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Fluid Inclusions as Tools in Mineral Exploration

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Introduction

The study of fluid inclusions in ore deposits has generally been a result of "academic" interest, at least in the Western world. But there are many applications in which their study can be either directly or indirectly helpful in the search for, and the development of, new deposits or extensions of known deposits. Where possible, these applications will be illustrated with specific examples from the Western literature, but, unfortunately, much of the work in this field is in the extensive Russian literature and is not generally available in English except as abstracts. Other potential applications can now only be suggested in hope that they will be tested in suitable field situations in the future. Thus, the study of fluid inclusions, although no panacea for exploration, should be considered as a potentially useful tool in exploration for many types of ore deposits.

As with every exploration tool, inclusions should not be used blindly or by themselves, but data from them should be interpreted in conjunction with careful geologic and paragenetic studies. I do not claim that they provide us with a magic black box that finds ore, but merely that they are helpful. The potential usefulness of inclusions should not, however, be considered as limited to the types of deposits chosen as examples here, as these may in fact be far from the optimum testing grounds. Thus, the purpose of this report is simply to alert the exploration geologist to some possibilities which have been rather neglected in the Western world.1

The interpretation of most inclusion data is necessarily subject to various degrees of ambiguity with respect to its validity, as detailed beyond. Misunderstanding of the degree of this ambiguity, in either direction, is unfortunate. If significant ambiguity exists but is ignored or minimized, the resulting over-interpretation may be seriously in error; conversely, if the degree of ambiguity is exaggerated, valuable data may be ignored or not even obtained. Both of these situations have occurred all too frequently in the history of the study of fluid inclusions in ore deposits, and it is important that we try to chart a safe course between this Scylla and Charybdis.

This paper will review briefly the general nature of inclusions and the types of data available from them, and then discuss four, in part overlapping, aspects of the use of such inclusion data in mineral exploration.

General Nature of Inclusions

The use of fluid inclusions in exploration requires, of course, some knowledge of the general features of inclusions, the types of data that are available from them, and their significance and limitations (see Roedder, 1967 and 1972, for more detailed reviews).

Origin and occurrence of inclusions

Fluid inclusions are small volumes of fluid which are trapped within crystals by any of several mechanisms during their growth or by later processes. They are generally representative of fluids present during crystal growth or in which it was later bathed. They occur in almost all ore and gangue minerals, sometimes as many as a billion per cubic centimeter but are seldom >1 mm and most are <10 μm. They are usually studied under the microscope, in doubly polished plates of the host mineral, but small ones can be examined in ordinary petrographic thin sections and larger ones can be seen with a hand lens. Although they are almost ubiquitous, those from which optimum, meaningful data can be derived are very scarce.

Those trapped during the growth of host crystals in an ore (i.e., primary inclusions) are samples of the ore fluid, and hence may reveal much about the conditions of ore transport and deposition. Later shearing and re healing of fractures will cause trapping of large numbers of secondary inclusions; these provide information on the fluids that were present around

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the host crystal at some unspecified time after the original growth. As such, they may or may not be useful. Thus in many gold quartz veins, the gold-bearing fluids have come in later than the quartz, and hence at least some of the secondary inclusions so common in these veins are actual samples of the "ore fluid."

Distinction between primary and secondary inclusions is occasionally either obvious or impossible, and frequently difficult. The assignment of origin is thus the critical step in any inclusion study, and it usually introduces at least some ambiguity.

Nature of the trapped fluid

Ordinarily, the fluid trapped in primary inclusions is assumed to be a sample of the fluid from which the crystal grew. The validity of this assumption has been challenged by Barnes et al. (1969) but the discrepancies they report are small. If the fluid surrounding the growing crystal is not a single homogeneous fluid, some rather unusual and distinctive inclusions may be trapped; examples include the trapping of two immiscible liquids, such as oil and water, or CO₂ and water; liquids and gases, such as boiling water and steam; and liquids plus solids. Such inclusions may be very misleading and unsuitable for thermometry, but, if their heterogeneous origin is recognized, they can be very informative.

Fortunately, most fluid inclusions, in most ore deposits, were trapped from a single, homogeneous fluid, and because of thermal contraction from filling temperature to surface temperature, now consist of liquid plus a vapor bubble.

Leakage

The term leakage is used to include movement of material either into or out of the inclusion after the original trapping. At one time, leakage of inclusions was generally considered to be common (or even universal), negating the significance of most inclusion data (Skinner, 1953). More recent studies (Roeder and Skinner, 1968) indicate that, although leakage (particularly of H₂) can and does occur, it is rather rare and generally recognizable. It is most evident in the presence of planes of empty inclusions in samples that have been fractured after inclusion trapping.

Phase changes since trapping

On cooling after trapping of an originally homogeneous fluid, the most common phase change is the formation of a vapor bubble due to differential shrinkage of the fluid and the host crystal. Other commonly observed changes include separation of immiscible fluids (such as CO₂ + H₂O); crystallization on the walls; and saturation and precipitation of additional solid phases, called daughter crystals, the most common being NaCl. These changes are plainly visible under the microscope in a single small inclusion <10 μm in diameter, and each provides compositional data on the ore fluids, even though the mass of the fluid in the inclusion studied is orders of magnitude too small (~10⁻⁷ g) for extraction and total quantitative analysis by even the most sensitive chemical analytical methods. Opaque daughter minerals are important in providing a lower limit on the heavy metal content of the ore fluids (Roeder, 1960b).

In this connection it should be mentioned that minerals crystallizing from lavas also trap fluid inclusions, but these inclusions consist of silicate melt, rather than being aqueous. The environments and the techniques of study are quite different, but the same principles apply. Thus in both lunar and terrestrial basalts, olivine crystals commonly contain silicate melt inclusions in which a globule of sulfide has separated as a daughter phase. This globule is found to be an iron-copper-nickel sulfide melt that has become immiscible in the basaltic melt on cooling and has separated (Roeder and Weiblen, 1971). As such, these inclusions could provide valuable insight into some magmatic sulfide deposits.

Physical changes since trapping

Most inclusions do not now have the shape they had when trapped, because solution of some parts of the wall and deposition on others is a rather general process. Such recrystallization is, of course, effectively isochemical but may cause serious problems in the application of criteria for a primary vs a secondary origin. As the system will trend toward minimum surface energy, long tubular inclusions, or thin flat ones, will tend to become more equant (or spherical) with time and may even separate into several more equant inclusions, a process called "necking down." The inclusion system as a whole remains isochemical, but if any phase separation has occurred before necking down, the two or more resultant inclusions may have very different compositions or phase ratios and hence can yield very discrepant thermal data.

It is important to remember always that the fluid inclusions in a mineral provide information only on the fluids present at the time of sealing of the inclusion, whether that be during the growth of the host crystal or during rehealing of a later fracture. Thus, if a fine-grained syngenetic deposit were recrystallized to a coarse-grained metamorphic orebody, the fluid inclusions would generally represent the pressure, temperature, and composition of fluids present during the metamorphism (or during still later shearing).
Types of Data Available from Inclusions

Composition

A large number of types of qualitative or semi-quantitative data for phase identification may be obtained with the petrographic microscope even on very tiny inclusions. These tests are generally non-destructive. Still other types may be obtained by determining the phase changes on heating, cooling, or pressure release on crushing the microscope. There are numerous experimental problems in obtaining good data by these various procedures, but the most important step is still the selection of inclusions to study that are valid samples of the ore fluids.

If large inclusions are available (i.e., 1 mm), or large numbers of small ones of a single generation, the inclusions may be opened and the contents (≥10^-4 g) extracted and analyzed by microchemical techniques to obtain quantitative data on the chemical and isotopic composition of the ore fluid. Several thousand such analyses, of widely varying accuracy and completeness, are reported in the literature (Roedder, 1972). Although the small sample size may require special instrumental techniques, this is not the major limitation. The two real problems are valid sample selection and gross loss and/or contamination on opening and extraction. I know of no panacea for these problems.

Although the qualitative studies by microscopy mentioned above require samples ~6 orders of magnitude smaller than those for normal quantitative microanalysis (10^-8 g 10^-3 g), several analytical techniques recently applied to fluid inclusions can provide compositional data on certain constituents in single small inclusions in the same 10^-8-g range. Thus mass spectrometry is very effective on small amounts of gases (e.g., Ohmoto, 1969; 1970), non-destructive analysis by laser-excited Raman spectroscopy can provide identification of some tiny daughter crystals (Rosasco et al., 1975) and is particularly suited for sulfur species in solution (Rosasco and Roedder, 1976), and the scanning electron microscope (SEM) is excellent for identifying daughter crystals remaining in opened inclusion cavities (Metzger et al., 1975).

Although all of the foregoing procedures have considerable value in fluid inclusion research, the single most frequently used method of evaluating composition of the ore fluids is the freezing stage, which permits an estimation of the total salinity of the ore fluid (Roedder, 1962). When such data are combined with data on the temperature of formation of the deposit (see next section and summary diagram by Nash, 1972, his figure 2), it is apparent that there were very significant differences in the fluids forming various types of ore deposits.

Temperature and pressure

Fluid inclusion geothermometry based on the homogenization method is probably one of the most accurate and certainly the most widely applicable technique. Basically, it consists of heating the inclusions on the microscope stage up to the temperature where a single homogeneous fluid fills the cavity. Although the precision of the method may be high, in that the resultant homogenization temperature may be duplicated to ~1°C, there are difficult problems in estimating the accuracy of the measurement, due to experimental problems in measurement and calibration.

The temperature of homogenization (T_H) obtained on the heating stage is normally a minimum value for the temperature of formation. The compressibility of the fluid generally results in the need for a pressure correction, based on some independent evidence as to pressure, that must be added to T_H to obtain the temperature of formation (T_P). The magnitude of this pressure correction will vary with the pressure, and, for a given pressure, with both the density and composition of fluid. The pressure corrections for low-temperature deposits, formed from dense, strongly saline brines at shallow depths, are usually <25°C, but those for high-temperature deposits formed from low-salinity fluids at depths of ≥10 km may be ≥300°C, so the estimate of the pressure (from geological data) becomes very important. If this pressure estimate is accurate, reliable T_P values can still be obtained even with large pressure corrections (Roedder and Kopp, 1975).

Only under certain special conditions is it possible to obtain both T and P from inclusion data alone. Frequently, however, inclusions can provide crude but still useful upper or lower limits on the pressure at the time of trapping. But even such crude estimates may provide limits on the depth of cover at the time of mineralization that may be helpful in exploration and have even been used to estimate rates of denudation (Voskresenskii et al., 1972). Even though fluid inclusions normally can only establish that a mineral deposit formed along a given line (isochore) on a P vs T diagram, this information can be combined with other geothermometer-geobarometer combinations to yield both P and T. Thus Bethke and Barton (1971) have shown that certain trace element distributions between codeposited phases, plus fluid inclusions, can provide both P and T of deposition.

In addition to the homogenization method, large amounts of geothermometric data from inclusions have been reported using the decrepitation method,
first proposed by Scott (1948) and then developed by F. G. Smith, P. A. Peach, and coworkers in Canada (see Smith, 1953, and a series of later papers in Economic Geology). Since then it has been used mainly in the Soviet Union. In this, a coarse-crushed sample containing inclusions is heated until the buildup of internal pressure causes violent rupture (decapitation) of the host; the sound is detected, amplified, and recorded electronically. Instrumentation for heating samples and detecting decapitation runs the gamut from a simple stethoscope to various electronic integrating and recording equipment (see Roedder, 1972, p. 28, and indices in Roedder, 1968-on). In some applications, a vacuum is used (Maishki, 1973).

Although I have not been personally involved in much decapitation work, it is obvious that the method has many serious problems both in theory and in practice (see, e.g., Roedder, 1967, p. 561-562). The temperature of decapitation of any given inclusion is a function, in part, of the temperature of homogenization, but it is also a function of a series of other factors, only some of which can be controlled by the use of standardization techniques. The first and most obvious step is to use well-sized, relatively pure mineral separates rather than merely using crushed rock, as has been done all too frequently. I have serious doubts that the method can ever be truly calibrated to yield accurate data on the temperature of homogenization (or formation) of fluid inclusions, free of error and subjectivity. The only possible exception may be runs made on rather uniform sample suites that have been previously standardized by the homogenization method. But, decapitation is fast, it is inexpensive, it can be used in the field, it can be used on opaque samples, and it requires little training, so it should not be ignored simply because its use must necessarily be empirical. It is probably most useful as a screening method to recognize differences between samples or the presence of several different generations of inclusions, particularly in opaque minerals and in the low-temperature range.

Density

The density of the ore fluids at the time of trapping in an inclusion can be obtained from estimates of the volumes and densities of the phases present at room temperature. This is the only known source of such data and can be as accurate as ±0.01 g/cm³. It is of importance in any hydrologic modeling of ore deposition.

Applications of Inclusion Data to Clarify the Regional or Local Geology

An understanding of the geological or structural setting of an orebody can be important to exploration. Fluid inclusion data can contribute to such an understanding in several ways. For example, an ore-bearing vein occurring near several different possibly related plutons has been genetically related to one of the plutons, on the basis of horizontal gradients in inclusion temperatures rising toward that pluton (N. P. Ermakov, pers. commun., 1970).

A second example is found in a study by Piznyur (1957), who showed that the inclusion temperatures, pressures, and CO₂ contents were higher and densities lower in those veins in the Barsukchi quartz crystal deposit that were closest to the assumed granitic intrusive source. The temperature range was large, from 515°C in a vein near the intrusion to 80°C in one far away. The density difference was also reflected in the mode of homogenization—in the vapor phase for inclusions near the intrusion and in the...
liquid phase at some distance. Secondary inclusions in the adjacent wall rock for the veins had homogenization temperatures 27° to 52°C lower than those in the vein itself.

Another example of the value of "mapping" fluid inclusion data is shown in Figure 1, from the early work of Laz'ko (1957). With this map of fluid inclusion data in the Kurumkan quartz crystal deposit, he showed that the large Archean pegmatite bodies to the north could be excluded as the source of the quartz vein fluids, and that, instead, they seem to be related to the Proterozoic granodiorite intrusions to the south. This conclusion was based on the distribution of inclusions with low, medium, and high homogenization temperatures. These range from a minimum of 110°C to a maximum of 400°C.

Any parameter that could indicate which of several intrusives is most likely to have ore deposits associated with it would be useful. For example, Stollery et al. (1971) suggested on the basis of studies at the Providencia stock, in Mexico, that high chlorine contents in intrusives may correlate with ore formation and hence provide a possible prospecting tool. They showed that, at Providencia, this chlorine is present in biotite and as highly saline fluid inclusions in various minerals. Haynes and Clark (1972a) developed a rapid technique, based on ion-selective electrodes, for analysis of chlorine and for fluorine and tested it on biotite and whole rocks in a series of intrusives in Chile (Haynes and Clark, 1972b). A somewhat similar procedure, measuring water-soluble Cl and F, was tested on a series of granodioritic rocks from Central America (Kesler et al., 1973; Van Loon et al., 1973). Although hydrothermal or deuteric biotites from ore deposits were high in halogens, these studies found no simple relation between either of these elements and copper mineralization. Haynes and Clark (1972b) did find a high whole-rock Cl content in intrusives within a regional zone of metasomatic iron deposits. Recent studies on the halogen content of apatites show promise as an indicator of the Cl/Cl⁻ ratios in granitic magmas (Roegge et al., 1974).

It is apparent, however, that neither leachable nor total chlorine (or fluorine) is necessarily a good measure of the halite content of the inclusion fluid, since both of these will be influenced by exchange with later hydrothermal fluids (this is particularly true for biotite), by ground-water leaching, by contamination from airborne salt, and most importantly, by the volume of saline fluid inclusions opened in the analysis. Optical estimates of the actual salinity of individual inclusions present, regardless of their abundance (even though only semiquantitative), should provide a much more accurate and valid proof of the former presence of a saline-rich fluid and hence of the possibility of ore deposits formed by such fluids.

In this connection, Ishihara and Terashima (1974) have shown that granitic rocks related to kuroko-type mineralization have NaCl crystals in their fluid inclusions and high total Cl (~800 ppm), whereas lava dome rhyolites have low chlorine.

Many studies of individual veins have shown horizontal temperature gradients that presumably indicate source regions and at least some horizontal component of fluid flow. Thus, Lyakhov (1968) found a horizontal gradient of 3° to 7°C/100 m along the strike of a vein in the Baley ore field in Eastern Transbaikal.

In a structurally complex area, cut by many generations of barren quartz veins, differences in the composition or temperature of the inclusions from the several generations of quartz-precipitating solutions may provide a clarifying chronology (e.g., Sharonov, Kozlov, and Nikitin, 1973). Another related aspect is the recognition of ore-stage veins among numerous other similar veins that are from barren generations. Thus, Ermakov (1972) was able to show that the ratio between the decrepitation activity at two different temperatures was very different in ore-rich and ore-poor veins in the Sadonskoye polymetallic vein deposit. Similarly, Scott and O' Connor (1971) found homogenization temperatures of 165° to 250°C in gangue minerals from the ore veins at Cobalt, Ontario, but Taylor (1970) found that inclusions in barren cross veins in this same deposit homogenized at only 40° to 120°C.

The search during World War II for radiograde quartz (i.e., for piezoelectric uses) in the USSR spurred many studies of the fluid inclusions in quartz crystal veins and their country rocks, several of which indicate significant differences in the inclusions between those veins that have productive “nests” of high-grade crystals and those that produce only poor crystals. The differences found were based on either decrepitation temperatures or composition (e.g., Anufriev, 1968; Anufriev et al., 1971). Although the empirical data derived in these studies may be directly applicable only in those specific deposits, the principle should be applicable in any deposit. In all probability there were differences between the fluids that formed a barren (or ore-poor) vein and those that formed a rich vein in any given metalliferous district. Inclusions of these two fluids should differ in one or more parameters, and intuitively one would expect that these differences might even be larger than those between the two types of quartz veins described above.

Similar studies of various districts show differences between gold-bearing and the all-too-frequent barren quartz veins. In contrast to the barren quartz veins, the gold-bearing ones (in the various deposits) had
multiphase inclusions (Davidenko and Valpeter, 1969), had CO₂ in the inclusions (Boyer et al., 1967; Machairas, 1970), had inclusions with a lower molar ratio H₂O/CO₂ (Vertushkov, 1968; Vertushkov and Emlin, 1968), or had more inclusions per volume of sample (i.e., greater weight loss on heating) and higher decrepitation temperatures (Ryabova, 1973). In contrast to the last item, Nash (1972) noted that fluid inclusions from nine gold districts in Nevada had a wide range of homogenization temperatures (200°-330°C), suggesting that temperature was not a prime factor in the formation of these deposits; he found the fluids to be characteristically low in salinity. In a related study Ritter (1973) recognized a correlation between gold values and certain trace elements in gold quartz veins, which he believes are partly present in the secondary fluid inclusions. Even within the ore stage, however, at every deposit where the inclusion host minerals were characterized as to their positions in a zoning and/or paragenetic sequence (i.e., spatially and/or chronologically), there are readily recognized correlations between the inclusion data and the positions in the sequence. In most examples, temperature and salinity drop with both time and distance, but there are exceptions. Good examples of major changes in the fluids with time during the ore stage, all from the literature for 1974 alone, are found at Panasqueira, Portugal (Kelly), Tui mine, New Zealand (Robinson), Pasto Buena, Peru (Landis and Rye), Casapalca, Peru (Rye and Sawkins), and Limousin and Forez uranium deposits, France (Poty et al.). Significant variations are evident as a “fine structure” even within what might normally be termed a single short stage of ore deposition (see discussion of Creede, Colorado, beyond). All these variations are trying to tell us important things about the formation of the deposit, and even though we are far from understanding this wealth of data that nature has provided us, these variations can be put to empirical but practical use in many ways in exploration by helping to clarify the chronology of events in a complex district, including structural, mineralization, alteration, etc.

One seemingly rather obvious but apparently seldom-used application of fluid inclusions lies in the recognition of age relationships of intersecting dikes and veins. Although these relative ages may be important in unravelling a complex structural picture, they may not be obvious in the field or mine due to later shearing and alteration. Even without such later effects, the macroscopic and mineralogical effects of a dike on a quartz vein would be minimal, and hence the age relations unknown unless the actual intersection is exposed. However, such dikes may cause decrepitation of inclusions in the quartz vein. Such natural decrepitation of the fluid inclusions in quartz veins due to the heat of later dikes, as evidenced by empty inclusions or greatly diminished decrepitation of samples near the dike, has been recognized and could provide a relatively unambiguous assignment of relative ages (Lokerman, 1962, 1965); similar findings are reported by Prokhorov et al. (1968) and by Korobeynikov and Matsushesvskiy (1973).

Applications of Inclusion Data in the Search for Blind Orebodies

Since orebodies are actually rather small features, geologically, many exploration techniques are based on attempts to recognize the existence of some halo or anomaly around them that is larger than the orebody itself, thus improving the chances of finding it. This is particularly important in blind orebodies. As was first detailed by Ernakov (1966), fluid inclusions provide such halos.

The hot fluids that have formed many ore deposits heat the surrounding wall rocks and penetrate them, either by mass flow or through diffusion, causing various mineralogical changes. The resultant wallrock alteration halo obviously presents a larger exploration target than the orebody itself. During this alteration process, however, the fluid in the pores of the wall rocks is also being changed chemically and eventually may approach or actually reach equilibrium with the wall-rock minerals. Any additional movement of this fluid (or diffusion of its constituent ions or heat) further into the wall rock may not cause visible alteration, but such changed fluids can be found there as inclusions trapped during recrystallization of the wall-rock minerals, or more commonly as secondary inclusions from healing of fractures. Recognition of such new inclusions by the measurement of any appropriate parameter may thus provide an even larger target for exploration than the alteration. Thirty papers, almost all Russian, that deal with such data are summarized in Table 1. Of course, it must be kept in mind that the halos defined by fluid inclusion data are thermal (or chemical) anomalies that do not necessarily reflect the presence of an ore fluid. Thus fluid inclusions have been formed in geothermal fields and provide useful information on the previous history (Browne et al., 1974) as well as permit the recognition of fossil geothermal areas (Touray, 1973).

The most commonly used parameter for recognizing halos is the temperature of decrepitation (or homogenization) of the inclusions, as the new inclusions generally have been formed at higher temperatures toward ore. These inclusion zones are sometimes termed “steam bath,” “steaming-through,” or “streaming-through” halos, or “aureoles of evapora-
tion” in the Russian literature, and are reported to be recognizable tens or hundreds of meters from ore (Table 1). Fortunately, there is little need for the accuracy afforded by the normal optical determination of the homogenization temperatures, and hence relative parameters, obtained quickly by the decrepitation method, may be adequate, as long as all the limitations of such data are kept in mind. The leading Soviet figure in the use of fluid inclusion techniques, mainly decrepitation, in the search for blind orebodies is Prof. N. P. Ermakov of the University of Moscow. In an address in 1954 (Ermakov, 1957, p. 558) he briefly summarized the use of decrepitation in prospecting for various types of deposits. This was expanded in a later paper (Ermakov, 1966).

A few examples of halos from decrepitation data from Table 1 are illustrated in Figures 2 through 5. The first (Fig. 2) shows decrepitation activity for 10 meters away from the vein along a drift in a bismuth deposit in Uzbekistan, and Figure 3 shows a similar increase toward a skarn deposit in Kazakhstan. Figure 4 shows an increase in decrepitation activity for 80 meters toward a crystal-bearing stockwork in Kazakhstan, along the traverse indicated. Figure 5 presents a map of the total decrepitation activity in the granite surrounding a chambered pegmatite. This correlated best with the outcrop of the pegmatite.

Some of the possible hazards in the interpretation of such decrepitation data are indicated in Table 1. Thus it would be good to have some independent source of evidence that the several reversals noted there (i.e., decreases in decrepitation temperature or activity toward ore) were actually due to later leaching, shearing, recrystallization, or dikes, since many other ad hoc explanations could be suggested. Similarly, it would be good to verify that decrepitation activity anomalies do not occur in unmineralized rocks. Only rarely is such a clear statement made to this effect (e.g., Korubeynikov and Matsyushevskiy, 1973), although such verification may be commonly obtained. Also, in view of the charges that have been made in the past of subjectivity in the interpretation of decrepigraphs, it is unfortunate to find that the supporting data and even basic details on the procedures used in data acquisition and reduction are frequently missing, so a real evaluation of the work is simply not possible.
| Table I. Changes in Fluid Inclusion Data with Horizontal Distance from Apparent Source of Fluids (vein or orebody). Such changes might well provide a larger exploration target. |
|---|---|---|
| Type of data obtained | Changes noted toward source | Reference |
| **Fluorite deposits** | | |
| Agata fluorite dep., USSR | Decrep. activ. | Recognizable increase at 30–40 m from 10–15 m thick orebody; 4–6 m from 0.5 m orebody. Anomalies larger and more pronounced in footwall than in hanging wall. | Polykovskiy, Kolibaeva, and Ermakov, 1968 (see also Ermakov and Gromov, 1971) |
| Besh-Bulak fluorite dep., Central Asia | Decrep. activ. | Increases greatly toward veins, from 17 m distance. | Ermakov, 1966 |
| Unnamed fluorite deps., USSR | Decrep. activ. | Increases following asymmetric log normal distribution toward ore. | Babaev et al., 1970 |
| Takob fluorite dep., USSR | Decrep. activ. of granite | Increases from 50 m toward a 1.5 m ore vein. | Ermakov, 1966 |
| **Polymetallic deposits** | | |
| Rudni Altai polymet. deps. (Tyshinski, Starkovski, and Strejchanski) | Decrep. activ., decrep. temp., and homog. temp. | All increase toward ore; halo exceeds 7–8 times width of ore in all three orebodies; width varies with CR porosity. | Demin, 1970 |
| Sadonsk polymet. veins, USSR | Decrep. activ. of CR | Decrease immediately adjacent to vein (from later leaching). | Ermakov, 1972 |
| Sadonsk polymet. veins, USSR | Decrep. temp. of ore fluids (calculated) | Increase 25–60°C to ore. Increase from 140 to 210 atm near ore. | Kuznetsov, 1968 |
| Tishinskoe polymet. dep., USSR | Temp. beginning of decrep. of pyrite | Decreases toward orebody. | Avdonin and Kel’kh, 1973 |

| | Homog. temp. of inclusions in quartz of granite CR | Increase systematically from ~200°C at 300 m from ore to 300–315°C at ore (temps. in ore = 25–40°C higher). | |
| | Decrep. activ. of sized quartz separated from granite CR | Increases from ~16–30 impulses/2g at 250 m to 475 at ore. | |
| | Decrep. temp. (max.) of same samples | Increases from ~225°C at 300 m to 350–400°C at ore. | |
| | Abund. of DM and CO₂ | Increase toward ore for 100 m. | |
| | Weight loss of quartz on heating | Increases from 0.02% at 300 m to 0.23% at 1 m from ore. | |
| | Avg. salinity (from freezing temps.) | Increases from 200 m toward ore. | |
| | Pressure of ore fluids (calculated) | Increases from 110–140 atm at 200 m to 210–220 atm. near ore. | |
### Table I—(Continued)

<table>
<thead>
<tr>
<th>Pegmatites</th>
<th>Type of data obtained</th>
<th>Changes noted toward source</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>Unspecified chambered pegmatite, USSR</td>
<td>Decrep. activ. of granite CR</td>
<td>Increases for 5–10 m toward pegmatite.</td>
<td>Ermakov, 1968, p. 196 (see Fig. 5)</td>
</tr>
<tr>
<td>Volynian pegmatites, USSR</td>
<td>Decrep. activ. of granite CR in specified temp. ranges</td>
<td>Increases for 7–25 m toward pegmatite; some have inner zone of decreased activ.</td>
<td>Myaz' and Kornilov, 1973</td>
</tr>
<tr>
<td>Mama mica pegmatites, USSR</td>
<td>Decrep. activ.</td>
<td>Halo of increased activity 10–40 m wide around mica-bearing pegmatites.</td>
<td>Zorin et al., 1973</td>
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<tr>
<td><strong>Porphyry copper deposits</strong></td>
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<tr>
<td>Copper Canyon porphyry copper dep.</td>
<td>Visual estim. of abun. of incs. with halite DM</td>
<td>Recognizable increase toward core of deposit (&lt; 2500 m) and toward source fractures. High-salinity incs. occur in zone up to 2 km from ore.</td>
<td>Nash and Theodore, 1971, and Theodore and Nash, 1973 (see Fig. 2)</td>
</tr>
<tr>
<td>Bingham, Utah porphyry copper dep.</td>
<td>Visual estimates of salinity based on freq. of occurrence of DM halite</td>
<td>Relative abundance of high-salinity incs. increases toward Cu-Mo core of deposit.</td>
<td>Moore and Nash, 1974 (see Fig. 6)</td>
</tr>
<tr>
<td>Sapo Alegre porphyry Cu prospect, Puerto Rico</td>
<td>Visual estim. of abun. of incs. with halite DM</td>
<td>Recognizable increase from 95 m from vein zone.</td>
<td>Cox et al. 1975</td>
</tr>
<tr>
<td>Bingham, Utah porphyry copper dep.</td>
<td>Occurrence of DM, particularly halite (visual), and occurrence of gas-rich incs. (visual)</td>
<td>Both increase toward Cu-Mo core; neither are found in Pb-Zn periphery.</td>
<td>Roedder, 1971</td>
</tr>
<tr>
<td></td>
<td>Temp. of homog.</td>
<td>Increases dramatically, from 294–330°C in Pb-Zn depts. of periphery to &gt;400 (as much as 725°C) in the Cu-Mo core.</td>
<td></td>
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<tr>
<td><strong>Quartz crystal deposits</strong></td>
<td>Decrep. activ.</td>
<td>Increases for 80 m toward ore.</td>
<td>Ermakov and Gromov, 1971, p. 132 (see Fig. 4)</td>
</tr>
<tr>
<td>Kalmy-Kyrgyz quartz crystal-bearing stockwork, central Kazakhstan</td>
<td>Conc. soluble salts and % Na</td>
<td>Both increase toward economic &quot;nests.&quot;</td>
<td>Anufriyev, 1968</td>
</tr>
<tr>
<td>Southern Ural quartz crystal depts.</td>
<td>Decrep. activ.</td>
<td>Increases from 2–3 times background at 11 m from vein to 10 times background at 3.5 m from vein (when vein is at angle to bedding of CR).</td>
<td>Polykovskiy, Merkulov, and Boshko, 1968</td>
</tr>
<tr>
<td>Pamir quartz crystal vein, USSR</td>
<td>Decrep. activ. at 120–300°C</td>
<td>Increases toward vein, then decreases at 25–30 m.</td>
<td>Ermakov and Lapshin, 1973</td>
</tr>
<tr>
<td></td>
<td>Decrep. activ. at 300–480°C</td>
<td>Increases toward vein suddenly at 25–30 m; up to 20X background at vein.</td>
<td></td>
</tr>
<tr>
<td>Yakutia quartz crystal dep.</td>
<td>Decrep. temp. gradient</td>
<td>Increases 1°C/m &quot;along&quot; dip.</td>
<td>Koplus and Kudakova, 1968</td>
</tr>
<tr>
<td>Unnamed quartz crystal dep., USSR</td>
<td>H₂O/CO₂ ratio</td>
<td>Decreases toward economic &quot;nests.&quot;</td>
<td>Anufriyev et al., 1973</td>
</tr>
<tr>
<td>Type of data obtained</td>
<td>Changes noted toward source</td>
<td>Reference</td>
<td></td>
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<tr>
<td>-----------------------</td>
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<tr>
<td>Miscellaneous mineral deposits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unnamed alkaline metasomatite, USSR</td>
<td>Decrep. activ.</td>
<td>Increase toward metasomatite.</td>
<td>Goleva and Mel'nikov, 1972</td>
</tr>
<tr>
<td>Ken-Kol lead-zinc dep., USSR</td>
<td>Decrep. activ. of granite core samples</td>
<td>Increases greatly toward blind ore dep. from 60 m distance.</td>
<td>Ermakov, 1966</td>
</tr>
<tr>
<td>Chorukh-Raydon skarn ore district, USSR</td>
<td>Decrep. temp.</td>
<td>Increases toward ore.</td>
<td>Zlenko and Mamontov, 1973</td>
</tr>
<tr>
<td>Slushty skarn deposit, central Kazakhstan</td>
<td>Decrep. activ.</td>
<td>Increases for 6 m toward ore.</td>
<td>Ermakov and Gromov, 1971, p. 136 (see Fig. 3)</td>
</tr>
<tr>
<td>Boordinsko and Ishmetausko Sb-Hg ore districts, USSR</td>
<td>Decrep. activ. of sandy CR</td>
<td>Increases toward ore then decreases near ore.</td>
<td>Kornev and Myaz', 1973</td>
</tr>
<tr>
<td>Symapskoe Hg district, USSR</td>
<td>Decrep. activ. of carbonate CR</td>
<td>Increases toward ore from 0-25 imp. to 35-400 imp. in 15-20 m.</td>
<td>Korobeynikov and Matsyushevsksiy, 1973</td>
</tr>
<tr>
<td>Unnamed Au dep. in Siberia and Far East, USSR</td>
<td>Decrep. activ.</td>
<td>Abrupt increase (10-70 X background) near ore; activity correlates with Au concentration.</td>
<td>Korobeynikov and Matsyushevsksiy, 1973</td>
</tr>
<tr>
<td>Deputatsko Sn dep., USSR</td>
<td>Decrep. activ.</td>
<td>Decreases sharply within 0.5-1.2 m of later dike.</td>
<td>Lir et al., 1973</td>
</tr>
<tr>
<td>Amur quartz-tourmaline Sn dep., USSR</td>
<td></td>
<td>Higher for orebodies closer to parent granite.</td>
<td>Ryabov et al. 1968</td>
</tr>
<tr>
<td>Cornish Sn-W-Cu dep., England</td>
<td>Homog. temp. of incs. in cassiterite</td>
<td>Strong increase from weakly sericitized wall rock to strongly sericitized to ore.</td>
<td>Bradshaw and Stoyell, 1968</td>
</tr>
<tr>
<td>Unidentified Sn-W dep., USSR</td>
<td>Decrep. activ.</td>
<td>Rise of ~33°/km toward each “emanative center.”</td>
<td>Baybulatov et al., 1973</td>
</tr>
<tr>
<td>Unidentified volcanogenic ore vein, USSR</td>
<td>Homog. (?) of inclusions in greisens</td>
<td>Vertical gradients found adjacent to granite-greisen contact.</td>
<td>Goncharov et al., 1973</td>
</tr>
<tr>
<td>Bom-Gorkhon ore field, Transbaikalia</td>
<td>Decrep. activ.</td>
<td>Decreased toward ore, due to recrystallization near vein.</td>
<td>Mel'nikov and Polanski, 1974</td>
</tr>
<tr>
<td>Unnamed Bi dep. in Uzbekistan, USSR</td>
<td>Decrep. activ. and temp. of maximum decrep.</td>
<td>Increase toward ore.</td>
<td>Losev and Lyashenko, 1973</td>
</tr>
<tr>
<td>Brichmull bismuth dep., Uzbekistan</td>
<td>Decrep. activ.</td>
<td>Decreases toward (later) shear zones.</td>
<td>Polykovskii, 1971 (see Fig. 2)</td>
</tr>
</tbody>
</table>

Abbreviations: abun. = abundance, activ. = activity, avg. = average, CR = country rock, decrep. = decrepitation, DM = daughter minerals, dep. = deposit, estim. = estimate, freq. = frequency, homog. = homogenization, imp. = impulses, incs. = inclusions, polymet. = polymetallic, temp. = temperature.

Note: Many specific items of data are in part missing in this table, such as the type or locality of a deposit, the scale of the features observed, the details on procedures used, etc. Some of these omissions stem from unavailability of complete translations, and others are the result of the data not being present in the quoted paper.

In addition to the recognition of thermal gradients, several authors (e.g., Ermakov and Kuykin, 1973; Zlenko and Mamontov, 1973) have reported good correlations between mapped geochemical anomalies and mapped decrepitation anomalies, and, in view of the obvious lateral changes in both composition and filling densities of fluid inclusions in some deposits, particularly porphyry copper deposits, it is reasonable to expect at least some differences in the decrepitation behavior. However, at Bingham, Utah, for
example, there is a very large difference in the salinity from the periphery to the core (0–5 to >60 weight percent salts; Roedder, 1971). As a result the pressures developed in inclusions from the core at any given temperature would be drastically less than those developed in inclusions from the periphery, even at the same degree of fill. Hence the relationships between decrepitation activity, decrepitation temperature, and homogenization temperature may be complex. It may be well that decrepitation can only be used as a guide to local exploration in such deposits after the general geological (and inclusion) features are known, permitting in effect a locally valid "calibration" of the significance of each type of decrepigram for that deposit.

In addition to homogenization temperatures and decrepitation activity and temperatures, other inclusion parameters can be expected to change on approaching ore, although these may differ from one ore deposit to another. Examples include the total concentration of salts in the inclusions, the abundance of halite daughter crystals and gas-rich inclusions, particularly toward several porphyry copper deposits (e.g., Roedder, 1971; Theodore and Nash, 1973; Moore and Nash, 1974; Cox et al., 1975); the ratio of Na to other ions in analyses of inclusions; the sample weight loss on heating; the sample H₂O content; and visual estimates of the number of inclusions. Details on these and other examples from the literature are summarized in Table 1.

Since the main anion in fluid inclusions is almost always Cl, the amount of water-leachable Cl should also increase toward ore, particularly in typical porphyry copper deposits. To my knowledge this has not been tested, but, as in the evaluation of various plutons as ore bearers on the basis of water-leachable chlorine described earlier, optical detection of the presence of even a few highly saline inclusions would be much less ambiguous.

Applications of Inclusion Data to the Evaluation of Altered or Weathered Material in Outcrop or Sediments

On weathering of ore deposits, resistant gangue minerals such as quartz will be found to persist into the gossan or soil with their original fluid inclusions unchanged; in fact there have been many studies in which the fluid inclusions in detrital quartz grains in sandstones were used to determine the provenance of the host grains (see indices in Roedder, 1968 onward) and even to correlate quartzites in iron-formations (Gusel’nikov and Volkov, 1973) or productive horizons in oil well sections, by decrepitation of inclusions in sand grains (Schepetkin et al., 1973). The first use of soils over blind orebodies is reported by Ermakov (1957). Several later Russian papers report success in the use of the decrepitation method on gangue minerals, such as quartz panned from steam sediments, to recognize the presence of particular kinds of inclusions indicative of ore in the water-
shed (see also Demin et al., 1973). The technique is identical to that used to pinpoint geochemical anomalies by working upstream. The presence of decrepitation activity in soils in the interval 300° to 480°C was used to delineate a 300-meter anomaly over quartz crystal veins in the Upper Aldan (Ermakov and Lapshin, 1973).

It should be possible to identify optically the presence of the more unusual “boiling” or polyphase inclusions typical of some ore deposits in quartz grains in stream sediments, even after all ore minerals are long gone. Such optical investigations are also helpful in evaluating soils, leached cap rocks, and gossans to determine the probable nature of the pre-existing (and buried) ore. Acid-insoluble residues are particularly helpful here, as they greatly concentrate the useful part of the sample. Thus I have found that the inclusions in a few percent of insoluble residues from acid leaching of some replacement manganese ores permitted identification of the nature of the material that had been replaced. Similarly, it is not uncommon to find that some silicate melt (glass) inclusions may persist uncharged in quartz from igneous rocks long after complete hydrothermal sericitic or argillic alteration has eliminated all other evidence as to the nature of the original rocks. Such procedures have been used to recognize the source of quartz grains in laterites (Clochiatte and Mervoyer, 1974). Studies of the inclusions present in the ore pebbles and boulders found in glaciated terraines should also help in delineating the nature of the target orebody outcrop upstream. In view of the usefulness of inclusions in sediment provenance, it would seem very appropriate at this time to attempt such a study to help clarify the origin of the rather enigmatic early quartz cobbles making up the Witwatersrand and similar conglomerates.

Applications of Inclusion Data toward an Understanding of the Environment of Ore Deposition

Prof. W. C. Kelly of the University of Michigan summed up this aspect of the use of fluid inclusions in mineral exploration in a recent letter to me as follows:

The greatest contribution of fluid inclusions lies in the subtle but pervasive impact they have had on the basic philosophy of explorationists. The most effective exploration geologists I know operate with “models” (whether they call them that or not), entering any new terrane with established models in mind, and sniffing out those bits of ground that show the critical ingredients symptomatic of model ground that has paid off elsewhere. To the extent that fluid inclusions have served to refine those mental models, they have honed the basic skills and mental outlook of the explorationist. It is here that they have had their greatest impact.

Dr. S. R. Wallace, in his Jackling Award address (1974), also strongly emphasized the need for a valid geologic model in mineral exploration. So now let us look at some examples of the use of fluid inclusion data in establishing presumably valid models for ore deposition.

Mississippi Valley-type stratiform deposits

One of the most obvious examples is provided by the broad and important group of Mississippi Valley-type stratiform lead-zinc-fluorite deposits. Classification of the origin of such deposits on the basis of fluid inclusion evidence of the pressure, temperature, and composition of the ore fluids may seem to be an academic pursuit that will hardly be expected to “put rock in the box.” However, the model that is used for the origin of the deposit, as indicated by this classification, has considerable significance to exploration by directing the effort to one or more geological environments, and by eliminating others from consideration.

Fluid inclusion data can be invoked in the arguments for an epigenetic vs a syngenic origin for these deposits. If they formed from surface waters in a karst or paleokarst environment, as some have proposed, the primary fluid inclusions in ore minerals from them should be filled with essentially fresh water and should homogenize at near-surface temperatures, as in some barite deposits. If, instead, they formed by sedimentation from sea water in shallow lagoons, as others have proposed, the fluids should resemble sea water and homogenize in the 25° to 50°C range. However, to my knowledge, all such deposits that have been examined for fluid inclusions have shown dense, very saline brines, much more concentrated than sea water, and have average homogenization temperatures ranging from a minimum of 75°C (Pine Point; Roedder, 1968) to a maximum near 200°C in several deposits (Roedder, 1976a). The combination of salinity and homogenization temperature, and other inclusion data, effectively preclude both the fresh-water karst and the sea-water lagoonal environments of origin and hence invalidate any exploration concepts based on them. Even if evaporites or sabkha-type environments are invoked for obtaining the brines under near-surface conditions, the temperatures remain prohibitive. Instead, the inclusion data seem to suggest an origin based on deep circulating connate brines, with possibly some magmatic component, as suggested by Hall and Friedman (1963).
The inclusions also tell us that the ore-forming fluids had densities greater than 1.0 at the temperature of formation. These densities place important constraints on the paleohydrology at the time of ore formation. Since the times involved are almost certainly long, even small density differences can drive fluids long distances through rocks of average permeability. Note, however, that any ore fluid in a hydraulic gradient will obviously follow the most permeable paths, so ore deposition is automatically related to various sedimentary or structural features such as reefs, breccia zones, or paleokarst. These paths also provide the opportunity for the mixing of different fluids that has been proposed as one possible cause for the actual precipitation. An exploration program that concentrates on searching for permeable sedimentary features, on the basis of a syngeneic model for the origin of the ore, may thus be eminently successful even though basically wrong.

Some have tried to rationalize the inclusion evidence with a surface-temperature origin for stratiform deposits by assuming that the inclusions examined were trapped during recrystallization or re-mobilization of the originally syngeneic ores by later, hot saline fluids. Since all such deposits that have been studied by fluid inclusion techniques show inclusion evidence of hot, saline brines, and no low-salinity inclusions homogenizing at surface temperatures have been found, these facts require not only that recrystallization occurred at all deposits, but that all deposits were completely recrystallized. It seems to me to be stretching coincidence too far to accept this conclusion, particularly in the face of a complete lack of any other evidence of such movement and recrystallization in these deposits.

**Kuroko deposits**

This important group of deposits has been studied extensively, particularly by Japanese geologists, and several models proposed for their formation. Some have proposed the deposition of these ores from volcanic exhalations on the floor of shallow ocean lagoons, on the basis of field and textural data. However, fluid inclusion evidence from a series of Japanese papers on these deposits indicates an ore fluid that was relatively low in salinity (generally less than 5 weight percent) and hot (up to 300°C). These inclusion data have two important consequences. First, as pointed out recently by Ridge (1974), such ore fluids would boil instantly at or below the ocean floor unless the water was rather deep. This minimum depth is 400 feet for 200°C fluids, and 2,400 feet for 300°C fluids—hardly a shallow lagoon. More important, perhaps, is that these fluids have a much lower density than sea water, even without boiling, and hence if they came out at such depths, they would rise rapidly through the sea and mix with it. Although the details of the mixing are complex functions of salinity and temperature (Sato, 1972), such mixing could well result in precipitation of various metals on the sea floor and yield the field and textural evidence of sedimentary sulfo-silicates but could not yield the crystals of various gangue and ore minerals that contain the inclusions studied. These inclusions almost certainly could not have formed in a shallow lagoon, and hence it may be necessary to assume two quite different conditions of ore formation for different parts of these ores.

There is one additional line of evidence from fluid inclusions on the mode of formation of the kuroko deposits that should be mentioned, since it is also pertinent to many other types of deposits. This is provided by data on the isotopic composition of hydrogen and oxygen in the water of the inclusions. Studies of inclusions from the Hokuroku district show a predominantly sea-water origin for the fluids, with <25 percent magmatic and/or meteoric water mixed in (Ohmoto and Rye, 1974; see also Sakai and Matubuya, 1974). This is but one of many important studies of the isotopic composition of C, H, O, and S in fluid inclusions and their host minerals that have had far-reaching effects on the hydrologic models proposed. Two generalizations may be made from these various isotopic studies—the prevalence of the local surface waters (generally meteoric, but sea water in the presumably marine kuroko ores) over magmatic water in many deposits, and the evidence for mixing of waters from several sources in most deposits studied (e.g., from the 1974 literature alone: Hall et al.; Landis and Rye; O’Neil and Silberman; Rye and Kelly; Rye and Sawkins; Sawkins and Rye; Sheppard and Taylor; and Taylor).

**Porphyry copper deposits**

The porphyry copper deposits provide an excellent example of input from fluid inclusion studies into a model for ore deposition. My reconnaissance work on the Bingham district (1971) showed that samples from the Cu-Mo core of the deposit contained a very different suite of inclusions than was present in samples from the important Pb-Zn deposits that occur peripheral to the core, 1 to 2 km away. In the core samples there was extensive evidence of boiling, and there were many inclusions with such large amounts of daughter crystals that the originally homogeneous fluids must have contained >60 percent salts and <40 percent water. These yielded very high homogenization temperatures—up to 725°C. Neither of these features was evident in the peripheral deposits where salinities were much lower, no daughter crystals were found and the homogenization temperatures were only about 300°C. A map of the area of occurrence of
these high-salinity inclusions at Bingham (Fig. 6; Moore and Nash, 1974) showed that it coincides very well with the copper ore zone. Subsequent work by others has shown that most if not all porphyry copper deposits over the world show evidence of boiling and contain highly saline inclusions, formed at high temperatures. This includes such deposits as El Salvador in Chile (Gustafson and Hunt, 1975), Sar Chesmeh in Iran (Etminan, 1974), E. Koukrad, USSR (Ernakov and Piznyur, 1974), Middle Asia (Sotnikov et al., 1973), and a series of porphyry copper deposits in the western United States (Nash, 1971a; Nash and Cunningham, 1974; Denis, 1974). At Copper Canyon, Nevada, Theodore and Nash (1973) found a very large area of highly saline inclusions surrounding the two orebodies (Fig. 7). They also show that the occurrence of high-salinity inclusions correlates with a fracture system believed to be responsible for the introduction of the copper. A porphyry copper-molybdenum prospect in Puerto Rico also had strongly saline inclusions in the metal-bearing zone and much less saline fluids away from this zone (Cox et al., 1975).

Such data do not make the model, but they do place important constraints on any proposed version. Thus, if it is assumed that the salinity gradients represent dilution of a very hot, saline ore fluid in the core with presumably fresh, cooler ground water toward the periphery, there is a severe hydrologic problem. The saline fluids, with >60 percent salts and <40 percent H2O, even though very hot, had densities, at homogenization temperatures, as high as 1.30 g/cm³ (Roedder, 1971). The problem lies in how such a fluid can be held in the obviously permeable, fractured rocks of the core, since the surrounding rocks at some distance must have been saturated with cold ground water at a density of 1.0. Perhaps these hot fluids precipitated enough quartz on cooling (or anhydrite on heating) to be self-sealing and hence made their own impervious container. If so, this behavior adds a new and severely limiting parameter to the calculations of flow lines in hydrologic models (e.g., Cathles and Norton, 1974). In any case, if mixing with ground water took place, these densities must certainly control the direction of circulation. Such mixing should be corroborated by isotopic studies on the rocks, or preferably on the fluid inclusions themselves. These questions are begging for answers, and in view of the significance of this type of deposit, the answers could be economically significant.

**Thermal gradients**

Regardless of the type of deposit, fluid inclusion data can be useful in the recognition of lateral or vertical thermal gradients within the deposit at a given time during the ore deposition. These in turn may delineate the feeder channels and the directions of ore fluid movement. At Guanajuato, Mexico, thermal gradients, established by studies of fluid inclusions, were found to be useful in finding ore (Gross, 1975). Telescopied ore deposition and changes in the “plumbing” of the deposit with time make it imperative that all such temperature studies

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**Fig. 6.** Map showing the distribution of high-salinity fluid inclusions, copper ore, and bornite at Bingham (Moore and Nash, 1974, their fig. 6c).

**Fig. 7.** Geologic sketch map of the Copper Canyon area showing extent of halite-bearing fluid inclusions (Theodore and Nash, 1973, simplified from their fig. 1).
be combined with very detailed paragenetic studies on the ore. Lateral and vertical temperature gradients have been detected in those deposits where the density of sampling was adequate (e.g., Imai and Takenouchi, 1968; Imai et al., 1971; Boroo, 1967; Bogolepov and Bocharov, 1968; Koplus and Kudakova, 1968; Dzhafarov et al., 1968; Doroshenko, 1968; Nash, 1971b; Nash and Theodore, 1971; Ivasiv, 1973; Markova and Boyko, 1973; Phillips and Smith, 1974). Such gradients can be expected generally, and their significance as a prime cause for ore deposition has been discussed extensively.

If the salinity is uniform, vertical gradients in the homogenization temperature indicate density gradients and hence the direction of convective flow. The opposite situation, in which little or no change is seen in the homogenization temperature of the inclusions with depth, also places significant constraints on the thermal and hydrologic regimen at the time of trapping that may be important. Vertical changes in inclusions may also signify changes in ore type, or bottoming, that can be of great importance in development work.

In detailed studies of inclusion homogenization temperature gradients in Pb-Zn-Ba-CaF$_2$ veins of the North Pennine field in northern England, Smith and Phillips (1974) found lateral gradients of 0.04 to 0.2°C/m, depending upon the distance between vein intersections, the vein width, and the size of the vein intersection zone. Apparently the geometry of the vein intersections permitted longer flow times, higher flow velocities, or larger fluid/rock ratios, and hence gave slightly higher homogenization temperatures. Vertical gradients of 0.1°C/m were found at 500-m depth and 0.5°C/m near surface.

Laterally uniform homogenization temperatures over a large area imply a broad source for the fluids. Thus the absence of a strong thermal or salinity zonation in the inclusions at the Jamestown, Colorado, fluorite and gold deposits relative to an outcropping stock caused Nash and Cunningham (1973) to conclude that the fluids emanated from a larger intrusive body at depth. Since the times involved are large, very small density differences are potentially important in controlling circulation (Roedder, 1967, 1971). Unfortunately, however, both temperature and salinity have significant effects on natural fluid densities, so any “density mapping” (Lahiry, 1973) must be based on careful homogenization and freezing data.

$K/Na$ ratios

When the nature of the available samples permits it, determination of the Na/K ratio in the inclusion fluids is relatively easy and sometimes very useful in understanding the environment of ore deposition. This ratio is a sensitive indicator of the mineral assemblage with which the fluids have been in contact, and as shown by Orville (1963) for a given assemblage it is a function of the temperature of equilibration.

Boiling of the ore fluids

Another significant application of fluid inclusion data to exploration lies in the recognition of boiling of the ore fluids, through the presence of both vapor-rich and vapor-poor fluid inclusions. Because such boiling gives a measure of the maximum hydrostatic pressure at the site of ore deposition, it places limits on the depth of cover at the time, which can be also useful in exploration. In some types of deposits, the gross changes in ore fluid chemistry from boiling may be responsible for the deposition of bonanzas. A very extensive study of the fluid inclusions in the Bolivian tin deposits (Kelly and Turneaure, 1970) established that boiling had occurred in the tin stage. This boiling was given as the probable explanation of the very rich bonanza-type tin ore zones that are found in many of these veins. Similarly, studies of inclusions in the Colqui district in Peru have shown that the rich silver and gold deposition there occurred only where and when the ore fluids boiled (Kamilli, 1974, 1975).

A difficult but not insoluble problem in such studies is that of differentiating between normal boiling and the effervescence of dissolved gases; either may be pertinent to ore deposition, but the pressures involved may be quite different. Thus, in a still-continuing study of inclusions of the fluids forming the polymetallic deposit at Creede, Colorado (Roedder, 1960a), I found evidence of boiling of the solutions from depths at which a solution of the salinity and temperature found in the inclusions would be on the boiling curve. This is not a case of effervescence of dissolved gas in the fluids. When the “gas” inclusions are crushed on the crushing stage, they are found to contain almost no noncondensable gas (Roedder, 1970, p. 52). Thus they were originally filled with essentially pure steam and now contain a vacuum that fills with the surrounding oil on crushing. On the other hand, the saline fluids forming a mercury deposit in Alaska were found to have contained globules of a separate, immiscible CO$_2$ fluid, which on pressure release would have expanded (i.e., effervesced) to form large volumes of lower density gas (Roedder, 1963). Evidence of boiling (or effervescence) has been found in many ore deposits (see indices in Roedder, 1968-on) and should be looked for in all, since it has so many important consequences.

Evidence of boiling is particularly abundant in tin deposits. In this connection, gas-rich inclusions in
granitic bodies have been found to be concentrated toward the apices and cupolas, as expected (Rodzianko, 1973), and hence such concentrations might provide useful structural guides.

There is an extensive literature, particularly in Russian, on the use of fluid inclusions to characterize ore deposits as formed from pneumatolytic vs hydrothermal solutions. In general, the division is made on the basis of homogenization behavior (into the gas vs the liquid phase), and the tacit assumption behind this distinction is that this is a real boundary. If a plot of temperature vs density of solutions is examined (e.g., Roedder, 1972, fig. 4), it is readily apparent that such a division is an arbitrary line on a broad continuum of fluids of varying density. Perhaps the two terms are useful to distinguish ore deposits formed from very low density fluids (i.e., \( \leq 0.2 \) g·cm\(^{-3}\)) from those formed from dense fluids (i.e., \( \geq 0.6 \) g·cm\(^{-3}\)). But a large group of deposits (particularly pegmatitic) have formed from fluids of intermediate densities, and whether or not their inclusions homogenize in vapor or liquid may be a consequence of trivial differences in P and T at the time of trapping. In the case of boiling, however, the distinction between gas and liquid is real and important.

**Hydrologic regimen in epithermal deposits, as at Creede, Colorado**

The epithermal Pb-Zn-Ag-Cu deposit at Creede, Colorado, has been under investigation by a group of U. S. Geological Survey geologists for many years. As one facet of this study, fluid inclusions in these ores have been examined in some detail (Roedder, 1960a, 1965; Barton et al., 1977). The application of fluid inclusion data to an understanding of the formation of such epithermal deposits is epitomized in a study of inclusions in a single 5-cm group of zoned sphalerite crystals (Roedder, 1976b). My colleagues, P. B. Barton, Jr. and P. M. Bethke, have made extensive studies of sphalerite zoning and the paragenesis at Creede in many samples. They have established a detailed sphalerite “stratigraphy,” complete with leached zones as discontinuities, etc. There are 20 such recognizable “formations” in the 5-cm crystal studied, numbered 1 to 20 from core to rim. I selected an average of 11 inclusions from various points in each of the 20 zones and then ran both freezing and heating tests on all 221 inclusions. The runs, which were made as “blind” experiments by two operators over a six-month period, were not plotted up until all the data were complete. They revealed some unexpected features that place interesting constraints on the model of ore formation for this deposit that may be applicable elsewhere (Fig. 8). The most striking feature is that the data for all 221 inclusions fall in one or the other of the fields indicated. Thus, for example, 32 inclusions in zone 18 all had almost identical salinities and homogenization temperatures and hence all fell in one small area. There are a number of important conclusions to be drawn from these data, but for now I want to point out only the following four features: (1) The color zone changes exactly parallel the changes in the inclusion data, but there is no simple relation between color and the inclusion data. (2) The fluids were amazingly uniform throughout the deposition of any given zone. (3) The fluid changes between zones were exceedingly abrupt and in part rather drastic, e.g., from zone 14 to zone 15. (4) Actually this is a necessary corollary of the other three. There are no intermediate data points, either in homogenization or salinity.

It is difficult to visualize a geologically reasonable fluid mixing and circulation model that would yield all four of these features, even without including data from other sources, such as studies of the isotopes of hydrogen and sulfur, yet quite obviously nature has done it. My colleagues and I are still puzzled by several of the details of this model and would welcome ideas.

**Practical Problems**

Every exploration tool that is considered for any given application must be evaluated in terms of (1) the probability of usefulness of the data that might be obtained, (2) when, where, and at what scale should the tool be applied, and (3) the cost of these
data, in time and money. If the study of fluid inclusions is being considered as a possible tool, how should the individual exploration geologists (or company management) decide these questions? The first question must be decided on the basis of the available information on the ground involved, the nature of the possible targets, and the evidence in the literature (or company files) of previous success. The second aspect is a little more nebulous. Obviously there can be no set time in an exploration program when such an application would be fruitful. The most effective use of fluid inclusion data should always involve first a reconnaissance examination of a few samples to determine the general nature of the inclusions present. This stage may represent one of the most useful applications of inclusion study (e.g., if a drill core has intersected a vein of unknown affiliation). If this reconnaissance reveals the presence of inclusions that are physically suitable and potentially useful, that information has value in planning further work; if the inclusions are very poor or nonexistent, hope for possible use of the tool should not be given up completely since there may be gross differences in the suitability of even adjacent samples for inclusion studies. This inherent variability of sample material is an unfortunate fact of life and hence must always be kept in mind, and when reconnaissance samples are selected for inclusion work, they should, of course, be the optimum material that is available yet still applicable to the problem at hand. A series of practical tips on sample selection and preparation and on inclusion observation and study are given elsewhere (Roedder, 1976a) and need not be repeated here.

The cost of inclusion studies will vary widely with the nature of the specific work involved. Sample preparation for decrepitation studies in the field or laboratory can be set up on an assembly-line basis, similar to geochemical tests. Decrepitation requires equipment which, outside of the USSR, is usually homemade, and Ermankov (1966) reports handling 90 samples per working day for a field unit. Optical microscopy (except reconnaissance work) normally requires the preparation of doubly polished plates or thick sections, although ordinary petrographic thin sections are of some use. The single most important equipment cost, however, is the microscope. It would be shortsighted indeed to try to economize on the quality here since this is the major tool for all inclusion work.

Most chemical analyses of inclusion fluids require fairly extensive laboratory work, but a simple cleaning, crushing, and leaching (Roedder et al., 1963) will provide a solution adequate for analysis of the K/Na ratio by the conventional flame photometer present in many company laboratories. All samples should be checked with the microscope before attempting extraction and analysis of inclusion fluids to verify the presence of inclusions and the absence of possible contaminants. Inclusion constituents other than K and Na are generally present in quantities that are too small for analysis without special procedures. The various special methods mentioned, such as mass spectrometry (for gases or for isotopic ratios), electron microprobe, laser Raman spectroscopy, etc., generally require rather expensive instrumentation.

Heating stages can be inexpensive, homemade affairs, or can be purchased commercially for $1,000, but freezing stages are usually more expensive. Before any decision is made on such equipment, however, I would suggest that consultants be considered, at least to begin with. The main reason is that the equipment is not the only expense. Far more important in the long run is the time required to learn the techniques, to find suitable inclusions, and then to run them. Although the newly available commercial heating and freezing stages have greatly simplified the mechanical problems in making the runs, the total time involved can still be large, and much of it cannot be delegated to technicians. If preliminary work by an academic consultant (or his graduate students) shows that more extensive inclusion studies are desirable, then the decision can be made to dedicate manpower and money for equipment to establish inhouse expertise. In any case I personally believe that any exploration geologist that has access to a microscope would do well to learn at least to recognize the presence of fluid inclusions in his slides. Far too often I have found geologists who have used a microscope extensively but have "never seen a fluid inclusion," yet their slides were full of them.

Conclusions

The study of fluid inclusions provides a variety of potential aids to mineral exploration, only a few of which have been adequately investigated. They can be and in part have been helpful in clarification of various aspects of the regional or local geology of a district, in providing larger targets in the search for blind orebodies, in examining weathered or leached outcrops and soils from ore deposits, and in understanding the environment of ore deposition and hence in developing possible models of origin. Although many of the possibilities suggested have not, to my knowledge, been tested in the field, they should be. Others have been tested, but not necessarily under optimum conditions. Obviously the presence of usable fluid inclusions is a prerequisite, so these methods are either difficult or impossible to apply to
most fine-grained ores (e.g., White Pine) and many metamorphosed ones but there are many other areas where they may be applicable but have not been tried. Just as with any other exploration tool, even an occasional success can justify the effort. But one should always keep in mind that lots of ore has been found by wrong ideas and even wrong data, so 

Caveat emptor!

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