the 14 inclusions in ER 63-212 homogenized over a very narrow (4° C) range, and were all within a range of a few millimeters, they occur in various zones of strongly zoned sphalerite, and the freezing temperatures of some of these same inclusions (not all were run) ranged from −10.90° ± 0.20° to −3.50° ± 0.05° C. Sample ER 63-228 was similar, in that the homogenization spread is only 5° C, yet these same three primary inclusions froze at −10.00° ± 0.05°, −13.72° ± 0.03°, and −20.95° ± 0.15° C.

A vertical zoning is recognized in these deposits, both in gross mineralogy and in color of sphalerite (more marmatic with depth; Rubbright and Hart, 1968, p. 897) that might easily be assumed to be from temperature, but these inclusion data indicate that the wide range in color of sphalerite, at least in these samples, more likely stems from fluid compositional variables rather than from temperature. Rose (1967) has shown that the sphalerite-forming fluids at Bingham must have varied with time and may even have come in separate surges from separate sources. From the freezing and homogenization data, and the density data for NaCl-H₂O given by Lemmlein and Kleptsov (1956), these fluids had densities, at the time of trapping, of 0.75–0.95 g·cm⁻³.

In contrast with the above, 25 inclusions in quartz from sample ER 63-229, collected very near to ER 63-228, gave a range of homogenization temperatures that did vary with salinity. A group of six presumed primary inclusions in this sample all yielded freezing temperatures of −7.72 ± 0.02 to −7.85 ± 0.05° C; three of these same inclusions, and seven others in the same group, all homogenized in the range 320°–330° C. On the same basis as above, these fluids had a density of about 0.82 g·cm⁻³. A few millimeters away in this same plate is a group of 16 pseudosexual (?) inclusions. These froze in several discrete intervals in the range −3.65° ± 0.05° to −1.22° ± 0.05° C, and 10 of them had homogenization temperatures of 308°–311° C (corresponding to a density of 0.73 g·cm⁻³). In addition, one each homogenized at 328° and 341° and three with large vapor bubbles at room temperature had not homogenized by 360° C. Although limited in number, these data are sufficiently grouped to be interpretable. Within the group of ten homogenizing at 308°–311° C three with very large bubbles (similar to Fig. 11) homogenized in the vapor phase, and seven with small bubbles homogenized in the liquid phase, all in the same very narrow temperature range (309.5° ± 1.5° C). The optics permitted measurement of the freezing temperature on only one of the three with large bubbles; it had the lowest salinity (−1.22° C). These results are strongly suggestive of the simultaneous trapping of liquid and steam from boiling solutions. The three with large bubbles that had not homogenized at 360° C, and the two at 328° and 341° C, could well represent the trapping of both steam and liquid.

Obviously many more samples need to be studied before any patterns of temperature variation with paragenetic stage or spatial distribution can be established reliably. The narrow range of temperature for these various samples, in spite of the vertical range of several thousand feet in sample location and an unknown range in paragenetic sequence, suggests that during the mineralization a rather large body of rock was maintained at nearly uniform temperature.

Results—Samples from Core of District

Homogenization runs were made on several hundred inclusions in four samples of quartz from the core. This group included types A, B, and other possibly intermediate types. The specific differences between samples are probably less significant at this frequency of sampling than are the similarities. The largest group of runs were on a sample (ER 61-40), collected by the late B. Stringham some time before 1961, unfortunately from an unspecified location in the pit. However, other similar but located samples, particularly ER 63-209 and ER 69-16, behave in the same manner, and many other samples showed...
visually similar inclusions. On gradual warming (on the Leitz stage) the first noticeable change is the rapid solution of the KCl crystal (Figs. 17-18). In most this dissolves completely by 60°-70° C, but some do not dissolve until about 100° C (Figs. 2-5). Several different small birefringent crystals mostly dissolve by about 125° C, but the largest birefringent crystal (the one thought to be anhydrite) merely becomes visibly smaller by 250° C and very small by 350° C. In most such inclusions, the NaCl crystal is visibly smaller and rounded by 350° C; in a few it dissolved in the range 250°-350° C. Those type B, low-density inclusions whose optics permit observations have lost some liquid into the vapor phase by 350° C.

On the Richter-Abell stage, all NaCl crystals dissolve by 495° C (some by 375°, most by 393°, all by 495° C; Fig. 20). The anhydrite (?) crystals become very tiny by 410°, but experimental difficulties precluded determination of the temperature of disappearance. The bubble is gone by 450° C in perhaps 10 percent of the inclusions; by 645° C it is gone in most (perhaps 90 percent); but some of the rest do not lose their bubble until 725° C. Where observations are possible, the opaque speck persists apparently without change, even after several hours of heating.

The liquid in type B inclusions in the same plate evaporates into the vapor bubble, and as the remaining liquid clings to the walls, the homogenization temperature (in the gas phase) cannot be determined with any accuracy. Some seemed to be homogeneous by 375° C, and most by 450° C, but others, including groups in obviously secondary or pseudosecondary planes (Fig. 21), did not homogenize until 700° C. This variation in homogenization temperature of type B inclusions does not require that the trapping temperature varied at all. It could be a result of variations either in pressure at the time of trapping, or in salinity, or both. At constant temperature and salinity, the higher the pressure the greater the density of the fluids on trapping and the higher the homogenization temperature (for this type of inclusion). It is not possible to measure the gas/liquid ratio, and hence the density, in these inclusions with any precision, as tubular or planar inclusions are rare in this material. Estimates of the volume percentage of gas in inclusions with large bubbles, as shown in Figure 21, are particularly poor. Even at constant gas/liquid ratio, the salinity of the fluid will also have major effects on the homogenization temperature. The possible magnitude of this effect can be seen from the critical temperatures for liquids in the system NaCl-H2O (Sourirajan and Kennedy, 1962), which rise approximately 100° C for each added 8 percent salt in the range 400°-700° C.

These 700° temperatures are unexpectedly high, by perhaps 200° C, and hence the possibilities of error should be considered carefully. First, there is the possibility that necking down has occurred, resulting in a concentration of halite daughter crystals (or vapor bubbles) in some inclusions. Either of these occurrences would yield higher homogenization temperatures (for type A inclusions). However, the inclusions run were visually typical of a large number of inclusions, and frequently there were adjacent inclusions in a plane, all of which behaved similarly (e.g., Fig. 21 bottom, Fig. 22). Fine details cannot be duplicated for all members of such groups because of problems of visibility of the individual phases. Second, there is the possibility of error in calibration or experimental technique. The presence of “internal” standards with sharp melting points seems to preclude any major errors here, and although the probable error of ±25° C is far larger than desirable, it could hardly be much larger than ±25° C. Third, there is the possibility of leakage, before or during the experimental work. If fluid leaked out, particularly before the NaCl dissolved, the apparent concentration of salt would increase and the apparent gross density would decrease, both yielding higher homogenization temperatures. In addition to the general evidence against widespread leakage of inclusions (Roedder and Skinner, 1968), the uniformity of homogenization for some planes of inclusions seems to preclude it. Furthermore, if leakage has occurred at all, one would expect the relatively high pressure gases in type B inclusions to force liquid out of them before the type A leaked, and this would lower their homogenization temperatures. Yet some whole planes of these type B inclusions homogenized at 700° C (Fig. 21 bottom).

The occurrence of leakage during the experiments is also a valid possibility, and a number of inclusions did leak visibly at about 450° C. Also, there was extensive decrepitation at 500°-530° C, possibly related to the quartz inversion, but the data reported here are for inclusions that returned to their original appearance on cooling. Shortly after turning off the power to the heating elements there is a sudden crystallization of NaCl, and some hours or even months are needed to restore the daughter crystals to near their original condition, but reheating caused their solution at the same temperatures as before. Leakage of hydrogen may well have occurred in the geological past, yielding the hematite flakes (Roedder and Skinner, 1968, p. 721) but this would cause only a very minute volume change.

These high inclusion-homogenization temperatures are not without precedent. Nearly 70 papers have
been published, mostly in the Russian literature, in which fluid-inclusion homogenization temperatures (i.e., without pressure corrections and not including decrepitation studies) of higher than 500° C are reported (Roedder, 1971, Table 7). Many of these are from pegmatitic samples, but others are from metallic ore deposits and in effect bridge the gap between silicate melts and the fluids that form ordinary epithermal “hydrothermal” ore deposits.

As the Bingham district comprises a volume of rock at least 5,000 feet in vertical dimension by 10,000 feet laterally, it seems evident that a core at temperatures as high as 700° C, surrounded, presumably simultaneously, by a wide band of rock at lesser temperatures would cool slowly, even with convective overturn in the fluids permeating the porous fractured mass. The pervasive alterations (including some of the mineralization stages) imply considerable periods of time of contact between fluid and rock, and Rubright and Hart (1968, p. 900) mention pyrite crystals as much as 6 inches across at a depth of about 5,000 feet in one crosscutting fissure, which also seem to require conditions of very slow crystallization. Much of the finer grained minerals, particularly in the upper parts, may well have been precipitated rapidly, during pressure fluctuations, rather than from temperature change.

Another line of evidence for high temperatures and long cooling periods is found in the inclusions in sample ER 69-16. This sample is unique among the Bingham samples in the degree to which the inclusions have recrystallized to sharp euhedral negative crystals (Figs. 25 and 26). This presumably requires a considerable length of time at high temperature. Although they homogenize over a range, some of the highest temperatures recorded were from this sample, and this particular quartz sample has yielded the lightest oxygen of any of the eight Bingham quartz samples run, corresponding to the highest temperatures (Wm. J. Moore, verbal communication, 1969; manuscript in preparation).

**Pressure of Formation and Pressure Corrections**

The pressure correction is the amount that must be added to the homogenization temperature of an inclusion to obtain the trapping temperature. If the fluid that is trapped in an inclusion is on the liquid-vapor curve (i.e., it is boiling or nearly boiling), there is no pressure correction. Both steam and liquid inclusions will then homogenize at the temper-

---

**Inclusions from Bingham and Climax**

**Figs. 17-20.** Serial photomicrographs of multiphase type A inclusion from Bingham, sample ER 63-209, taken at the temperatures indicated. At 25° C the phases visible are vapor (v), halite (H), sylvenite (Sy), hematite (?), and several unidentified crystals. The sylvenite goes at 80° C, most of the halite is gone by 310° C, and all of the halite is gone at 365° C. The hematite (?) and anhydrite (?) remain.

**Fig. 21.** Secondary, high-gas inclusions in Bingham sample ER 61-40, homogenizing at 400° C (upper) and 700° C (lower). The opaque grain (hematite ?) in the lower inclusion did not dissolve. This latter inclusion is one of many identical inclusions in a plane, all of which homogenized at 700° C. The difference in homogenization temperatures is probably due to differences in salinity.

**Fig. 22.** Secondary (?), high-gas inclusion in Bingham sample ER 61-40, one of a tight group of five, all of which had not homogenized at 700° C. Photograph taken after the run, but this had caused no change.

**Fig. 23.** Multiphase inclusion in quartz in Bingham sample ER 63-209, showing results of necking down. Upper and lower parts of large inclusion are connected by a tiny tube (arrow). The halite cube (H) is invisible where in contact with quartz since the indices of refraction of the two are identical (actual contact indicated by added dots). Other phases are hematite (?), anhydrite (?), and large octahedron of sylvenite (Sy).

**Fig. 24.** Effect of diagonally incident light on bubble visibility. The upper photograph was taken with normal hot-stage transmitted illumination. The lower shows the same field, using light from a thin flexible fiber optics light pipe placed beside the objective lens. Bingham sample ER 63-209.

**Fig. 25.** Quartz phase from Bingham sample ER 69-16, cut normal to c axis, showing complete recrystallization of all inclusions to hexagonal negative crystal shape. Inclusions out of focus are also sharply euhedral. (Compare with Fig. 13.) Although these appear randomly distributed they are probably secondary, as vague curving planar arrays can be found (one rather obvious plane is indicated by the arrow). Most of these inclusions are hexagonal bipyramids with only a large bubble, just tangent to the walls (upper left inset), but a few contain a salt crystal as well (arrow in upper right inset, which is a magnified view of the group in the center).

**Fig. 26.** Another area of same plate, showing adjacent high-gas inclusions (common), and high-salt inclusions (uncommon). These salt crystals dissolve between 340° and 495° C, and most of the inclusions of both types homogenize in the range 400°-500° C, but approximately 10 percent are not homogenized at 700° C.

**Fig. 27.** High-gas inclusion in Climax sample ER 62-20, homogenizing at 322° C. Approximate composition: vapor, 40 percent by volume; hematite (?), 0.5 percent by weight. Another small transparent crystal about the size of the hematite (?) is out of focus.

**Figs. 28 and 29.** Multiphase inclusions in same Climax plate as Fig. 27, showing about 7 weight percent halite (H), less than 1 weight percent hematite (?), 5 volume percent vapor (V), and several percent of two other phases (X), none of which are visibly birefringent. Most of these halite crystals dissolve around 250° C, corresponding to 34 weight percent NaCl (Fig. 32), in fortuitously good agreement with the crude optical estimate of 33 percent.
ature of trapping. A pressure correction becomes necessary only when the pressure at the time of trapping was greater than this vapor pressure.

If the dense saline inclusions and the low-density steam inclusions (types A and B), are actually cogenetic (i.e., the liquid was boiling), as seems likely, then these homogenization temperatures of 400°-700° C are correct trapping temperatures. If we assume for the highest temperature inclusions that all the salts behave as pure NaCl, that the fluids were boiling at 700°, and that the liquid had a gross composition of 50 percent NaCl–50 percent H₂O, then the data of Keevil (1942) and Sourirajan and Kennedy (1962) would indicate that the last NaCl crystal ought to dissolve at 425° C (very close to the experimental value) and the vapor pressure then would be only 230 atmospheres. The pressure at the temperature of homogenization (700° C) would be 1,120 atmospheres. This corresponds to 4.3 kilometers (2.7 miles) of lithostatic load. This calculated maximum pressure might be very significantly reduced by several other factors such as the presence of mixed salts. The wide variation in the homogenization temperature of the inclusions (375°-725° C) would be expected if the pressure varied between lithostatic and hydrostatic, as is probable with hydrothermally altered and choked passageways above and irregular tectonic movements opening new channels during mineralization.

As there is no evidence for boiling in many samples from the peripheral deposits, there is more chance that a pressure correction is needed there. The problem of the interdependence of temperature and pressure can be skirted by making the assumption that the pressure in the periphery during mineralization was equal to that in the core (1,130 atmospheres). This assumption may not be valid, as it implies contemporaneous deposition and no pressure gradient from the core outward, but it permits a crude estimate of the maximum pressure correction. Inclusions from the peripheral deposits homogenizing at 300° C would then have a pressure correction of 100°-115° C, depending on whether the salinity was 5 or 10 percent, and hence would have been trapped at 400°-415° C. Without such an independent estimate of pressure, all that can be said about the pressure from the inclusions is that it had to be at least equal to the vapor pressure of the solution involved, at that temperature. For 10 percent NaCl inclusions homogenizing at 300° C, this minimum (vapor)
pressure is 80 atmospheres. If an open system is assumed, this 80 atmospheres being applied as hydrostatic pressure from a column of 10 percent NaCl brine, at its boiling point throughout, and hence with the top surface at 101.9°C, the depth must have been 907 meters (Haas, 1971).

By use of the freezing stage it is possible to estimate the salinity, and hence know which pressure correction data to use, once an estimate of pressure can be established. The question frequently arises, however, as to how serious are the errors in pressure correction if the salinity is not as it was thought to be. Figure 31 is a plot of the magnitude of this error in the pressure correction if the wrong salinity is assumed, from the data on NaCl-H₂O of Lemmlein and Klevtsov (1961). From this figure, it is apparent that as long as the homogenization temperature is 300°C or less and the actual salinity is 5 percent or more, the errors involved in using the data for the wrong salinity are minor as long as any number in the range 5–20 percent is assumed. There is little difference, but the errors are probably minimum if 10 percent is assumed. If the actual inclusion salinity is zero, or if the data for pure water are used for saline inclusions, the errors can be large and either positive or negative. The errors resulting from assuming the wrong salinity are largest if the homogenization temperature is 350°C or higher, as expected from the much greater compressibility of such hot fluids.

Gross Composition and Density of the Trapped Fluids

Fluids Forming the Peripheral Deposits

Relatively little is known about the actual composition of the fluids trapped in the inclusions from the peripheral deposits. Except for the special case of the H₂S-bearing samples, the crushing stage indicates only that some gas, presumably CO₂, is present under moderate pressure. The large size of the opaque daughter minerals in a few inclusions indicates that the concentrations of heavy metals in these solutions must have been in the range of 1 percent, as has been found by analysis in a sample from Creede, Colorado (Czamanske et al., 1963), but the lack of such opaque daughter minerals in most of these inclusions is evidence that the heavy-metal concentration may be generally under 100 ppm (Roedder, 1960).

The freezing-stage data provide evidence as to the gross salinity, from the depression of the freezing point for the nine samples studied. A few of the larger frozen inclusions became somewhat translucent
(i.e., had "first melting temperatures") in the range of \(-30^\circ\) to \(-35^\circ\) C, indicating that some salts other than NaCl and KCl must be present. The conversion of the freezing-point depressions to salinity is inexact at best, because the various major salts depress the freezing point different amounts (Table 1), and of course these values are only very roughly additive. However, if the composition of the salts in the more dilute fluids forming the peripheral deposits is at all similar to that indicated by the daughter minerals for the fluids in the core, the salinity, in weight percent, is about double the depression of the freezing point, in degrees Celsius. For the more concentrated fluids, the salinity is approximately equal, numerically, to the depression of the freezing point. From the freezing data and the homogenization data, the density of the fluids forming these peripheral deposits was generally in the range 0.75-0.95 g·cm\(^{-3}\).

**Low-Density Fluids in the Core — Type B Dense Steam Inclusions**

Only certain parts of the gross composition of these fluids can be estimated at present. The liquid phase in these low-density inclusions, condensed from the trapped steam, generally contains little salt, as it seldom freezes below \(-4^\circ\) C. This corresponds to a maximum of about 6-7 percent salt, and even this figure is probably too high, because of trapping of some liquid phase also. The volume of the hematite (?) flake (Figs. 1-9) is difficult to measure precisely, but is seldom more than 0.05 volume percent. The CO\(_2\) (?) gas pressure in the bubble can only be roughly estimated, but from the behavior on crushing it is probably more than 10 atmospheres, and from the lack of evidence of liquid CO\(_2\), even on cooling, it must be well under the pressure of liquid CO\(_2\) at room temperature (63 atmospheres). Assuming 20 atmospheres of CO\(_2\) in the vapor and a solubility of 1 weight percent CO\(_2\) in the solution (Takenouchi and Kennedy, 1965), 5 percent salts in solution, made of 75 NaCl-25 KCl by weight (see below), and a volume ratio of 75:25 for gas:liquid, plus 0.05 volume percent hematite, the gross composition and density of the trapped fluid is as given in Table 2 (I). Obviously this calculation is exceedingly rough at best and ignores all other possible constituents. For comparison, however, Souriiran and Kennedy (1962) found that at 700° C, in the pure system NaCl-H\(_2\)O, the pressure needed to maintain 3.2 weight percent NaCl in the gas phase was 940 atmospheres. The Fe\(_2\)O\(_3\) was not in solution as such, because it does not redissolve on heating the inclusions. If originally present in the ferrous state, it might easily be soluble to this extent in chloride-bearing steam, and may have converted to hematite from auto-oxidation due to later loss of hydrogen by diffusion through the quartz walls (Roedder and Skinner, 1968, p. 721). The densities of these fluids

**Table 1. Depression of the Freezing Point and Salinity for 1-mol Water Solutions**

<table>
<thead>
<tr>
<th>Salt</th>
<th>Freezing Temperature, °C</th>
<th>Salinity, wt %</th>
<th>Depression, °C/wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaCl(_2)</td>
<td>-5.85</td>
<td>9.99</td>
<td>0.59</td>
</tr>
<tr>
<td>KCl</td>
<td>-3.250</td>
<td>6.94</td>
<td>0.47</td>
</tr>
<tr>
<td>KHCO(_3)</td>
<td>-2.91</td>
<td>9.10</td>
<td>0.32</td>
</tr>
<tr>
<td>MgCl(_2)</td>
<td>-6.35</td>
<td>8.69</td>
<td>0.73</td>
</tr>
<tr>
<td>MgSO(_4)</td>
<td>-2.02</td>
<td>10.74</td>
<td>0.19</td>
</tr>
<tr>
<td>NaCl</td>
<td>-3.37</td>
<td>5.52</td>
<td>0.61</td>
</tr>
</tbody>
</table>

**Table 2. Approximate Composition and Density of Fluids as Trapped in Inclusions from the Core at Bingham**

(See text for limiting assumptions)

<table>
<thead>
<tr>
<th>Illustration</th>
<th>Low-Density “Steam” Inclusions (Type B)</th>
<th>High-Density Multiphase Liquid Inclusions with NaCl Only (Type A)</th>
<th>High-Density Multiphase Liquid Inclusions with NaCl and KCl (Type A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig.</td>
<td>1B</td>
<td>1C</td>
<td>2, 4, 7, 8, and 9 (average)</td>
</tr>
<tr>
<td>Composition no.</td>
<td>I</td>
<td>II</td>
<td>III</td>
</tr>
<tr>
<td></td>
<td>g·l(^{-1})</td>
<td>wt %</td>
<td>g·l(^{-1})</td>
</tr>
<tr>
<td>H(_2)O</td>
<td>2.24</td>
<td>83.3</td>
<td>7.22</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>33</td>
<td>11.4</td>
<td>2</td>
</tr>
<tr>
<td>NaCl</td>
<td>9.7</td>
<td>3.3</td>
<td>4.01</td>
</tr>
<tr>
<td>KCl</td>
<td>3.2</td>
<td>1.1</td>
<td>—</td>
</tr>
<tr>
<td>Fe(_2)O(_3)</td>
<td>2.5</td>
<td>0.9</td>
<td>5</td>
</tr>
<tr>
<td>CaSO(_4)</td>
<td>—</td>
<td>—</td>
<td>3</td>
</tr>
<tr>
<td>Unknowns</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Total</td>
<td>2.90</td>
<td>100.0</td>
<td>1.13</td>
</tr>
<tr>
<td>Density, g·cm(^{-3})</td>
<td>0.29</td>
<td>5.3</td>
<td>1.13</td>
</tr>
</tbody>
</table>
at trapping is difficult to estimate with assurance, except to specify maxima, as some liquid may have been trapped with the steam in many of the inclusions. The present densities, as measured from optical estimates of volume percentages of phases, range from 0.1 to 0.3 g·cm⁻³, although some are even less than 0.1 (e.g., Fig. 11).

High-Density Fluids in the Core — Type A Multiphase Liquid Inclusions

Here also, are many compositional unknowns, including visible but unidentified daughter minerals, and unknown quantities of invisible salts in solution. If a simple case is taken, such as inclusion A in Figure 1, the approximate phase ratios are liquid, 82; vapor, 12; NaCl, 6.5; Fe₂O₃(?) 0.1; CaSO₄(?), 0.1, all as volume percent. Assuming the vapor contains CO₂ at 2 atmospheres pressure, a solubility of CO₂ in the brine of 0.14 weight percent, and a saturated NaCl solution (26.3 weight percent, density 1.2 g·cm⁻³), the gross composition and density of the fluid as trapped are as given in Table 2 (II).

More complex inclusions, containing recognizable sylvinite as well as halite, require a knowledge of the mutual solubilities of NaCl and KCl in H₂O. The available data on this system have been used to plot a phase diagram (Fig. 32). From this diagram the composition of the fluid saturated with respect to both NaCl and KCl at 25°C is: NaCl, 21.0; KCl, 11.0; H₂O 68.0 weight percent. Its density is assumed to be 1.28 g·cm⁻³. The volume percentages of the phases present in the five multiphase inclusions shown in Figs. 2, 4, 7, 8, and 9 were averaged, yielding: liquid, 59.3; vapor, 20.8; NaCl, 14.0; KCl, 3.5; CaSO₄, 0.6; Fe₂O₃ (all opaques), 0.3; unknowns (birefringent and isotropic), 1.5; all as volume percent. The unknowns were assumed to have an average density of 2.5, and the assumptions about CO₂ were as in the previous example. The results for this average of five inclusions are given as composition III on Table 2, and the results for the inclusion shown in Fig. 2 by itself are given as composition IV. Note that these fluids are only 32 and 42 percent water—the balance consists of solids. These fluids are closer to "hydrosaline melts" than water solutions.

It is interesting to see how these values compare with estimates of the composition based on the phase behavior on heating, independent of all optical volume estimates. For want of better information, I ignore all other constituents and assume for this purpose that the inclusion composition lies in the pure system NaCl-KCl-H₂O, that the KCl crystal dissolves by 70°C, and that the NaCl dissolves by 400°C. This behavior is typical of many inclusions containing NaCl and KCl (Figs. 2-9). At room temperature the inclusion liquid is on the boundary line at M (Fig. 32). On warming, only KCl dissolves (actually a small amount of NaCl precipitates on heating, as shown by the intersection of the tangent to the boundary curve at point M with the line NaCl-KCl extended). By 70°C (point N) all KCl is gone, so by definition only a liquid and solid NaCl are left. With further heating and solution, the liquid must follow the line N-O, towards NaCl. At point O the 400°C isotherm is intersected, and by definition all solid NaCl is now gone and only solution (and vapor) is left. The gross composition of the solution (and hence of the original inclusion), is now that of point O: NaCl, 39; KCl, 13; H₂O, 48 weight percent. In chemical terms, the composition of point O is 17.5 molal (13.9 NaCl and 3.6 KCl), giving atomic ratios Na/K of 3.9 and K/Na of 0.26. This is in reasonable agreement with the range of compositions II-III-IV on Table 2, arrived at by an entirely different route. The deviations are minor considering the gross inaccuracy of visual measures of daughter minerals, the heating stage, the extrapolation needed to draw the isotherms on Figure 32, and particularly the simplifying assumptions as to composition.

These hydrosaline melts may seem strange to some, but they are surprisingly common. More than 170 reports have been published of NaCl daughter crystals in fluid inclusions, from a wide range of types of rocks and ore deposits (Roedder, 1971). Semiquantitative estimates of composition are seldom made, but although many of these daughter crystals are the result of crystallization of only 5 or 10 weight percent excess NaCl on cooling, and hence correspond to original fluids with only 28-33 weight percent NaCl solution, the apparent size of the daughter crystals in the illustrations presented by some of these authors indicate compositions of more than 50 weight percent NaCl. These large daughter crystals of halite are characteristic of inclusions in granites and skarns and are particularly characteristic of porphyry copper deposits. (Hematite has also been reported in inclusions from porphyry copper deposits.) This does not necessarily mean that these dense brines were the ore-bearing fluids, although they may well have been, nor that all fluids forming porphyry copper deposits were dense. Thus Spencer (1917, p. 63) reports the presence of isotropic cubes in some inclusions at Ely, but Fournier (1967) presents evidence that at least certain parts of the porphyry copper deposit there may have been exposed only to attenuated gases. The common occurrence of dense brines, however, implies a possible genetic significance. The origin of at least some of these hydrosaline melts seems to be in late-stage immiscibility between granitic silicate melts and hy-
drosaline melts. Roedder and Coombs (1967) found inclusion evidence for the separation of hydrosaline melts with as much as 70 weight percent halite, as immiscible liquids, from some granite melts on Ascension Island. This process of separation of an immiscible dense aqueous fluid phase from a granitic melt (but without mention of NaCl as the major constituent) was also invoked by Jahns and Burnham (1969) to explain many of the features of pegmatites. White et al. (1970) have proposed an entirely different mechanism for the origin of the brines involved in the formation of porphyry copper deposits, invoking concentration of salts by the boiling of brines at the base of a vapor-dominated hydrothermal system. All that can be said at this time is that a hydrosaline melt, of unknown origin, was probably involved in the separation, transportation, and deposition of the ore metals in the porphyry copper deposits. Regardless of the origin chosen, however, it must be compatible with the data derived from inclusion studies.

Inclusions in Other Porphyry-Type Deposits

Butte, Montana

Only five samples were examined in detail (see Appendix) and these only by normal microscopy and in part the freezing stage. No homogenization
FLUID INCLUSION STUDIES ON PORPHYRY-TYPE ORE DEPOSITS

studies were made (Meyer, 1950, determined many in the range 275°–335° C). On testing with a hot wire probe, all bubbles that moved at all moved toward the probe. This uniform behavior is very unusual compared with most other areas examined.

Sample ER 63-336, from a potassium silicate alteration assemblage vein with molybdenite (Meyer et al., 1968, p. 1385), shows three main types of inclusions, visually almost identical with the three types most commonly seen in samples from Bingham. The three types are: 1) moderate-sized bubble and no daughter minerals; 2) very large bubble, some having a birefringent and/or an opaque or very dark crystal; and 3) small- to moderate-sized bubble, having a cube of halite somewhat larger on an edge than the bubble diameter, some having a red grain of hematite (?) and/or a birefringent grain in the 1 volume percent range. The birefringence of these grains is apparently too high for anhydrite and seems to fall in the range for the rhombohedral carbonates. When these grains are as large as 2.5 μm, they appear yellowish in color. No freezing data were obtained.

Sample ER-335 was from a 6-inch quartz-molybdenite vein. It has many secondary inclusions with about 90 percent vapor and an opaque speck in the fluid; other planes of inclusions have 20 percent vapor and an opaque speck that may be slightly red in some (hematite?). Some inclusions with isotropic crystals, presumably halite, were found in which the bubble is somewhat smaller than the bubble. A few of the larger high-gas inclusions have a small birefringent crystal as well. Freezing temperatures were obtained on eight of the best liquid plus vapor inclusions (no halite) which ranged from 25 to 50 percent by volume of vapor (visual estimates). The results were −1.40°, −2.52°, −2.82°, −3.60°, −4.40°, −4.60°, −5.35°, and −9.95° C, with no apparent relationship between salinity and bubble size.

The quartz phenocrysts in a sample of quartz porphyry (ER 63-312) showed abundant liquid CO₂ inclusions, which also contained a birefringent mineral and a small amount of water. A quartz veinlet with enargite in this same rock had secondary inclusions ranging from 10 to 70 volume percent vapor. Freezing temperatures were determined on 14 of these, yielding a wide spectrum of results, from −0.22° to −24.80° C. Those with lower salinity were generally higher in volume percent vapor. Several of these inclusions contained a small red plate of hematite(?), and several others (not run) contain about 15 volume percent halite and the same amount of vapor.

Sample ER 63-315, from a late stage in the mineralization, has many probably primary inclusions with moderate-sized bubbles that were runnable on the freezing stage. Only a very few, from the quartz, have a small birefringent daughter crystal. Eleven inclusions in sphalerite ranged from −1.20° ± 0.05° to −2.80° ± 0.10° C, and 16 in the quartz ranged from −0.57° ± 0.05° to −3.10° ± 0.04° C. Most of the primary inclusions in the barite had obviously leaked, but two that seemed suitable yielded −0.15° ± 0.02° and +3.85° ± 0.10° C (superheated ice).

From this very cursory examination, it can be concluded that the early molybdenum-copper mineralization at Butte had closely associated with it, but in unknown time relationship, highly concentrated, dense, hot solutions of salts, and relatively low density steam, very similar to Bingham. The one late-stage sample that was run only had low salinities (<1 molar NaCl equivalent), apparently lower temperatures, and no evidence of boiling. Liquid carbon dioxide was found in secondary inclusions in quartz porphyry. This gas is present in some of the steam-phase inclusions at Bingham, but it has not been found there in high enough concentration to yield liquid CO₂.

Climax, Colorado

The exceedingly complex geology of this deposit has been described in detail by Wallace et al. (1968). Most of the material examined from this deposit is too fine grained and complex to be very suitable for inclusion studies, but four specially selected samples (see Appendix) provided some useful information. Sample ER 61-14, of relatively large quartz crystals from the main tungsten mineralization stage, contained many inclusions that are obviously secondary or pseudosecondary, and some that are probably primary. A very few contained small birefringent crystals. On testing for response of the bubbles to a thermal gradient, from a hot wire probe, all that seemed primary were repelled (i.e., the bubbles moved down a thermal gradient). The bubbles in other obviously secondary or pseudosecondary inclusions moved up the gradient, and two did not move at all, yet were free to move. All had rather small vapor bubbles. On the crushing stage, moderate amounts of gas under pressure were emitted.

On freezing and homogenization, these same group differences were evident. The apparently primary inclusions (about 20 in all) gave freezing temperatures in a tight group from −4.36° to −4.27° ± 0.06° C, and homogenization at 221°–256° C. The group of about 20 secondary inclusions in the same crystals all had freezing temperatures in the range −1.0° to −0.8° C, with most in the narrow range −0.87° to −0.80° ± 0.03° C, and all homogenized in the range 192° to 205° C. The two inclusions whose bubbles did not move in a gradient froze at
-2.52° and -2.60° ± 0.02° C; one of these homogenized at 227° C but the other was not run. Apparently at least three distinct fluids have bathed these crystals at various times.

A sample from a quartz-molybdenite vein, ER 62-20, contained large numbers of probably secondary or pseudosecondary inclusions of a wide variety of types. Many had small to moderate-sized bubbles (Figs. 28-29), some of which moved up a thermal gradient and some moved down. Inclusions with small bubbles and daughter crystals of halite were common, with or without one or more highly birefringent grains or rods, many in the range of several volume percent. Inclusions with 50-80 volume percent vapor plus a small opaque crystal, although not as common as at Bingham, were present, mainly as healed fractures outlined by many inclusions of this type (Fig. 27). These inclusions were all too small for freezing runs, but the crushing stage revealed that considerable high pressure gas was present.

Several homogenization runs were made on inclusions in this sample. Some of the inclusions with small bubbles and no halite homogenized as low as 214° C. Most of the halite daughter crystals dissolved around 257° C (corresponding to 35 weight percent NaCl in the pure system). Approximately half the inclusions of all types (including the high-gas type, homogenizing in the vapor phase) homogenized by 322° C, and about three quarters homogenized by 360° C. The remainder are spread out from 360° to 460° C.

The “high silica rock” (sample ER 62-22) similarly had a range of inclusion types, and high-pressure gas, but these inclusions were generally too small for any studies other than simple microscopy.

The late-stage vuggy quartz veins with fluorite, etc., sample ER 62-21, provided many usable primary and secondary inclusions. Although this quartz enclosed many clumps of solid, birefringent crystals, and some fluid inclusions have been trapped along with these, no daughter minerals were found in any of the inclusions. All inclusions, both primary and secondary, were low in salinity and had rather small bubbles, generally 15 volume percent or less. Some inclusions in the fluorite had a bubble that was small enough to be eliminated on freezing, yielding as much as 60 percent superheated ice at temperatures as high as +1.2°. Another inclusion, which had no bubble as found, formed superheated ice up to ±4.1° C on a freezing run, and after the run had a bubble of the same relative size as the balance. Whether this represents metastable failure to nucleate a bubble in geological time (Roedder, 1970a), or permanent stretching of the walls of the inclusion on freezing (Roedder, unpub. data) is not certain.

Freezing runs were made on 17 primary inclu-
FLUID INCLUSION STUDIES ON PORPHYRY-TYPE ORE DEPOSITS

salinity. The pattern was complex in detail, but some general features are evident. The zonal array of mineralization in the district indicates a district-wide relationship, both in space and time, and the fluid inclusion evidence supports this concept. The temperatures of these fluids varied both in time and space, but reached their highest values in the core. Similarly, the concentration of salts in solution varied in time and in space, the highest values being in the core. Some of the variations may well stem from boiling induced by intermittent pressure release, as the inclusions show considerable evidence of boiling in the core, and to a lesser extent in the periphery. The inclusion data are compatible with almost any model involving a central source of heat and salts. The densities and temperatures found make convective mixing and dilution with the surrounding and overlying ground water almost inevitable, and this may have led to the formation of the peripheral deposits. As there is a gross drop in the salinity of the fluids found in inclusions from the core outward, I consider that the old concept of an ore fluid moving outward and upward, precipitating the various metals in the various zones of the deposit with simple drop in temperature, is invalid.

This inclusion work is only a small part of the current U. S. Geological Survey work in progress on the Bingham district, which involves studies of detailed areal and underground structure, petrology, stable and radioactive isotopes, ore and alteration mineralogy, and geochemistry of the sulfide phases (e.g., Field and Moore, this commemorative issue).

Future work on the inclusions alone should involve far too many roads for any one individual to follow. Obviously, good, quantitative chemical analyses of these fluids are needed. They will have to be made on much smaller samples of fluid than has been possible in the past, but even simple K/Na ratios would be of value in tying in which wallrock alteration on the one hand and the composition of the feldspars in suspected source rocks on the other. Similarly, isotopic studies on H, O, and S in inclusion fluids should be undertaken, to complement work in progress on the isotopic composition of the solid phases. Such studies, particularly of the high-temperature inclusions, should help to clarify whether these are truly magmatic waters, but unless differentiated bulk samples are used, this also is apparently beyond the scope of present techniques. The sulfur species and quantities present in the original fluids, now represented in part by anhydrite (?) and presumed sulfide daughter minerals, presents a particularly difficult but important problem, in view of the possibility of changes in Eh since trapping from the diffusion of hydrogen; some experimental studies on this latter problem are feasible with existing techniques. The volatile components present, even in single, moderate-sized inclusions, can be readily analyzed by present-day mass spectrometric methods using vacuum crushing, but the choice of sample material from Bingham that will yield unambiguous results is a major hurdle. Similarly, modern electron-probe techniques are adequate to identify the individual micrometer-sized daughter crystals, provided they can be removed from their quartz cages and placed in the beam. Quite apart from all these "new-fangled" techniques, additional detailed studies should be made by straightforward simple microscopy, including heating, cooling, and crushing, on many samples and with careful geologic and paragenetic control. These are time consuming, but should contribute to an understanding of the fluid-circulation patterns, the origin of the fluids, and possibly might even provide guidelines for further exploration in this or similar districts.

Acknowledgments

The writer wishes to acknowledge the help received from the many men on the geological staffs at the several mines visited, who took so much time out of their already crowded schedules to escort the author and his colleagues around and explain the geology. Space does not permit naming these individually, but particular thanks must go to the staffs of the U. S. Smelting, Refining, and Mining Company, the Anaconda Company, and the Kennecott Copper Corporation for their cooperation and help. The author has profited from many stimulating discussions and guidance in the field from colleagues, and the manuscript has profited from the thoughtful reviews of John L. Haas, Jr., Wm. J. Moore, Edwin W. Tooker, and Laurence P. James. The writer also wishes to express his special appreciation of the efforts of his assistant, the late John P. Creel, who made most of the excellent polished sections and did the tedious work on many of the freezing runs.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C. 20242,
August 21, 1970

REFERENCES


---, 1962, Studies of fluid inclusions I: Low temperature application of a dual-purpose freezing and heating stage: Econ. Geol., v. 57, p. 1046-1061.

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


Appendix

Sample descriptions and miscellaneous inclusion data not specified in text

Note—Localities referring to “pit” are from the working face of the open-pit mine at the specified level at the time of collection (e.g., ER 63-207 was collected in 1963). All were collected by the author except as noted. Samples in which the inclusions were too small, or optically too poor for unambiguous phase identification and effective study are not listed. The bed designations, locations, and mine coordinates were obtained from the geological staffs at the individual mines. DM—daughter minerals.

Bingham district

ER 61-40 Quartz-molybdenite vein, with some calcite-quartz, 10-cm wide, from Bingham pit. Collected by the late B. Stringham. Freezing data cover wide range. Multiphase inclusions run for homogenization (see text).

ER 62-14 Quartz phenocrysts from main body of porphyry, east side of Bingham pit. Two types of inclusions: large bubble and no daughter mineral; small bubble and large NaCl cube. Freezing data only obtained. Collected by the late B. Stringham.

ER 63-207 Quartz latite porphyry dikes, Bingham pit, 5,590 level, north side, Large feldspar phenocrysts (both rounded and sharply euhedral) coated with...
mica; inclusions in them too difficult to work with. Small quartz phenocrysts given number ER 63-207Q. Three types of inclusions evidenced by freezing—see Fig. 30.

ER 62-209—Quartz-molydbende ne vein, 5 to 10-cm wide, Bingham pit, 6,090 level, southeast side, below Ohio Copper. Most such veins (including this one) show molydbende lining the walls and vuggy quartz cores, with some brown sphalerite. A little chaledonic quartz coats some vugs. Three types of inclusions, with freezing temperatures from −22.25° to superheated ice at +0.42° C; homogenization temperatures high.

ER 63-211 Quartz vein in granite, Bingham pit, 5,940 level, northeast side at 1 + 30 south. Euhedral clear quartz crystals projecting into vugs. Most NaCl crystals dissolve by 300° C, but the bubbles are still present at 355° C.

ER 63-212 Polymeric fissure ore, Bingham pit S' level, west side, over U. S. mine. Galena and color- zoned sphalerite with later quartz crystals in vugs. Calcrete, as recrystallized veins, has H2S odor on breaking but inclusions too small and optically poor to work with. Sphalerite inclusions froze at −10.90° to −3.50° C, and homogenized at 294°–298° C.

ER 63-213 Sphalerite, euhedral 1-cm crystals, colorless, green, yellow-orange, and red, Bingham pit, K level, 6,968, west side, from fissure in quartzite over U. S. mine. Collected by Eldon Bray. Primary or possibly pseudosecondary inclusions froze at −3.45° to −2.55° C.

ER 63-214 Quartz crystals from vug in barren pyrite, U. S. mine, 500 feet north of Niagara #2 shaft on Niagara level, 6,674 elev., 630S, 5,145W, from quartzite below middle Highland limestone. Some inclusions have a small birefringent daughter crystal. Freezing temperatures on 22 probably pseudosecondary inclusions ranged from −3.70° to −2.32° C.

ER 63-216 Quartz crystals from vug, U. S. mine, 200 feet east of no. 3 shaft, Niagara level, 5,919 fissure. A few inclusions show a vague “rim” around bubble, but too difficult to run.

ER 63-228 Sphalerite and in part contemporaneous quartz crystals from vugs, Lark mine, 6 sets below 3,000 level, 6,907 stope 1, 6,930N, 695E, 4,339 elev. Freezing results in Fig. 30. Sphalerite inclusions homogenize at 304°–309° C.

ER 63-229 Quartz crystals in vug in galena, Lark mine, 6,803 ore shoot 6,880N, 570E, 4,290 elev. Freezing temperatures from −23.67° to −0.54° C, and some with superheated ice at +0.2° C. Homogenization temperatures 308°–330° C.

ER 63-230 Quartz crystals in vugs in very coarse galena, Lark mine, Commercial limestone, 6,907 crosscut just west of Raise 1, 6,803 ore shoot, 6,880N, 570E, 4,239 elev. Freezing temperatures range from −8.27° to −1.15° C, plus some superheated ice as high as +3.45° C.

ER 63-232 Calcite, fetid, from U. S. mine, B limestone hanging-wall bedding, 463 raise 1 sub 1 east, above 800 level (elev. > 5,845). Sample from company collections. Coarsely crystalline bluish marble appears to replace limestone (R. Rubright, oral communication, 1963). Homogenization data only.

ER 63-236 Scheelite and fluorite, with pyrite, Ophir Hill mine, 1,600 level, 15 fissure. Donated by Richard Rubright. Inclusions in both scheelite and fluorite contain large amounts of daughter crystals. Most show two large birefringent crystals, one much smaller isotopic one, a very small opaque grain, and a small bubble. A few contain also a hematite (?) flake. Tubular inclusions permitted moderately accurate volume measurements (from micrometer measurements of the linear intercepts), yielding the following volume percent estimates: birefringent crystals, 20; gas, 20; and liquid, 60. In addition there were many simple two-phase gas-liquid inclusions, some with as much as 60 volume percent gas. Some of these froze at −3.6° to −1.6° C.

ER 63-239 Calcite crystals from vugs in Commercial limestone, Lark mine, 5 feet below ore, 13 fissure, 13 winze, Mascotte tunnel level, 4,670E, 6,870N. Primary inclusions froze at −15.25° to −10.25° C.

ER 63-245 Calcite crystals from vug in Lark vein, Lark mine, 50 feet north of 7,441 incline, 1,000 level, 7,200N 3,280E, 5,125 elev. One primary inclusion gave a (probably poor) freezing temperature of −4.07° C.

ER 69-16 Quartz, pod-like mass, about 2 feet wide, dark gray, with molybdenite, chalcopyrite, and bornite. Bingham pit 5,490 level, south central. Large amounts of gas on crushing. Homogenization data only. From Wm. J. Moore, his number 67-B-3.

Butte district

ER 63-312 Quartz porphyry 3 cm from contact, Berkeley pit, 5,167 level, northeast. Quartz phenocrysts contain liquid CO2 inclusions with minor H2O.

ER 63-312a Quartz-epargmite vein in quartz porphyry, same locality as ER 63-312 above.

ER 63-315 Barite with quartz and sphalerite, Gagnon south vein, A1972 drift SW, 350 feet west of main crosscut south. Sample donated by T. Gilbert. Quartz is earliest, then sphalerite (strongly zoned colorless-yellow-green and brown) and then barite; each is perched, with no simultaneous growth.

ER 63-335 Quartz-molydbende vein (15-cm width), Mountain Con mine, very near contact with A4510, hanging wall of Dernier vein, 4,500 level. Euhedral quartz crystals from vugs in vein.

ER 63-336 Potassium silicate alteration assemblage vein with molybdenite, Mountain Con mine, 4,582 crosscut southeast.

Climax district

Note: Most ore samples from Climax are rather poor material for fluid inclusion studies. The following group of samples, especially selected to be optimum for inclusion work, was provided through the courtesy
of D. C. Jonson, formerly the resident geologist at Climax. See Wallace et al. (1968) for geological background.

ER 61-14 Quartz crystals, 1 × 3 cm, from main tungsten mineralization stage.

ER 62-20 Quartz, from an unusually wide and coarse grained quartz-molybdenite vein from the "lower" molybdenite ore body.

ER 62-21 Quartz, vuggy, from the east fault zone. Associated with white and gray chalcedonic quartz, fluorite, rhodochrosite, pyrite, calcite, dolomite, sphalerite, and galena. It is postmolybdenum and post-tungsten mineralization. Four specimens, labelled "a" through "d".

ER 62-22 Quartz of the "high silica rock," a form of hydrothermal alteration that replaced and destroyed the quartz-molybdenite veins of sample ER 62-20, and predated the quartz of sample ER 62-21.