Fluid-Inclusion Petrology— Data from Porphyry Copper Deposits and Applications to Exploration
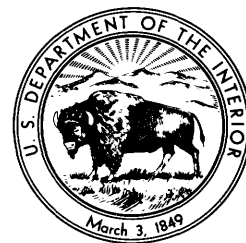
Fluid-Inclusion Petrology—

Data from Porphyry Copper

Deposits and Applications

to Exploration

By J. THOMAS NASH

GEOLOGY AND RESOURCES OF COPPER DEPOSITS

UNITED STATES DEPARTMENT OF THE INTERIOR

THOMAS S. KLEPPE, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

APPRAISAL OF MINERAL RESOURCES

Continuing appraisal of the mineral resources of the United States is conducted by the U.S. Geological Survey in accordance with the provisions of the Mining and Minerals Policy Act of 1970 (Public Law 91-631, Dec. 31, 1970). Total resources for purposes of these appraisal estimates include currently minable resources *(reserves)* as well as those resources not yet discovered or not currently profitable to mine.

The mining of mineral deposits, once discovered, depends on geologic, economic, and technologic factors; however, identification of many deposits yet to be discovered, owing to incomplete knowledge of their distribution in the Earth's crust, depends greatly on geologic availability and man's ingenuity. Consequently, appraisal of mineral resources results in approximations, subject to constant change as known deposits are depleted, new deposits are found, new extractive technology and uses are developed, and new geologic knowledge and theories indicate new areas favorable for exploration.

This Professional Paper discusses aspects of the geology of copper as a framework for appraising resources of this commodity in the light of today's technology, economics, and geologic knowledge.

Other Geological Survey publications relating to the appraisal of resources of specific mineral commodities include the following:

Professional Paper 820—"United States Mineral Resources"
Professional Paper 926—"Geology and Resources of Vanadium Deposits"
Professional Paper 933—"Geology and Resources of Fluorine in the United States"
Professional Paper 959—"Geology and Resources of Titanium in the United States"

CONTENTS

ILLUSTRATIONS

TABLE

SYSTEM OF MEASUREMENT UNITS

In this report both the English and the metric systems of units are used. English units are given first and the equivalent measurement in metric unit is given in parentheses. Abbreviations are noted below. The English units are converted to metric units by multiplying by the factors in the following list.

English unit		Metric unit
To convert	*Multiply by*	*To obtain*
Miles (mi)	1.609	Kilometres (km).
Feet (ft)	0.3048	Metre (m).
Inches (in.)	2.54×10^4	Micrometres (μm).
	25.4	Millimetres (mm).
Pounds per square inch (lb/in²).	0.608947	Bar.

The conversion from temperature in degrees Fahrenheit (°F) to temperature in degrees Celsius (°C) is expressed by: °C $= (^5/_9)$ (°F-32). The conversion from temperature in degrees Celsius to temperature in degrees Fahrenheit is expressed by: °F $= [(1.8 \times °C) + 32]$.

FLUID-INCLUSION PETROLOGY—DATA FROM PORPHYRY COPPER DEPOSITS AND APPLICATIONS TO EXPLORATION

By J. Thomas Nash

ABSTRACT

Fluid-inclusion studies of 37 porphyry copper deposits, mainly in the United States, demonstrate that all but 3 evolved through a hydrothermal stage characterized by very high salinities, generally in excess of about 35 weight percent NaCl equivalent. Temperatures of these fluids ranged from about 250° to 700°C for various stages and deposits. Most systems boiled. High salinities, shown by halite-bearing inclusions, and boiling, suggested by coexisting gas and liquid-rich inclusions, are considered to be diagnostic of epizonal intrusions which are the most favorable parents for porphyry copper mineralization. Depth of emplacement of many copper-bearing stocks is deduced from fluid inclusions to have been about 6,000 to 10,000 feet (1,800 to 3,000 metres); fluid pressures during mineralization are interpreted generally to be less than 500 bars.

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

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

INTRODUCTION

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

It should be emphasized at the outset that fluid inclusions are by no means rare or unusual in rocks and vein-forming minerals. The problem is knowing how to recognize them and interpret their significance. More than 50 years ago, petrographers commonly made reference to fluid inclusions and, in their early concepts of ore genesis, considered such inclusions to be evidence. One of the most astute observers was Lindgren, who devoted several pages to the description of fluid inclusions in the copper deposit at Morenci, Ariz. Part of his observations (Lindgren, 1905, pp. 213–214) are as follows:

> Fluid inclusions have been observed in the quartz grains of the granite, the quartzite, the porphyry, and the vein quartz occurring in this district. There is nothing uncommon in this; it is indeed the ordinary condition of affairs. As these fluid inclusions beyond doubt contain aqueous solutions, it may be regarded as certain that such fluids were present when the quartz grains in question were formed.

At present I know of fluid-inclusion data for 37 porphyry copper deposits (table 1) and for a number of prospect areas. Observations have been made by many people, but, for consistency, reliance will be placed mainly on my own studies (many of which were reconnaissance in nature) of 25 economic deposits. Figure 1 shows the location of 22 of the deposits in the South-

western United States. Discussion will focus on the general composition (salinity) of inclusions, especially where this may be estimated at room temperature from conventional thin sections. Although some geochemists have advocated the use of inclusion thermometry in ore exploration — (for example, Ermakov (1966) and Bradshaw and Stoyel (1968) — that parameter by itself does not appear reliable or discriminating as a guide to disseminated sulfide deposits of the porphyry copper type.

TABLE 1.—*Fluid-inclusion data for porphyry copper deposits*

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

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

[1] Reference: 1, Observed by J. T. Nash (this report); 2, Nash and Cunningham (1973); 3, D. P. Wheeler (written commun., 1973); 4, Roedder (1971); 5, Drake (1972); 6, Lindgren (1905); 7, Logsdon (1969); 8, J. D. Davis (written commun., 1973); 9, Nash and Theodore (1971); 10, Spencer (1917); 11, D. Norton (oral commun., 1971); 12, Moore and Nash (1974); 13, Meyer, Shea, Goddard, and others (1968); 14, Roberts (1973); 15, Gustafson nd Hunt (1975); 16, Sillitoe and Sawkins (1971); 17, T. G. Theodore (oral commun., 1974); 18, Observed by D. P. Cox and J. T. Nash; 19, Observed by R. G. Schmidt and J. T. Nash; 20, Bamford (1972); 21, A. R. Chivas and R. W. T. Wilkins (written commun., 1975).
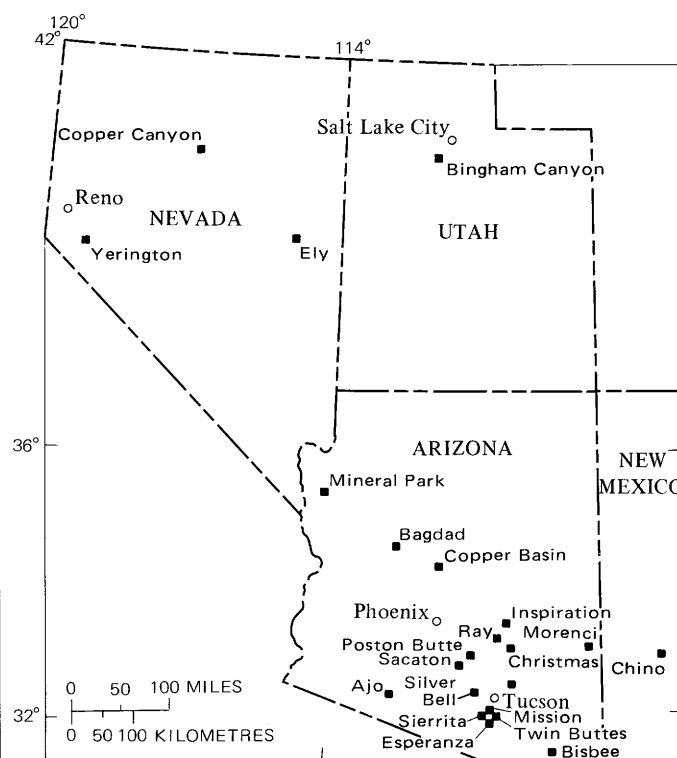
FIGURE 1.—Map of the Southwestern United States, showing locations (squares) of porphyry copper deposits whose fluid inclusions are described.

This paper presents a brief summary of fluid-inclusion observations from porphyry copper deposits, makes some inferences from the data, and suggests ways in which fluid inclusions can be used as a tool in exploration. This is clearly a "state of the art" report and reflects my current ideas. Hopefully, new data, refined concepts, and better applications will emerge from additional studies of these copper deposits. Qualitative features rather than quantitative numbers will be emphasized.

ACKNOWLEDGMENTS

TYPES OF FLUID INCLUSIONS

Fluid inclusions can be classified according to many schemes, from simple to complex. The classification

employed here is based on phase relations observable at room temperature, as in normal petrographic investigations. Additional discussion of fluid-inclusion classification is given by Kelly and Turneaure (1970) and Roedder (1971, 1972). Four general types are recognized.

TYPE I. MODERATE SALINITY

A common type of inclusion contains two fluid phases — a liquid and a small vapor bubble amounting to 10 to 40 percent of the volume of the inclusions (fig. 2–I, fig. 3). One or more birefringent daughter minerals[1] may be present. The volume of vapor is roughly proportional to temperature; calculated filling curves may be helpful in estimating temperature (Kalyuzhnyi, 1965), although consideration should be made of salinity. Tests on a freezing stage indicate a wide range of salinities from about 23 to nearly 0 weight percent NaCl equivalent. Freezing tests and chemical analyses of extracted fluids indicate sodium, potassium, calcium, and chlorine to be the major constituents (Roedder, 1972) in the aqueous phase. The vapor is mainly H_2O, but crushing tests indicate positive pressures attributable to CO_2 in some inclusions from porphyry copper deposits. More rigorous tests of vapor pressures and compositions are reported by Drake (1972), and Drake and Ypma (1969). Identification of daughter salts is generally difficult; birefringent crystals that are probably dawsonite $[NaAlCO_3(OH)_2]$, rhombohedral carbonate, and anhydrite are relatively common in these inclusions, and hematite is found in some. Also, there are several unidentified daughter salts.

Type I inclusions are ubiquitous in intrusive rocks, wallrocks, and veins of porphyry copper districts. In these rocks the presence of type I inclusions of many different ages along crisscrossing planes reflect introduction during repeated fracturing. Commonly, these inclusions are associated with propylitic or sericitic alteration, or with relatively late-stage ore veins, such as gold and pyrite at Copper Canyon, Nev. (Nash and Theodore, 1971); galena and sphalerite at Mineral Park, Ariz. (Drake, 1972; Nash and Cunningham, 1974); or fluorite at Ajo, Ariz., as observed by J. T. Nash. More important, however, is the association of moderate-salinity type I inclusions with chalcopyrite and molybdenite veins in many deposits, such as those at Bagdad, Esperanza, Morenci, and Ray, Ariz. The amount of copper associated with these inclusions appears to be highly variable in the many porphyry deposits studied.

TYPE II. GAS-RICH

These inclusions generally contain two fluid phases, liquid plus more than 60 percent vapor (fig. 2–II, fig. 4); a reddish or opaque hematite daughter mineral is com-

---

[1] Minerals precipitated from inclusion fluids during cooling.
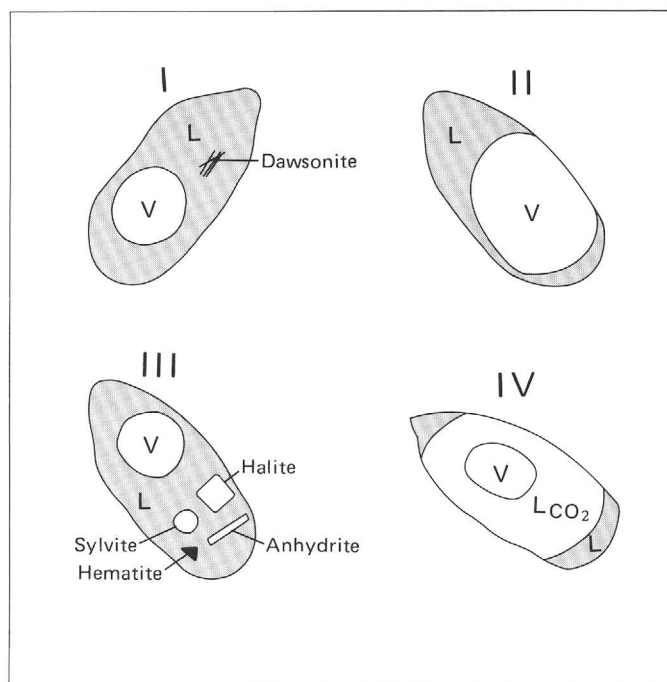
FIGURE 2.—Sketches of typical fluid inclusions obsderved in porphyry copper deposits. Types I to IV correspond to those described in text. L, liquid; V, vapor; LCO_2, liquid CO_2.
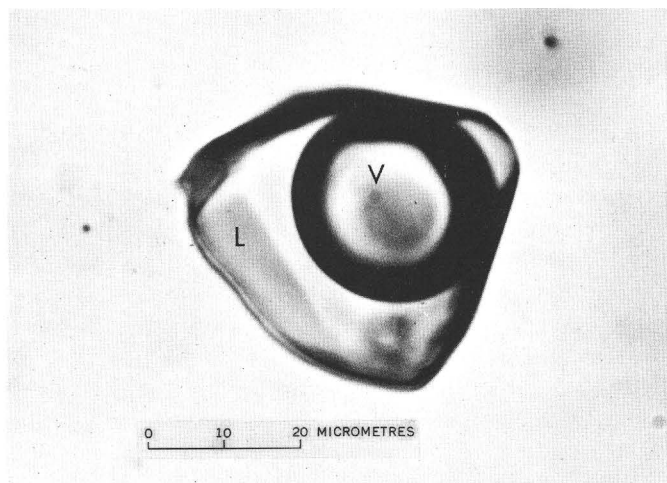
FIGURE 3.—Photomicrograph of type I inclusion in quartz-chalcopyrite vein, Copper Canyon, Nev. L, liquid; V, vapor bubble.

monly present. The liquid has salinities in the range 0.4 to 7 weight percent; the higher salinities are believed to reflect trapping of some high-salinity liquid with vapor (Nash and Theodore, 1971; Roedder, 1971). Crushing tests made by Roedder (1971) and by J. T. Nash commonly indicated positive pressures attributable to CO_2. The amount of CO_2 present probably ranges from traces in type II inclusions to more than 25 percent in type IV inclusions (CO_2-rich). The phase proportions and composition are as expected of trapped steam, and such an origin is consistent with their occurrence.

FIGURE 4.—Photomicrograph of type II inclusions in vein quartz, Copper Canyon, Nev. L, liquid; V, vapor.

The abundance of type II inclusions varies from deposit to deposit and from sample to sample. Some gas-rich inclusions are generally present in the igneous quartz of the porphyries and, in many samples, constitute 50 percent or more of the population. Quartz in some intrusives, notably the Mesozoic intrusives of British Columbia, does not contain gas-rich inclusions of any age. Many quartz veins contain moderate to large numbers of type II inclusions; others contain few or none. These observations will be considered further relative to evidence for boiling.

TYPE III.   HALITE-BEARING

Inclusions that contain well-formed, cubic halite, and generally several other daughter minerals (fig. 2–III, fig. 5) are characteristically observed in igneous quartz of the porphyries and in many quartz-sulfide veins. A second isotropic daughter mineral, sylvite, commonly is present; it has rounded edges, lower relief, and a higher thermal coefficient of solubility than halite. Hematite generally is present in type III inclusions; some is translucent red, and some is opaque, depending upon thickness, and may be anhedral or euhedral hexagonal or trigonal plates. A number of birefringent daughter minerals occur in these inclusions. One is rectangular, has parallel extinction, moderate relief, and is length slow in the position of minimum birefringence — it may be anhydrite (Nash and Theodore, 1971; Roedder, 1971). An equant, highly birefringent mineral probably is calcite. Others with vague optical properties cannot be identified at present. In heating tests halite and sylvite dissolve, yielding information on salinity (Roedder, 1971, p. 113–114). From the volume of NaCl and KCl present and from their behavior in heating tests, it is deduced that salinities commonly were near 40 percent and, at Bingham Canyon, were more than 50 percent (Roedder, 1971; Moore and Nash, 1974). Filling tem-

peratures range from about 225° to 725°C. Other daughter salts generally do not dissolve in 3 hours at the temperature of filling, indicating either disequilibrium or the effects of post-trapping changes, such as hydrogen diffusion
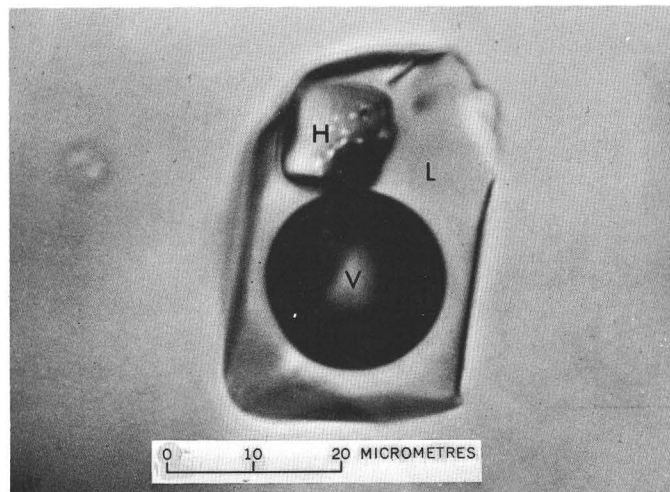
FIGURE 5.—Photomicrograph of type III inclusion in a quartz-chalcopyrite-molybdenite vein, Bingham Canyon, Utah. L, liquid; V, vapor; H, halite crystal.

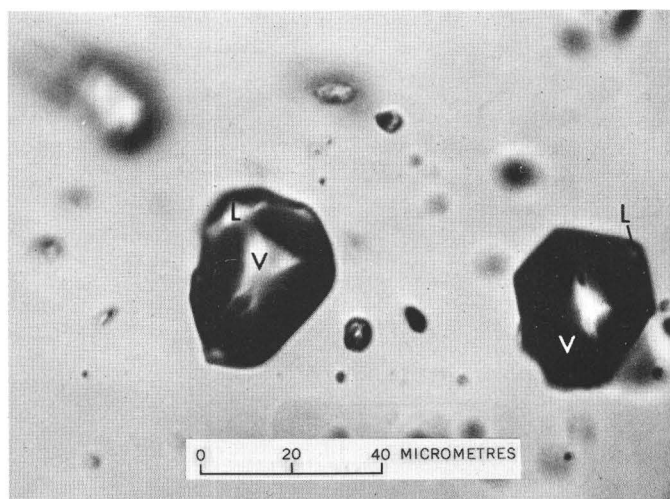Halite-bearing type III inclusions are noted in at least some samples from all but two porphyry copper districts. Halite-bearing inclusions have been noted in both mineralized and unmineralized stocks examined from the Basin and Range province; they occur in a high proportion of veins associated with them. Indeed, early petrographers noted that such inclusions were the "ordinary condition of affairs." However, not all plutonic rocks contain high-salinity inclusions, nor do all veins in porphyry copper deposits. Halite-bearing inclusions are characteristic of porphyry copper deposits (Nash, 1971; Roedder, 1971) but are not exclusive to that environment and not uniquely associated with copper mineralization. Hence, the significance of these diagnostic inclusions needs to be assessed, and this will be done in this report.

TYPE IV.   CO₂-RICH

The presence of a third fluid phase, liquid CO_2, at reduced temperatures distinguishes these inclusions (fig. 2–IV). Some have salinities near 2 weight percent (Nash and Cunningham, 1973), whereas others contain halite cubes and salinities believed to be approximately 30 weight percent (Nash and Theodore, 1971). The CO_2:H_2O ratio varies greatly also from the limits of optical detection (approximately 3 mole percent CO_2) to more than 30 mole percent. These grade into type IV inclusions with no optically detectable liquid CO_2 but with somewhat large CO_2 pressures at room temperature. Many type IV inclusions, as commonly indicated

by their phase proportions, were trapped as vapor, such as in an effervescing hydrothermal system. Type IV inclusions are not typical of most porphyry copper deposits, but they have been noted in some samples from Copper Canyon, Nev. (Nash and Theodore, 1971), from Butte, Mont. (Roedder, 1971), and from Bagdad, Ray, and Yerington, Nev., by the author. The liquid CO_2-bearing inclusions appear to have filling temperatures of about 300°C, and are associated with relatively low temperature porphyry-type deposits, or their low temperature stages. This probably reflects the miscibility gap in the system CO_2–H_2O (Takenouchi and Kennedy, 1964) which develops below 350°C; at higher temperatures CO_2 is readily dissolved in aqueous solutions. For the porphyry coppers the concentration of CO_2 generally is insufficient to form discrete liquid CO_2 at room temperature. Ore fluids in the porphyry coppers typically contain <3 mole percent CO_2.

GENERAL PHYSICAL AND CHEMICAL CHARACTER OF THE ORE FLUIDS

A broad range of fluid compositions and physical conditions are recorded in inclusions from porphyry deposits. Physical conditions, such as temperature, pressure, and fluid density, are effectively determined from fluid inclusions. However, only gross chemical characteristics may be determined from fluid inclusions unless the inclusions are crushed and subjected to chemical and isotopic analysis, methods which are too costly and time-consuming for routine application to exploration. Studies of alteration and ore mineral assemblages (Meyer and Hemley, 1967) yield important information on the chemistry of ore fluids and are a necessary prerequisite upon which to base fluid-inclusion studies, especially regarding the crucial matter of sulfur fugacity.

TEMPERATURE

Filling temperatures have been recorded in the range from as high as 725°C at Bingham Canyon (Roedder, 1971) to less than 200°C in several deposits (fig. 6). Filling temperatures greater than 600°C have been determined for coexisting gas-rich and halite-bearing inclusions in samples from Bingham Canyon, from El Salvador, Chile (Gustafson and Hunt, 1975), and from San Manuel (J. D. Davis, written commun., 1972). Filling temperatures require a correction for pressure unless the pressure at trapping is the same as that at filling; this condition is met when inclusions are trapped on the liquid-vapor curve (that is, from a boiling fluid). Because these fluids were in a boiling condition, they do not require a pressure correction and, hence, are the same as the temperature of trapping.

Filling temperatures determined from vein samples
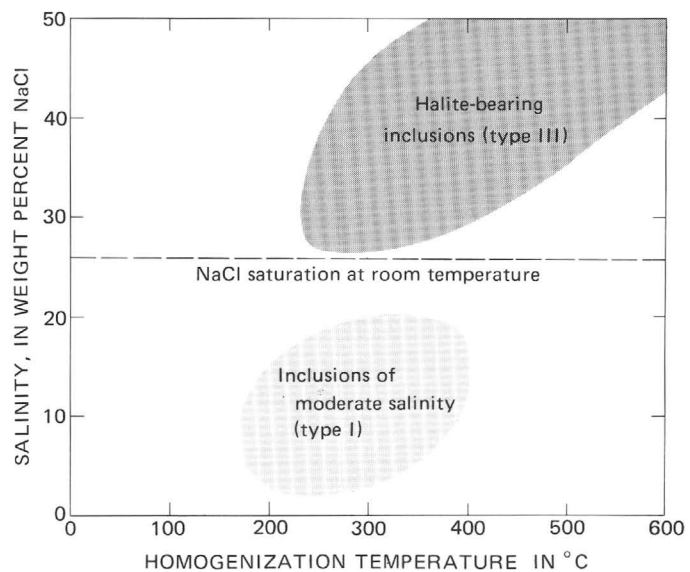
FIGURE 6.—Generalized ranges of homogenization temperatures and salinities for type I and type III inclusions from porphyry copper deposits.

from individual deposits show a considerable range: 300°–400°C at Copper Canyon (Nash and Theodore, 1971), 230°–450°C at Mineral Park (Drake, 1972; Nash and Cunningham, 1974), 233°–373°C at Bagdad (Nash and Cunningham 1974), and 350°–440°C in copper-bearing breccia pipes in Chile (Sillitoe and Sawkins, 1971). In the Butte, Mont., district pre-main (Cu–Mo) stage veins contain type I inclusions with filling temperatures of 370°±20°C (Roberts, 1973); interpreted pressure corrections are large (180°–330°C) and yield temperatures of formation of 550°–700°C. Main stage veins at Butte contain inclusions with a range of compositions (types I, II, and III), and filling temperatures range from 275° to 335°C (Roedder, 1971). Type I inclusions in garnet from the skarn orebody of Copper Canyon studied by T. G. Theodore (written commun., 1975) have filling temperatures as high as 540°C; the type I inclusions coexist with type II, and boiling conditions are inferred.

Filling temperatures can be estimated from room temperature phase proportions, but such estimates are subject to large errors on high salinity fluid inclusions because of the likelihood of misjudging the compressibility of the saline liquid and deducing erroneously low homogenization temperatures. Estimates of filling temperatures for typical inclusions in quartz-sulfide veins in many porphyry deposits range from about 250° to 500°C. On the basis of estimates of pressure corrections required (generally small), it is my interpretation that in most porphyry deposits temperatures were typically about 400°±100°C. Higher temperature pulses, where present, probably were of brief duration during intrusive surges.

PRESSURE

Pressure determinations based on fluid-inclusion properties are generally less than 2,000 bars and are commonly less than 500 bars. Gas-rich and liquid-rich inclusions commonly coexist in vein and wallrock quartz, a relationship that probably reflects trapping from a heterogeneous liquid plus gas or boiling system. In this situation filling temperatures are the same as trapping temperatures because no pressure correction is required for fluids trapped in the two-phase boundary (boiling point curve). (See Haas, 1971.) With a temperature determined from heating tests or estimated from phase proportions, and a composition determined from freezing tests or from daughter minerals, one may refer to data from the system $NaCl-H_2O$ (Sourirajan and Kennedy, 1962; Haas, 1971) for an estimate of pressure. Application of such relations suggested about 160 bars pressure at Copper Canyon (Nash and Theodore, 1971) and about 1,100 bars at Bingham Canyon (Roedder, 1971).

Conversion of pressures to geologic depth is highly subjective. In many systems one must invoke fluctuating pressures, such as in a system changing from lithostatic to hydrostatic, to explain inclusion and geologic observations (Nash and Theodore, 1971; Roedder, 1971; Moore and Nash, 1974; Drake, 1972). Different reasoning was employed by Nash and Cunningham (1974) to explain conditions at Bagdad: although very little volcanic cover is preserved, the rarity of boiling requires that pressures were typically greater than those of the boiling point curve, and that the inferred depth of cover was somewhat more than 6,000 feet (1,800 m). Depths of formation, interpreted from fluid-inclusion data, range from 6,000 to 10,000 feet (1,800 to 3,000 m) for Bingham Canyon (Moore and Nash, 1974), Bagdad (Nash and Cunningham, 1974), Copper Canyon (Nash and Theodore, 1971), and Mineral Park (Drake, 1972), as well as for breccia pipes in Chile (Sillitoe and Sawkins, 1971). Somewhat more shallow levels of intrusion and deposition have been deduced for El Salvador (Gustafson and Hunt, 1975), and at Jamestown, Colo. (Nash and Cunningham, 1973), for a Tertiary stock which contains no economic copper mineralization. As an indicator of depth of formation, fluid-inclusion barometry is consistent with estimates made from geologic data. When the thickness of the overlying rocks at the time of metallization cannot be estimated geologicaly, fluid-inclusion barometry is the only reliable method for estimating depth of formation.

There is considerable evidence that many porphyry copper deposits form at depths greater than about 3 miles (5 km) in batholithic settings (for example, Hylands, 1972; Roberts, 1973; Cheney and Trammell, 1975). The copper deposits of the Guichon batholith, British Columbia, and at Butte, Mont., are the best known examples. The limited amount of fluid-inclusion data available for these localities (Nash, this report; Roberts, 1973) indicate that gas-rich and halite-bearing fluid inclusions are not characteristic of these deposits as is apparent for copper deposits in epizonal stocks.

DENSITY

Densities of hydrothermal fluids may be determined with fair precision from measurements of phase proportions in fluid inclusions (Roedder, 1967). Fluid inclusions are the only source of this information. The density of high-salinity type III fluid inclusions from porphyry copper deposits is commonly greater than 1.0 g/cm^3 (grams per cubic centimetre), and is as high as 1.3 g/cm^3 at Bingham Canyon (Roedder, 1971). Commonly coexisting with these dense liquids are gas-rich type II inclusions representing trapped steam with densities that range from 0.1 to 0.3 g/cm^3. Temperature is the major determinant of densities in the low density region. Moderate-salinity type I fluid inclusions commonly have densities that range from 0.7 to 0.9 g/cm^3 (Nash and Theodore, 1971). Fluid densities, particularly the density contrasts between high- and moderate-salinity fluids, may be of importance in controlling the circulation of hydrothermal fluids and help explain, for example, why high salinity fluids are generally restricted to the vicinity of intrusives (Nash and Theodore, 1971). The influence of fluid density on such factors as mixing or nonmixing of hydrothermal fluids and mineral solubility may have real academic and practical importance.

COMPOSITION

Some general inferences regarding fluid compositions can be made from fluid-inclusion data. The common presence of salt daughter minerals indicates salinities that range from about 30 to more than 50 weight percent. Excellent data from halite and sylvite in inclusions from Bingham indicate compositions that range from 13 to 22 weight percent KCl, 28 to 39 weight percent NaCl, and 47 to 51 weight percent H_2O (Roedder, 1971; Moore and Nash, 1974). K:Na molar ratios range from 0.26 to 0.59 (Moore and Nash, 1974). The concentration of $CaSO_4$ may be as much as 1.5 weight percent (Roedder, 1971) if the rectangular daughter mineral is anhydrite. Iron contents commonly are high, from approximately 1,000 ppm (parts per million) to as much as 1.2 weight percent (12,000 ppm; Roedder, 1971). Similar but generally lower concentrations of Na, K, Fe, and SO_4 are deduced from relative volumes of daughter minerals in selected inclusions from other deposits. A nonmagnetic, often triangular, opaque mineral, occurring with hematite, is noted in inclusions from several deposits. It may be chalcopyrite, indicating relatively large copper concentrations (Roberts, 1973).

The presence of hematite and anhydrite might appear to provide evidence of oxygen fugacity, but because hydrogen diffusion is likely and would cause self-oxidation, the daughter minerals are not valid indicators of oxygen fugacity.

The composition of moderate-salinity type I inclusions is best determined on the freezing stage. Measurements of depression of freezing point indicate salinities generally less than about 12 weight percent NaCl equivalent (Nash and Theodore, 1971; Roedder, 1971; Nash and Cunningham, 1974). These inclusions occasionally contain hematite and anhydrite (?), indicative of appreciable Fe, Ca, and S. An elongate, birefringent mineral with the optical characteristics of dawsonite (Coveney and Kelly, 1971) is common.

The most characteristic fluid-inclusion feature revealed by studies of porphyry copper deposits is the general occurrence of cubic crystals of halite. Halite-bearing type III inclusions occur in primary quartz of 27 intrusive bodies associated with the copper mineralization; only igneous bodies of the Guichon batholith, British Columbia (Victoria and Valley Copper deposits, Hylands, 1972), appear to be notably devoid of type III inclusions. Halite occurs as primary and secondary inclusions in some secondary quartz of hydrothermal mineralization in most deposits, and is notably sparse or absent only in the Esperanza, Ray, and British Columbia deposits. Therefore, very saline hydrothermal fluids were present during at least one stage of the porphyry copper mineralizing system. The fact that halite-bearing inclusions occur in more than 90 percent of the deposits so far studied, makes them a feature to be sought in any porphyry copper prospect.

Halite-bearing inclusions are deemed to be a general attribute of porphyry copper systems and a guide to them; however, several cautions are in order. (1) Barren intrusive bodies are also known to contain halite-bearing inclusions. Probably these inclusions are typical of epizonal intrusives in general, not just the copper-bearing variety of great economic interest. (2) Favorable fluid composition in terms of salinity of course does not by itself create an orebody; hence, it is absolutely imperative that other evidence be considered in exploration (for example, presence of Cu minerals, structure, alteration, and geophysical data). (3) The abundance, in relative and absolute senses, of halite-bearing inclusions is highly variable within and among deposits. These inclusions are very abundant and obvious at Bingham Canyon, somewhat less abundant and smaller at Copper Canyon and Ely, and sparse at Ray. Their abundance per unit volume is low, but relative abundance to type I and II inclusions is high in the small Puerto Rico deposits. Presumably, the abundance of halite-bearing inclusions reflects many factors, including volume of hydrothermal fluid, tectonism, and pressure-

temperature conditions. Clearly, most of the copper ore at Bagdad, Esperanza, Mineral Park, Ray, and Sierrita formed from moderate salinity fluids; hence, the viability and importance of these fluids should not be discounted.

DISTRIBUTION OF FLUID INCLUSIONS IN SPACE AND TIME

Zonal relations of alteration and metallization have been used for years in exploration for porphyry copper deposits. Because the population and general composition of fluid inclusions can be determined at relatively low cost during petrographic study of conventional thin sections, this information can be plotted on a map with other geochemical data. Available qualitative and quantitative data bearing on the distribution of fluid types and inferences which can be drawn from that data are presented in this section of the report.

The complexity of the distribution of fluid inclusions in and adjacent to a porphyry copper deposit must be emphasized. The spatial occurrences of hydrothermal alteration are not easily mapped, and the ages of the inclusions relative to these occurrences is difficult to assess. Also, inclusions cannot be mapped in the field, and microscopic examination does not yield definitive ages. Even if the age of a vein can be determined, inclusions in quartz of that vein may be the same age as the vein (primary inclusions). More typically, however, inclusions are on microfractures through the quartz (secondary or pseudosecondary inclusions) and thus are younger than the vein.

Determination of the ages of inclusions in igneous quartz of the intrusive bodies is particularly problematical, because recrystallization obscures original textures. Spatial distribution can be defined with good reliability, although possible errors may result from sample bias, destruction of certain inclusions, and comparison of inclusions of different ages; similar sampling problems pervade all geochemical studies.

FLUIDS IN INTRUSIVE ROCKS

All intrusive rocks contain fluid inclusions, but abundance and types present are variable and correlate with other factors of interest to geochemists. Particular attention should be paid to type II and III inclusions in intrusive rocks. Halite-bearing type II fluid inclusions are likely to form in chlorine-rich intrusive rocks crystallizing at low pressures (<1,000 bars) on the basis of experimental studies in the system $NaAlSi_3O_8–NaCl – H_2O$ (Koster van Groos and Wyllie, 1969), and gas-rich type II inclusions will form from low to moderate density fluids that are boiling or in the three phase (NaCl–vapor–liquid) region. As previously discussed under "Fluid Inclusion Types," type III inclusions are

noted in intrusive rocks in most porphyry copper districts, and type II inclusions, probably cogenetic with type III, occur in many of these same rocks. Type II and III inclusions are rare in granitoid rocks, such as those of the Sierra Nevada batholith, which crystallized at greater depths than typical copper-bearing stocks. The abundance of inclusions appears to correlate with the amount of fracturing, especially where there are multiple intrusives. Post-ore intrusives at Ray, Ariz., Ely, Nev., and Park City, Utah, are characterized by the paucity of fluid inclusions, especially type III. Cox, Pérez Gonzáles, and Nash (1975) observed this at the Sapo Alegre porphyry copper prospect in Puerto Rico.

The composition and quantity of fluids present during emplacement of an intrusion is a major question of petrogenesis (Burnham, 1967; Fournier, 1967, 1972). Petrologists generally cite data from experiments and geologic features such as the presence of miarolitic cavities or the compositions of minerals to determine fluid pressures. Fluid-inclusion data could be useful for the determination of physical conditions if the specific time at which the inclusions were trapped can be established. Quartz phenocrysts commonly contain prominent fluid inclusions, but these inclusions are generally along microfractures indicative of secondary formation; isolated "primary-appearing" inclusions are likely to reflect recrystallization at high temperatures. A good description of probable primary inclusions in granitic intrusive rocks was presented by Roedder and Coombs (1967). They noted the presence of glass in some inclusions, an important feature not reported from porphyry copper deposits. The hypothesis of immiscibility between silicate magma and salt-rich hydrothermal fluids (Roedder and Coombs, 1967; Roedder, 1971) is an important model for fluid conditions at the magmatic stage in some intrusive rocks. However, immiscibility is determined by interpretation of relations between fluid inclusions and original features may be obscured by recrystallization. Some measured filling temperatures are in excess of 600°C for inclusions from copper-bearing stocks (Roedder, 1971; Moore and Nash, 1974; Gustafson and Hunt, 1975). No pressure correction is required, but these temperatures still are 100°C or more below likely solidus temperatures. Samples of intramineral veins (veins formed between magmatic pulses, Kirkham, 1971), would seem excellent for study, but recrystallization and formation of secondary inclusions by later intrusions and by subsolidus hydrothermal mineralization creates a complex assemblage of inclusions that cannot be objectively related to one magma (Hall and others, 1974; Moore and Nash, 1974).

FLUIDS IN INTRUDED WALLROCKS

Pre-ore wallrocks contain from 0 to about 90 percent of the ore in various porphyry copper deposits (Lowell and Guilbert, 1970). The character of the ore and alteration of the wallrocks is highly variable and will not be considered here. Fluid-inclusion types and abundances also are highly variable and are an aid to understanding the physical-chemical environment of ore emplacement and distribution in wallrocks.

The Copper Canyon deposit, which contains no economic mineralization in the associated intrusive, has been studied in detail (Nash and Theodore, 1971; Theodore and Nash, 1973; Theodore and Blake, 1975), and will serve as a model for copper deposits in pre-ore wallrocks. Siliceous sedimentary rocks, particularly conglomerate of the Pennsylvanian Battle Formation, contain abundant fluid inclusions. A zone that includes the intrusive and the copper deposits is characterized by halite-bearing inclusions (fig. 7). The halite-bearing fluid inclusions in this zone are similar to those observed in quartz-chalcopyrite veins in the pit. The zone of anomalous high-salinity inclusions is somewhat smaller than the pyrite halo but much larger than the orebodies. The zonation of fluid inclusions provides a more satisfactory target than do minor element or alteration halos, both of which are poorly developed in the siliceous rocks (Theodore and Nash, 1973; Theodore and Blake, 1975).

High-temperature halite-bearing fluid inclusions are abundant in zones of intruded metasedimentary rocks at Bingham Canyon, Ely, Mission, and Twin Buttes. Quartzites from the eastern part of the pit at Bingham Canyon, which carry minor amounts of ore, contain numerous gas-rich inclusions and sparse liquid-rich type I or III inclusions. Although high-salinity inclusions are abundant in the intrusive rocks, they are very rare in quartzites more than 100 feet (30 m) from the eastern contact (Moore and Nash, 1974). If the inclusion population is representative, the wallrocks in this eastern zone must have been bathed in vapors rather than liquids, a physical condition which may explain the paucity of ore in those rocks. In oxidized rocks of the Ely district, jasperized Ely Limestone (Mississippian, Pennsylvanian, and Permian) and silicified Rib Hill Sandstone (Lower Permian) contain numerous halite-bearing inclusions. Halite-bearing inclusions similar to those in primary ore veinlets occur in jasper several hundred feet above the Tripp orebody in the Ely district indicating that high-salinity fluids circulated through wallrocks above the intrusions at Ely, but the limits of this circulation have not been determined.

The Ray porphyry copper deposit deserves special comment because its geology (Metz and Rose, 1966) and its fluid inclusions (Nash, this report; Logsdon, 1969) are not typical. Most of the primary and secondary enriched mineralization occurs in Precambrian Pinal Schist and Precambrian diabase, with a very small percentage in the Paleocene Granite Mountain Porphyry, the "host

117°06'

NEVADA
Area of
this study

40°
33'

WEST ORE
BODY

EAST ORE
BODY

0   4000 FEET

0   1000 METRES

EXPLANATION

Tertiary volcanic rocks

Tertiary altered granodiorite

Permian to Cambrian sedimentary rocks

Surface projection of copper ore bodies

Area of very saline fluids

Sample traverse-fluid-inclusion studies

● Diamond drill hole sample locality

Outer limit of pyritized rocks — Hachures
outside of zone

Contact

▲▲▲ Thrust fault — Dotted where concealed or
inferred. Sawteeth on upper plate

High-angle fault — Dashed where approxi-
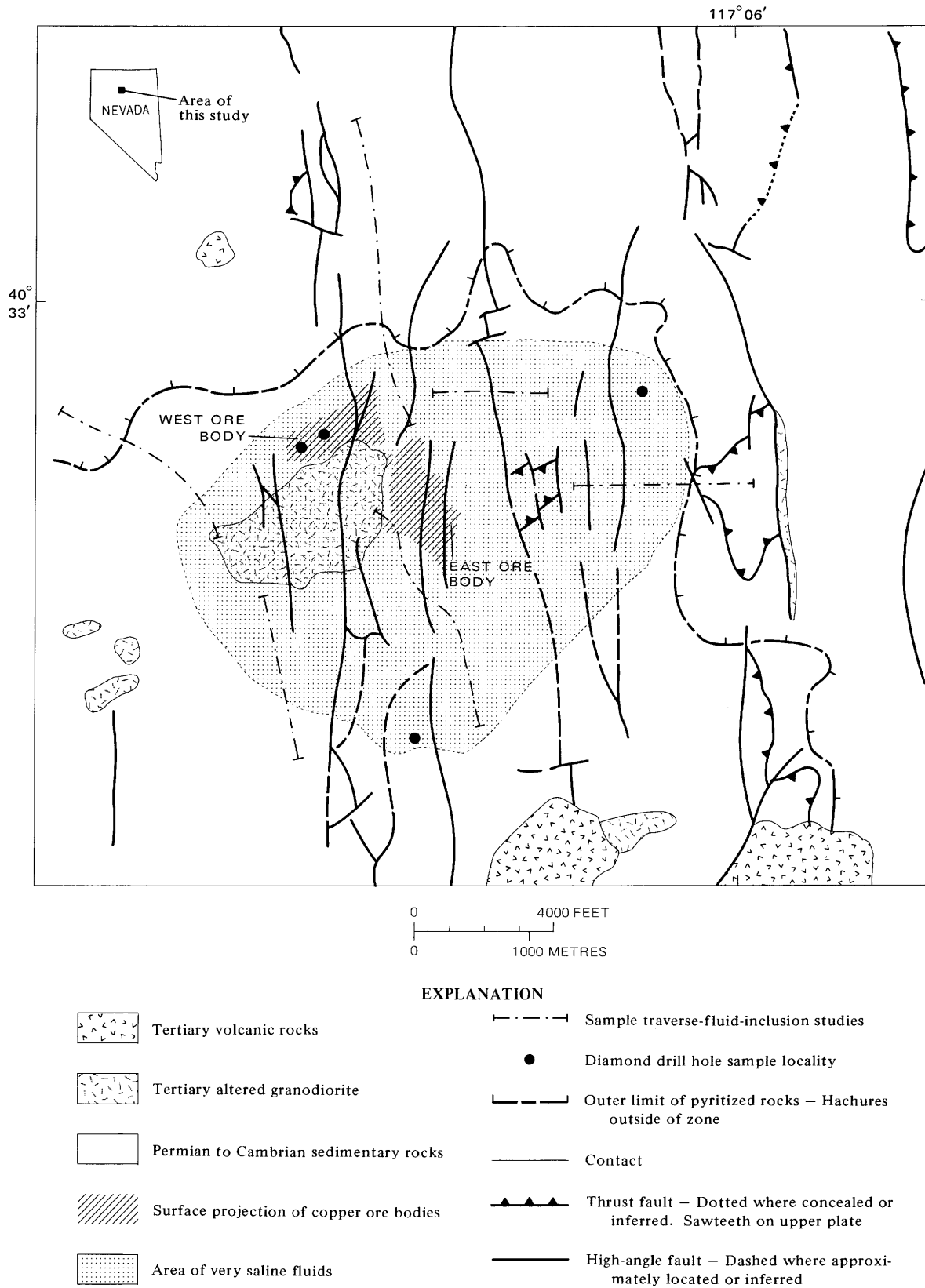mately located or inferred

FIGURE 7.—Distribution of high salinity fluids in intrusive and sedimentary rocks at Copper Canyon, Nev., as
deduced from occurrence of halite-bearing fluid inclusions. Modified from Theodore and Nash (1973).

porphyry" (Metz and Rose, 1966, p. 180). My observations were of 140 samples from the surface, pit, and drill core. Quartz-sulfide veins and wallrocks at Ray typically contain type I inclusions consisting of liquid, ~20 percent vapor, and commonly one or more daughter minerals: hematite, carbonate (?), and anhydrite (?). Gas-rich inclusions are conspicuously absent at Ray. Halite-bearing inclusions occur sparsely in some veins, wallrocks, and intrusive rocks including post-ore dikes, but such inclusions are not considered characteristic of the ore-depositing fluids. At Ray the fluid inclusions are monotonously similar. No differences were detected in the fluid-inclusion population in quartz-chalcopyrite, quartz-molybdenite, or barren quartz veins, or in quartz associated with anhydrite, biotite, chlorite, or sericite. Homogenization temperatures were estimated to be $300° \pm 25°C$ and recent determinations on the heating stage are about 300°C (T. G. Theodore, written commun., 1974). The pressure correction could be as much as $+75°C$ but probably is less.

VERTICAL DISTRIBUTION

The vertical distribution of fluid inclusions may be potentially informative, although at present little is known because of typical limitations on sampling. My sampling of several deposits, such as Bingham Canyon, Copper Canyon, Ely, and Ray, includes less than 500 feet (150 m) vertically through the deposits; in these examples no systematic changes with depth are detected in fluid-inclusion populations. However, some noteworthy changes have been observed in other environments. Distinct zones have been recognized in the Park City district (Nash, 1973), where rocks and veins were examined over a 6,000-foot (1,800-m) interval. A transition from non-boiling to boiling moderate-salinity fluids occurs at the upper part of the presently exposed Mayflower vein system; base- and precious-metal ores are limited to the lower part of the system, which is characterized by liquids rather than vapor. Also, in the intrusive rocks a different type of vertical zonation of fluids is noted; these rocks were later cut by the veins previously described. A gradual shift in the ratio of gas-rich to halite-bearing inclusions (roughly contemporaneous) is noted over a 3,000-foot (900-m) vertical interval. In samples at elevations from 9,000 feet (2,700 m) down to about 7,000 feet (2,100 m) gas-rich inclusions predominate by about 100:1, whereas below an elevation of about 5,500 feet (1,700 m) the ratio is about 1:1. These inclusion ratios are as expected of a saltwater system above and on the boiling point curve respectively. The lower part of the system, which was pre-vein ore, contains anomalous amounts of disseminated chalcopyrite (about 0.1 to 0.2 percent Cu).

Samples were studied from two base- and precious-metal districts in which changes in fluid inclusion types suggest possible underlying disseminated mineralization. In the Goldfield district, Nevada, a drill hole penetrated welded tuff and an altered quartz monzonite body. The quartz monzonite contained prominent halite-bearing and gas-rich inclusions resembling those from Bingham Canyon, whereas the volcanic rocks contained only low-temperature low-salinity inclusions. The deeper zone in quartz monzonite has fluid inclusions and other geochemical features not recognized in historic precious-metal ore zones of the district. A similar transition was observed in samples of drill core from a base- and precious-metal mining district in Colorado. In these examples the transition to considerably hotter, much more saline, more dense fluids occurred over an interval about 300 feet (100 m), near a lithologic contact, and was associated with a change in alteration and sulfide mineral assemblage. Changes such as these may be a guide to disseminated metallization below barren ground or below base- and precious-metal ores. Evidence for such a transition should be sought in deep drill holes.

Both the vertical distribution of fluids and their physical condition are sensitive to pressure in the epizonal environment, although factors, such as heat flow, permeability, and quantity of water, are also important (White and others, 1971). Massive boiling is to be expected in the high-temperature low-pressure environment in or above epizonal intrusions (Burnham, 1967; Fournier, 1972; White and others, 1971). Such boiling should be detected by the occurrence of gas-rich or coexisting gas-rich and liquid-rich inclusions. In some copper deposits, such as Bingham Canyon, Copper Canyon, and Ely, boiling was pervasive, and in some deposits, such as Bagdad, Butte, and Mineral Park, boiling occurred during some vein stages. In still other deposits (Bisbee, Silver Bell, Bethlehem, and Valley Copper) boiling conditions have not been detected, possibly because of insufficient sampling.

DISTRIBUTION OF FLUIDS IN TIME

The ages of copper-bearing porphyries studied range from Ordovician to late Tertiary. The oldest studied is the Ordovician Attean Quartz Monzonite exposed at Catheart Mountain, Maine (Young, 1968). The Sacramento stock at Bisbee is pre-Cretaceous (Bryant and Metz, 1966), and the productive intrusives in the Ely district are Cretaceous (Bauer and others, 1966). The copper-bearing intrusive at Saindak, Pakistan, is about 4 million years old (Ahmed and others, 1972), and many in the Southeastern United States are early Tertiary. Calc-alkaline intrusions of all ages generate very saline fluids; thus, geologic time does not appear to be a factor. The anomalously low salinities observed in the British Columbia deposits seem to be a function of their batholithic setting, not age (Jurassic). No Precambrian

porphyry coppers have been studied, but they are expected to have comparable salinity.

Individual hydrothermal systems span several million years; within this time, the earliest fluids that can be recognized in most copper-bearing stocks are highly saline. Bagdad may be an exception because hot moderate-salinity fluids may have preceded cooler high-salinity fluids (Nash and Cunningham, 1974). Likewise, at Butte the moderate-salinity fluids observed by Roberts (1973) probably preceded the high-salinity fluids described by Roedder (1971); both fluids deposited copper and molybdenum. In many places highly saline fluids have deposited quartz-chalcopyrite veins, with or without molybdenite, that have biotite, biotite plus potassium-feldspar, or no alteration envelopes. These features indicate that the solutions were not far from equilibrium with the granitic host rocks. In calcareous rocks the early high salinity fluids form calcium-iron-magnesium skarn minerals, as in the Pima, Ariz., district and the Copper Canyon, Nev., west orebody. Although age relationships between halite-bearing inclusions and disseminated sulfides are generally nonspecific, the fact that the two are coextensive and that both occur in microveinlets suggests that they are related.

All porphyry copper deposits contain moderate-salinity inclusions which generally are younger than halite-bearing inclusions. Age relationships of veins and fluid inclusions have not been defined with sufficient certainty in any deposit to define fluctuations in salinity. Post-copper quartz veins with galena, sphalerite, gold, or fluorite contain primary moderate-salinity inclusions at Copper Canyon (Nash and Theodore, 1971), Mineral Park (Drake, 1972; Nash, this report), Ajo (Nash, this report), El Salvador (Gustafson and Hunt, 1975), and other unspecified deposits (Roedder, 1971). Of greater economic importance are the many quartz-chalcopyrite and quartz-molybdenite veins that contain only moderate-salinity inclusions. In some deposits, such as Bagdad (Nash and Cunningham, 1974), Mineral Park (Drake, 1972; Nash, this report), Morenci, and Ray, and in three deposits in British Columbia (Nash, this report), moderate-salinity fluids deposited most primary copper minerals. These moderate-salinity fluids also deposited important amounts of molybdenum. Determination of the ages of inclusions and metallization stages, and quantifying their economic contribution is a complex and subjective task, but there are suggestions at this date that the relative importance of high and moderate salinity fluids varied in the porphyry deposits as a class.

CORRELATION WITH GEOCHEMICAL FEATURES

Fluid-inclusion data are especially useful when integrated with other geochemical information, yet there

have been few efforts to correlate geochemical expressions, such as alteration, metal zoning, or minor elements, with the fluids that produced them. Combined maps of these parameters have been instructive when attempted (Theodore and Nash, 1973; Moore and Nash, 1974). A study of this sort requires careful integration of many techniques, and samples must be carefully collected so that relations between all parts of the rock are understood. The attempt made at Copper Canyon (Theodore and Nash, 1973) illustrates some of the difficulties; for instance, experience there indicated that relatively unfractured wallrocks served best for minor-element distribution studies, but fractured samples were necessary for fluid-inclusion studies. Despite the sampling problems, at Copper Canyon good correlation was noted between the distribution of halite-bearing inclusions, alteration, the pyrite halo, and anomalous copper, mercury, gold, and bismuth. (See fig. 7.)

The geologic setting in the southern and central parts of the Bingham Canyon deposit is more favorable for study because initial rock compositions were more uniform than at Copper Canyon. At Bingham, alteration and metallization are unusually uniform rather than highly localized in or along veins. Good spatial correlation is noted between the outer limit of predominant halite-bearing inclusions, the copper ore body, and the inner limit of amphibole and magnetite (Moore and Nash, 1974; fig. 8). There was no detectable difference in fluid-inclusion populations in the sericitic and biotitic alteration zones. Note that a ratio technique was used in the Bingham Canyon study (fig. 8). The relative abundance of inclusion types changes across zones of the metallization system and is shown by plotting relative abundance in parts per ten; plotting presence or absence of inclusion types would not show nearly as much. Another factor recognized in the Bingham study was that the absolute abundance (per unit volume) of inclusions was vastly greater in the ore zone than in the "unaltered" amphibole-magnetite-bearing quartz monzonite. Absolute abundances were not determined because of the great difficulty making counts of inclusion types in three dimensions. The experienced eye, however, can quickly judge approximate abundances and it is helpful to record these semiquantitative estimates.

Several mineralogical associations have emerged from these fluid-inclusion studies. On the basis of many scattered observations, hydrothermal biotite (either disseminated or pseudomorphous after amphibole) and potassium-feldspar are associated generally with high-salinity fluids, although some exceptions are noted, as at Ray. These high-salinity fluids also sulfidized wallrock magnetite in many deposits. In the Cu-Mo deposits I have studied, fluid inclusions are not systematically different in quartz-chalcopyrite and quartz-molybdenite
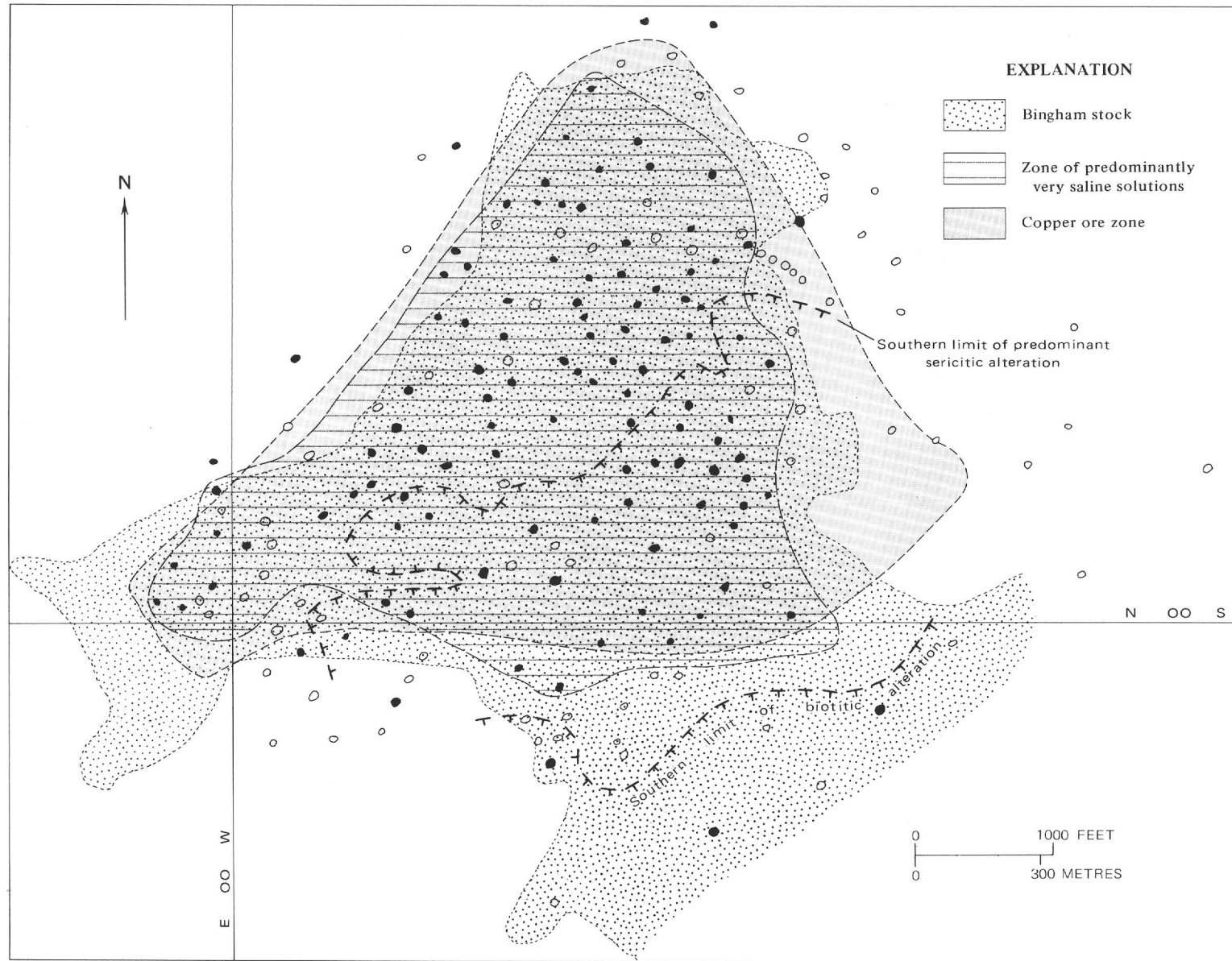
FIGURE 8.—Generalized map of Bingham Canyon area, Utah, showing distribution of very saline fluids and their spatial relationships to the copper ore zone, alteration zones, and the Bingham stock. The boundary of the zone of predominantly highly saline fluids was arbitrarily chosen at a natural break in the inclusion population. Four or more parts in 10 of type III inclusions is represented by a dot; less than 4 parts per 10 type III inclusions, by a circle. Modified from Moore and Nash (1974).

veins. Hydrothermal sericite forms from both high- and moderate-salinity fluids, although I suspect that the latter association is the most common. Chlorite and kaolinite typically form from moderate-salinity fluids. Available paragenetic and fluid-inclusion data suggest that lead, zinc, silver, and gold minerals in porphyry copper deposits may be deposited from later, cooler, less saline fluids than are the copper and molybdenum. Observations at Bingham Canyon (Roedder, 1971), Copper Canyon (Nash and Theodore, 1971), and Mineral Park (Drake, 1972; Nash, this report) support this generalization, but many more studies of such occurrences are needed.

APPLICATIONS TO EXPLORATION

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

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

SAMPLING AND PETROGRAPHIC TECHNIQUES

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

Three types of sample preparation may be used—thin section, polished thin section, or grains in immersion oil. Although the latter is the cheapest, it has the great disadvantage of conveying little or no textural information, and for that reason I have rarely used it. Conventional thin sections are highly advantageous; minerals are identified readily, textural relations are preserved, optical quality of inclusions in most minerals is very good even for those of 1 μm diameter, and the preparations are made at low cost. Thin sections may be prepared with or without coverglasses, but one must be able to focus into the thin rock slice with a × 100 immersion objective (focal distance generally 0.09 mm). Doubly polished sections cut to a thickness which allows adequate light transmission are required for heating- and freezing-stage study and are superior for petrography of larger inclusions and for minerals with high indices of refraction. Structural and textural relations should be determined in the field or with a binocular microscope.

Individual fluid inclusions are generally visible at × 100 to × 200, although at such magnification they commonly look like "foreign matter" (fig. 9). Depending upon size and morphology, the inclusions may be clear or dark from internal reflection. For study of typical rocks from porphyry copper deposits a good quality × 100 oil immersion objective and substage condenser are virtually indispensable for proper resolution of vapor bubbles and daughter minerals. At magnifications of about × 1,000, one focuses inside crystals and can resolve thousands of inclusions. Proper use of focused condensed light is required to illuminate the interior of inclusions. During petrographic study observations should be made of types of inclusions present, their textural occurrence (on fractures, isolated, healed or recrystallized, necked down, and so forth), identity and size of daughter minerals, phase proportions, and relative abundance of inclusion types; total abundance should be estimated. This estimate is best made by reference to type samples and is recorded in a relative sense (high, moderate, and low).
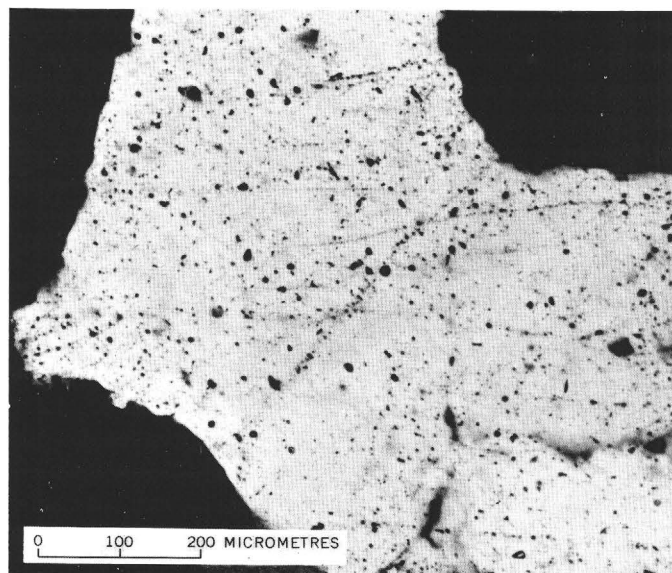
FIGURE 9.—Photomicrograph of crisscrossing planes of fluid inclusions in vein quartz, Bingham Canyon, Utah. The inclusions appear as dark specks from total reflection of transmitted light because no condenser was used.

IDENTIFICATION OF FAVORABLE INTRUSIVE BODIES

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

The fluid-inclusion criteria obviously should not be the only criteria used to evaluate the mineral potential of intrusive bodies because uneconomic hydrothermal systems can leave a similar record. Other features, easily noted while making the fluid-inclusion examination, should also be present, such as recrystallization, added potassium-feldspar or biotite, secondary biotite replacing amphibole, and sulfide minerals replacing magnetite.

CHARACTERIZING HYDROTHERMAL SYSTEMS

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

Studies of high-temperature halite-bearing and gas-rich inclusions in altered porphyry bodies in four precious-metal mining districts demonstrate specific application of this technique. Pyritized, potassic altered zones of intrusive bodies in the northwest San Juan Mountains, Colo., San Miguel Mountains, Colo., Park City district, Utah, and Goldfield district, Nev., bear reevaluation for potential disseminated sulfide mineralization at depth on the basis of these fluid-inclusion observations. Base- and precious-metal ores in these districts were deposited from moderate-salinity (<10 weight percent NaCl) moderate-temperature (<320°C) fluids (Nash, 1973, 1975). In three of these districts the observed zone of high-salinity fluids underlies the known precious-metal ore; it formed earlier than the precious-metal ore but during the same period of metallization. Alteration features in the deeper zone are not obviously different in the field.

GOSSANS AND LEACHED OUTCROPS

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

Silicified caprock above the Bagdad, Bisbee (Lavender pit), Copper Canyon, Ely, Mineral Park, and Ray deposits all contain distinctive inclusions identical to those in the underlying orebody. Samples of caprock from Bagdad and Mineral Park contain few halite-bearing inclusions, just as do ore veins in those deposits (Nash and Cunningham, 1974), but the samples from Copper Canyon and Ely contain abundant halite-bearing and gas-rich inclusions indicating the former

presence of hot, highly saline, boiling fluids. Silicified capping above the Ray deposit contains only moderate-salinity, moderate-temperature (about 300°C) inclusions like those in ore veins. Leached, oxidized capping derived from the "older porphyry" in the Lavender pit contains abundant halite-bearing inclusions but no gas-rich inclusions. Caprock above the La Caridad deposit, Mexico, contains prominent halite-bearing inclusions indicative of potent hot solutions (T. G. Theodore, oral commun., 1974).

LATERITE AND SOIL

Fluid inclusions in quartz survive even severe weathering in the tropics as shown by studies of deposits in Puerto Rico (Cox and others, 1975). Hence, inclusions can be examined in quartz in residual soils or laterite to determine the presence of hydrothermal alteration. For these studies soil samples are washed and coarsely sieved to remove clays, and the residual grains cast in epoxy prior to making thin sections. By study of the residual quartz grains it is possible to distinguish quartz phenocrysts from hydrothermal and supergene quartz on the basis of fluid inclusion types and abundance. Hydrothermal activity is clearly indicated by appropriate fluid inclusions, even in samples in which weathering destroys all textural and mineralogical evidence of hydrothermal alteration.

REFERENCES CITED

Ahmed, Waheeduddin, Khan, S. N., and Schmidt, R. G., 1972, Geology and copper mineralization of the Saindak quadrangle, Chagai District, West Pakistan: U.S. Geol. Survey Prof. Paper 716-A, 21 p.

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

Bauer, H. L., Jr., Breitrick, R. A., Cooper, J. J., and Anderson, J. A., 1966, Porphyry copper deposits in the Robinson mining district, Nevada, in Geology of the porphyry copper deposits; southwestern North America: Tucson, Ariz., Arizona Univ. Press, p. 232-244.

Bradshaw, P. M. D., and Stoyel, A. J., 1968, Exploration for blind orebodies in southwest England by the use of geochemistry and fluid inclusions: Inst. Mining and Metallurgy Trans., Sec. B, v. 77, Bull. 744, p. B144-B152.

Bryant, D. G., and Metz, H. E., 1966, Geology and ore deposits of the Warren mining district, in Geology of the porphyry copper deposits, southwestern North America: Tucson, Ariz., Arizona Univ. Press, p. 189-203.

Burnham, C. W., 1967, Hydrothermal fluids at the magmatic stage, in H. L. Barnes, ed., Geochemistry of hydrothermal ore deposits: New York, Holt, Rinehart and Winston, Inc., p. 34-77.

Chene, E. S. and Trammell, J. W., 1975, Batholithic ore deposits, [abs.]: Econ. Geology, v. 70, p. 1318-1319.

Coveney, R. M., and Kelly, W. C., 1971, Dawsonite as a daughter mineral in hydrothermal fluid inclusions: Contr. Mineralogy and Petrology, v. 32, p. 334-342.

Cox, D. P., Pérez Gonzáles, Ileana, and Nash, J. T., 1975, Geology, geochemistry, and fluid-inclusion petrography of the Sapo Alegre porphyry copper prospect and its metavolcanic wallrocks, west-

central Puerto Rico: U.S. Geol. Survey Jour. Research, v. 3, no. 3, p. 313-327.

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

Drake, W. E., and Ypma, P. J. M., 1969, Fluid inclusion study of the Mineral Park porphyry copper deposit, Kingman, Arizona [abs.], in Edwin Roedder, ed., Fluid inclusion research—Proceedings of COFFI, 1969: p. 15-16. [1972].

Ermakov, N. P., 1966, Use of gas-liquid inclusions in prospecting and exploration for postmagmatic ore deposits and blind orebodies: Sovetskaya Geologiya, 1966, no. 9, p. 77-90 [in Russian]; translated in Internat. Geology Rev., v. 9, no. 7, p. 947-956. [Listed there as "P. P. Ermakov."]

Fournier, R. O., 1967, The porphyry copper deposit exposed in the Liberty open-pit mine near Ely, Nevada—Part I, Syngenetic formation: Econ. Geology, v. 62, p. 57-81.

———1972, The importance of depth of crystallization on the character of magmatic fluids [abs.]: Internat. Geol. Cong., 24th, Montreal, 1972, sec. 10, p. 214.

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

Haas, J. L., 1971, The effect of salinity on the maximum thermal gradient of a hydrothermal system at hydrostatic pressure: Econ. Geology, v. 66, p. 940-946.

Hall, W. E., Friedman, Irving, and Nash, J. T., 1974, Fluid inclusion and light stable isotope study of the Climax mine, Colorado: Econ. Geology, v. 69, no. 6, p. 884-901.

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

———1972b, Distribution of chlorine and fluorine in granitoid rocks and associated ore deposits, northern Chile [abs.]: Econ. Geology, v. 67, p. 1005.

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

———1969, Thermodynamics of hydrothermal systems at elevated temperatures and pressures: Am. Jour. Sci., v. 267, p. 729-804.

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

Hylands, J. J., 1972, Porphyry copper deposits of the Guichon Creek batholith, British Columbia: Internat. Geol. Cong., 24th, Montreal, 1972, sec. 4, p. 241-251.

Kalyuzhnyi, V. A., 1965, The homogenization curves in mineralogical thermometry and their construction, in N. P. Ermakov and others, Research on the nature of mineral-forming solutions: New York, Pergamon Press, p. 565-577.

Kelly, W. C., and Turneaure, F. S., 1970, Mineralogy, paragenesis, and geothermometry of the tin and tungsten deposits of the Eastern Andes, Bolivia: Econ. Geology, v. 65, p. 609-680.

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

Kirkham, R. V., 1971, Intermineral intrusions and their bearing on the origin of porphyry copper and molybdenum deposits: Econ. Geology, v. 66, p. 1244-1249.

Koster van Groos, A. F., and Wyllie, P. J., 1969, Melting relationships in the system $NaAlSi_3O_8-NaCl-H_2O$ at one kilobar pressure, with petrological applications: Jour. Geology, v. 77, p. 581-605.

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

Logsdon, M. J., 1969, A fluid inclusion study of the porphyry copper deposits at Ray and San Manuel, Arizona [abs.], in Edwin Roed-

der, ed., Fluid inclusion research—Proceedings of COFFI, 1969: p. 20. [1972]

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

Metz, R. A., and Rose, A. W., 1966, Geology of the Ray copper deposit, Ray, Arizona, in Geology of the porphyry copper deposits, southwestern North America: Tucson, Ariz., Arizona Univ. Press, p. 176–188.

Meyer, Charles, and Hemley, J. J., 1967, Wall rock alteration, in H. L. Barnes, ed., Geochemistry of hydrothermal ore deposits: New York, Holt, Rinehart, and Winston, Inc., p. 166–235.

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

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

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

———1972, Fluid inclusion studies of some gold deposits in Nevada: U.S. Geol. Survey Prof. Paper 800–C, p. C15–C19.

———1973, Geochemical studies in the Park City district, Utah—I, Ore fluids in the Mayflower mine: Econ. Geology, v. 68, p. 34–51.

———1975, Fluid inclusion studies of vein, pipe, and replacement deposits, northwestern San Juan Mountains, Colorado: Econ. Geology, v. 70, p. 1448–1462.

Nash, J. T., and Cunningham, C. G., Jr., 1973, Fluid-inclusion studies of the fluorspar and gold deposits, Jamestown district, Colorado: Econ. Geology, v. 68, p. 1247–1262.

———1974, Fluid-inclusion studies of the porphyry copper deposit at Bagdad, Arizona: U.S. Geol. Survey Jour. Research, v. 2, no. 1, p. 31–34.

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

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

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

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

———1967, Fluid inclusions as samples of ore fluids, in H. L. Barnes, ed., Geochemistry of hydrothermal ore deposits: New York, Holt, Rinehart, and Winston, Inc., p. 515–574.

———1971, Fluid inclusion studies on the porphyry-type ore deposits at Bingham, Utah, Butte, Montana, and Climax, Colorado: Econ. Geology, v. 66, p. 98–120.

———1972, Composition of fluid inclusions, in Michael Fleischer, tech. ed., Data of geochemistry [6th ed.]: U.S. Geol. Survey Prof. Paper 440–JJ, 164 p.

Roedder, Edwin, and Coombs, D. S., 1967, Immiscibility in granitic melts, indicated by fluid inclusions in ejected granitic blocks from Ascension Island: Jour. Petrology, v. 8, p. 417–451.

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

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

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

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

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

Takenouchi, Suhune, and Kennedy, G. C., 1964, The binary system H_2O–CO_2 at high temperatures and pressures: Am. Jour. Sci., v. 262, p. 1055–1074.

Theodore, T. G., and Blake, D. W., 1975, Geology and geochemistry of the Copper Canyon porphyry copper deposit and surrounding area, Lander County, Nevada: U.S. Geol. Survey Prof. Paper 798–B, 86 p.

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

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

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

Young, R. S., 1968, Mineral exploration and development in Maine, in J. D. Ridge, ed., Ore deposits of the United States, 1933–1967 (Graton-Sales Volume), V. 1: Am. Inst. Mining, Metall. and Petroleum Engineers, p. 125–189.