Synthetic fluid inclusions in natural quartz I. Compositional types synthesized and applications to experimental geochemistry

S. MICHAEL STERNER
Department of Geosciences, The Pennsylvania State University, University Park, PA 16802

and

ROBERT J. BODNAR
Chevron Oil Field Research Company, P.O. Box 446, La Habra, CA 90631

(Received March 26, 1984; accepted in revised form September 18, 1984)

Abstract—Synthetic fluid inclusions having a wide range of geologically applicable compositions in the C-O-H-S-Na-K-Ca-CI-Cu-Fe system have been formed by healing fractures in inclusion-free natural quartz and by precipitating new quartz overgrowths on an original "seed" crystal. Inclusion types synthesized include: (1) liquid-rich, pure H2O inclusions of primary and secondary origin, (2) pure H2O inclusions with the critical density, (3) liquid-rich inclusions containing undersaturated aqueous solutions of NaCl or KCl or CaCl2, or mixtures of the three salts, (4) H2O-NaCl inclusions containing halite daughter minerals, (5) H2O-NaCl-KCl inclusions containing halite and sylvite daughter minerals, (6) H2O-CO2 inclusions of various compositions containing liquid H2O and either CO2 vapor or CO2 liquid, or both, at 25°C, (7) H2O-CO2-NaCl inclusions containing an aqueous phase, liquid and vapor CO2, and halite at 25°C, (8) C-O-H inclusions containing liquid H2O, a CO2-H2O liquid phase and graphite daughter minerals at 25°C, (9) H2O-NaCl inclusions containing a chalcopyrite daughter mineral, and (10) inclusions representing trapping of the coexisting, immiscible fluids in the H2O-NaCl, H2O-CO2, NaCl, and Na-C-O-H systems.

The inclusions exhibit uniform phase ratios at room temperature, and the temperatures of various phase changes within individual inclusions agree with those predicted from experimental and theoretical data, indicating that the inclusion fluid has the same composition and density as the parent solution. These 'miniature autoclaves' thus may be used to study various problems related to fluid inclusion research, to calibrate analytical equipment used to study natural inclusions, and to study phase equilibria, solubility and PVT relations of a variety of chemical systems.

INTRODUCTION

FLUID INCLUSIONS are microsamples of fluid trapped as imperfections within crystals during or subsequent to mineral formation. The study of fluid inclusions has found wide application in virtually all disciplines of the geologic sciences because of the wealth of data that may be obtained by performing a few relatively simple tests. However, many questions remain concerning the mechanisms of trapping of inclusions and the changes that might occur following initial fluid entrapment (see ROEDDER, 1984, Chapters 2, 3). Furthermore, the validity of many of the assumptions employed in fluid inclusion data collection and interpretation have yet to be verified.

Previous studies have shown that synthetic fluid inclusions may be used to test these assumptions and to study mechanisms of inclusion formation. Thus, ROEDDER and KOPP (1975) tested the validity of the fluid inclusion pressure correction using inclusions in synthetic quartz, and SHELETON and ORVILLE (1980) and MAZE et al. (1981) examined the processes involved in inclusion formation using synthetic inclusions. In this paper we present the results of an experimental study in which many of the compositionally-distinct types of fluid inclusions found in nature have been produced synthetically, and outline several potential applications of these 'miniature autoclaves' to fluid inclusion research and experimental geochemistry.

EXPERIMENTAL PROCEDURE

Synthetic fluid inclusions were formed by healing fractures in natural quartz at various temperatures and pressures and in the presence of various fluid compositions. Cylindrical cores 4.5 mm in diameter and 1-2 cm in length were cut from inclusion-free Brazilian quartz crystals and fractured by subjecting the quartz to thermal shock. Fracturing was accomplished by heating the cores to 350°C and then, immediately upon removal from the oven, quenching the cores in cold distilled water. Tests showed that 350°C was the optimum temperature to produce a large number of closely spaced fractures without causing the core to disintegrate.

After drying in a vacuum oven at 150°C overnight, the fractured cores were sealed with an arc-welder in noble-metal capsules along with the appropriate starting materials to generate the desired fluid composition at experimental conditions. The capsules were placed into either cold-seal or internally heated pressure vessels, depending on the experimental conditions, which ranged from 200°C to 850°C and 0 to 7 kbar. Experiment durations ranged from 3 hours to 87 days. After quenching, the quartz cores were cut into approximately 1 mm thick disks, polished on both sides, and examined with a petrographic microscope equipped with a Fluid, Inc. adapted USGS gas-flow heating/cooling stage.

RESULTS

The purpose of this study was to experimentally reproduce the different compositional types of fluid
inclusions found in nature. Most natural fluid inclusions have compositions that are closely approximated by the C-O-H-S system, plus various salts of which NaCl, KCl and CaCl₂ are the most common (ROEDDER, 1972). Lesser amounts of N₂, Ar, He, MgCl₂ and metals are also reported. Although in some inclusions these components are present in relatively large amounts (ROEDDER, 1984).

Pure H₂O inclusions

One of the simplest types of fluid inclusions found in nature contains essentially pure water; three synthetic inclusions formed by heating fractures in quartz at 600°C and 3 kbar in the presence of pure water are shown in Fig. 1. Each inclusion contains a liquid phase wetting the walls plus a water vapor bubble (essentially a vacuum) produced by differential shrinkage of the quartz and the trapped fluid during quenching from experimental conditions (600°C and 3 kbar) to room temperature. All of the inclusions appear to have the same liquid-vapor ratio when examined under the microscope. More importantly, the observed volume percent vapor at room temperature (~30%) is consistent with that predicted by ratio of the density of water at run conditions (600°C and 3 kbar, ρ_{H₂O} = 0.689 g·cm⁻³; BURNHAM et al., 1969) to the density of water at room temperature (25°C and the equilibrium vapor pressure, 0.032 bars, ρ_{H₂O} = 0.997 g·cm⁻³; KEENAN et al., 1978).

The liquid-vapor ratio or bulk density of an inclusion may also be determined from the measured homogenization temperature and known PVT properties of the inclusion fluid. When heated, the vapor bubble shrinks in size until finally, at the homogenization temperature, the bubble disappears and the inclusion contains a single phase with a density which corresponds to the density of pure water at formation conditions, provided that the inclusion has trapped a fluid with the same density as that of the parent solution. The measured homogenization temperature of these inclusions, approximately 311°C, does indeed correspond with the predicted homogenization temperature and indicates that these inclusions have the same density as that of the fluid present when the fracture healed. Similarly, the freezing temperature of these inclusions is 0.0°C, again consistent with the properties of pure water.

1 KENNEDY (1950) reports that the lower critical end-point in the silica-water system should be about 0.4 degrees higher than the critical end-point for pure water, although his experimental method was not sufficiently sensitive to actually measure the effect of dissolved silica on the elevation of the pure water critical end-point. All pure water critical density inclusions tested in this study homogenized at 374.1°C to 374.2°C. The difference between the predicted critical temperature of silica-saturated water (~374.5°C) and the measured homogenization temperature may be due to thermocouple error or, more likely, the slow rate of quartz dissolution in pure water during the heating experiments.

The distribution of fluid inclusions within the host crystal and the size and shape of individual inclusions have been used as criteria for distinguishing primary from secondary inclusions in natural samples. However, as ROEDDER (1979) points out, the exceptions to the rules are sufficiently common to invalidate this approach. In this respect, it should be noted that the secondary inclusions shown in Fig. 1 are of regular or equant shape, trending towards a negative crystal morphology. Characteristics often attributed only to primary inclusions. This feature is, however, characteristic of secondary inclusions in metamorphic rocks (J. TOURET, pers. commun., 1984). Within a given sample, and within individual fracture planes, inclusions formed in this study display a wide range in morphologies, from very irregularly-shaped to negative crystal-shaped. In general, smaller synthetic inclusions tend to be more regularly-shaped than the larger inclusions. The few primary inclusions formed in this study by precipitation of quartz overgrowths on the original quartz core also display a range in morphologies, a pure water primary inclusion formed at 600°C and 3 kbar and approaching a negative crystal morphology is shown in Fig. 2.

In order to evaluate the accuracy and precision with which the density of a synthetic fluid inclusion can be experimentally controlled, we attempted to synthesize pure water fluid inclusions with the exact critical density (0.317 g·cm⁻³; KEENAN et al., 1978). Inclusions were formed at 800°C and 1350 bars, i.e., along a P-T projection of the water critical isochore. Fluid inclusions with the critical density homogenize by fading of the meniscus between the liquid and vapor phases. If the inclusion density varies even slightly from the critical density, however, the inclusion will homogenize either by expansion or shrinkage of the vapor bubble, depending on the phase to which the inclusion homogenizes. Thus, by monitoring the behavior of an inclusion at homogenization, it is possible to determine whether the inclusion contains the critical density or a density greater or less than this value. Most importantly, the inclusion density may be verified independently of the measured homogenization temperature, which may vary considerably from the actual homogenization temperature owing to gradients in the stage, thermocouple error, inaccuracies in stage calibration, etc.

At 25°C, a pure water inclusion having the critical degree of fill contains 68 volume percent vapor (Fig. 3). When heated, the vapor bubble shrinks in size slightly, and occupies 56 volume percent of the inclusion at 350°C (Fig. 4). With continued heating, the liquid to vapor ratio remains essentially constant and, at 374.1°C, the meniscus between the liquid and vapor phases disappears, resulting in a one-phase fluid inclusion containing pure water with the critical density (Fig. 5). All of the inclusions tested in this sample homogenized by fading of the meniscus between the liquid and vapor phases. This behavior
only occurs when the bulk inclusion density equals the critical density, which suggests that the densities of synthetic inclusions can be very accurately controlled,\(^2\) provided PVT properties of the inclusion fluids are known. Similarly, PVT properties and phase equilibria (BODNAR and STERNER, 1984) may be determined using synthetic inclusions, as described in more detail below.

**H\(_2\)O-Salt inclusions**

Many fluid inclusions, particularly those found in near-surface environments, contain low salinity brines in which NaCl, KCl and CaCl\(_2\) are the major dissolved salts. Aqueous fluid inclusions containing each of these salts, as well as combinations of the three, at various concentrations, have been synthesized. A plane of fluid inclusions trapped at 600°C and 3 kbar, each containing a 10 wt.% NaCl solution and all exhibiting the same liquid-to-vapor ratio, is shown in Fig. 6. Homogenization temperatures (\(~233^\circ\)C) and freezing temperatures (\(~6.6^\circ\)C) of these inclusions are exactly as predicted by experimental data for a 10 wt.% NaCl solution. These observations indicate that the inclusions trapped a homogeneous fluid phase having the same composition and density as that of the parent solution.

The salt content of many fluid inclusions found in nature is sufficiently high that, upon cooling from formation temperatures, one or more solid phases are precipitated as daughter minerals, the most common of which is halite. Four fluid inclusions, each with a composition of 41 wt.% NaCl and each containing a vapor bubble, an NaCl-saturated aqueous phase, and a halite daughter mineral are shown in Fig. 7; formation conditions were 600°C and 3 kbar. Again, the uniform phase ratios indicate that the inclusions all have the same density and the same composition, and the temperature of dissolution of the halite crystal (341°C) is consistent with experimental data for a 41 wt.% NaCl composition (POTTER et al., 1977).

In addition to halite, many fluid inclusions, particularly those from the porphyry copper deposits, contain a second isotropic solid phase identified as sylvite. Figures 8 and 9 each show two synthetic inclusions formed at 600°C and 3 kbar, each with a composition of 22.5 wt.% KCl and 30.4 wt.% NaCl and containing, in addition to liquid and vapor, sylvite and halite daughter minerals. Because halite and sylvite are both cubic and isotropic, it is often difficult to distinguish between the two at room temperature when they occur together as daughter minerals. However, because of their significantly different solubilities, they are easily differentiated during heating tests (see ROEDDER, 1971, Fig. 32).\(^3\) During heating from room temperature to 100°C, KCl solubility increases rapidly whereas NaCl solubility actually decreases a small amount. As a result, the sylvite crystal becomes smaller and the halite crystal becomes slightly larger, as evidenced by the noticeably sharper corners on the halite cube at 100°C as compared to 25°C (Figs. 9 and 10). The halite crystal remains essentially constant in size with continued heating until the sylvite is completely dissolved (Fig. 11). With further heating the halite crystal begins to dissolve, increasing the Na/K ratio of the inclusion fluid (Fig. 12), and continues to do so at an increasing rate until it has completely dissolved (Fig. 13).

**H\(_2\)O-CO\(_2\) inclusions**

Carbon dioxide-bearing fluid inclusions are common in several geologic environments, including metamorphic rocks, olivine nodules, Athabasca-type uranium deposits, porphyry molybdenum and tin deposits, and both metamorphic and epithermal precious metal deposits. When observed at room temperature, carbon dioxide-water inclusions contain a CO\(_2\)-saturated aqueous phase plus CO\(_2\) vapor or CO\(_2\) liquid, or both, depending upon the fluid composition and temperature of formation.

H\(_2\)O-CO\(_2\) fluid inclusions with a low CO\(_2\) content and those formed at relatively low pressures contain an aqueous phase and a CO\(_2\)-rich vapor bubble at 25°C, as shown by the inclusion containing 10 mole% CO\(_2\) in Fig. 14. Thus, optical examination of this and similar inclusions at room temperature shows no evidence of CO\(_2\); rather, the inclusion appears similar to the simple H\(_2\)O or H\(_2\)O-salt inclusions shown in Figs. 1 and 6. However, when the inclusion is cooled, a small amount of liquid CO\(_2\) condenses from the vapor to form a thin rim around the vapor bubble (Fig. 15). The amount of cooling required to form liquid CO\(_2\), and the amount of liquid CO\(_2\) produced, depend upon the bulk composition of the inclusion and the bulk density of the CO\(_2\) phase. As the CO\(_2\) content and density decrease, increasingly lower temperatures are required to produce liquid CO\(_2\); inclusions containing only a few mole percent CO\(_2\) will never generate an observable liquid CO\(_2\) phase, even when cooled to the CO\(_2\) triple point of \(-56.6^\circ\)C (CONNOLLY and BODNAR, 1983). If a liquid CO\(_2\)-

\(^2\) ROEDDER (pers. commun., 1984) points out that, because of the relatively flat top of the water solvus in T-density space, a fairly wide range in densities might appear to homogenize by critical behavior. However, we used exceedingly slow heating rates (on the order of 0.1 to 0.3°C per minute) during our tests and still observed what appeared to be homogenization by fading of the meniscus. This suggests that the inclusion density is very close to the critical density, although the magnitude of the possible error cannot be evaluated.

\(^3\) Halite and sylvite may also be differentiated during freezing tests because NaCl reacts with the solution at low temperatures to form the birefringent dihydrate NaCl\(_2\)-2H\(_2\)O (hydrohalite) whereas sylvite does not react with water on cooling.
bearing H₂O-CO₂ inclusion is cooled sufficiently slowly, the liquid CO₂ phase will react with water to form the clathrate hydrate compound CO₂-5%H₂O. The clathrate usually forms in the inclusion at the position formerly occupied by liquid CO₂, that is, between the CO₂ vapor bubble and the ice or meta-stable liquid H₂O phase (Fig. 16).

H₂O-CO₂ inclusions with a high CO₂ content and those formed at high pressures also contain only two fluid phases at room temperature. However, owing to the higher bulk density of CO₂ in this inclusion type, the CO₂ is present as liquid rather than vapor at 25°C (i.e., the internal pressure is greater than the equilibrium vapor pressure at 25°C), as shown by the inclusion containing 50 mole% CO₂ in Fig. 17. When cooled, the liquid CO₂ phase will "boil," provided the liquid CO₂ density is sufficiently low, and generate a CO₂ vapor bubble within the liquid CO₂ phase (Fig. 18).

H₂O-CO₂ inclusions of intermediate composition, and those formed at moderate pressures, may contain both liquid and vapor CO₂ in addition to liquid water at room temperature, as exemplified by an inclusion containing 25 mole% CO₂ shown in Fig. 19. One of the phases in this inclusion type may be eliminated by heating the inclusion to homogenize the CO₂ phases (Fig. 20). The temperature and mode of CO₂ homogenization (i.e., to the liquid or to the vapor phase, or by critical behavior) define the bulk CO₂ density of the inclusion.

The H₂O-CO₂ inclusions described above are from a suite of inclusions ranging in composition from pure H₂O to ~95 mole% CO₂ that have been synthesized at 600°C and 3 kbar. The room temperature phase ratios and temperatures of various phase changes of these inclusions display a systematic variation with composition and are consistent with values predicted by an MRK equation of state (CONNOLLY and BODNAR, 1983; BODNAR and CONNOLLY, in prep.).

**Complex inclusions**

With the addition of NaCl to the H₂O-CO₂ system, it is possible to produce inclusions that contain four phases at room temperature—an aqueous phase saturated in both CO₂ and NaCl, liquid and vapor CO₂, and a halite crystal (Fig. 21). Owing to the lack of experimental data for the H₂O-CO₂-NaCl system, it is not possible to verify if the observed phase ratios and temperatures of various phase changes of this inclusion type are correct. However, the uniformity of phase ratios of inclusions in this sample would suggest that the inclusions did trap a homogeneous fluid phase at the formation conditions of 600°C and 3 kbar.

Methane-bearing inclusions are common in low-to medium-grade metamorphic rocks. Figure 22 shows two CH₄-bearing fluid inclusions formed at 600°C and 3 kbar and containing the following phases at 25°C: 1) a liquid phase composed of CH₄ and CO₂, 2) a water-rich liquid phase wetting the inclusion walls, and 3) graphite. When cooled, the CO₂-CH₄ liquid phase splits into a CO₂-rich liquid phase and a CH₄-rich vapor phase (Fig. 23). The presence of CO₂, CH₄ and graphite in these inclusions was verified by laser Raman microprobe analysis (J. D. PASTERIS, unpub. data) and by heating/freezing tests.

Experiments conducted in the H₂O-NaCl-Cu-Fe-S system at 600°C and 3 kbar produced inclusions...
containing an aqueous liquid phase, a vapor bubble, and a chalcopyrite daughter mineral* (Fig. 24). This inclusion type is common in porphyry copper deposits (cf. BODNAR and BEANE, 1980). Chalcopyrite was identified based on its color, reflectivity and crystal morphology.

All of the inclusions described above were formed in the presence of a homogeneous (one-phase) fluid. There is considerable evidence, however, to suggest that many fluid inclusions found in nature were trapped in the presence of two immiscible fluids (e.g., boiling or condensing), and many questions remain concerning the mechanisms of trapping and interpretation of such inclusions (ROEDDER and BODNAR, 1980). Four inclusions trapped from a mixture of immiscible fluids in the H$_2$O-NaCl system at 775°C and 750 bars are shown in Fig. 25; the bulk fluid composition was 5 wt.% NaCl. The two inclusions on the right trapped a high salinity liquid phase and contain liquid, vapor and three halite crystals at room temperature. The temperature of dissolution of the halite is 582°C which corresponds to a composition of 66.3 wt.% NaCl (POTTER et al., 1977). The two inclusions on the left trapped the low salinity vapor that was in equilibrium with the liquid phase, resulting in vapor-rich, two-phase inclusions at room temperature. The freezing temperature of the liquid in these vapor-rich inclusions is −2.3°C, corresponding to a composition of 3.9 wt.% NaCl. Optical examination and heating/freezing tests on inclusions in this sample suggest that most of the inclusions trapped one or the other of the two immiscible fluids present. Those few inclusions that did trap mixtures are easily recognizable owing to their anomalous (i.e., intermediate) phase ratios and temperatures of phase changes.

Synthetic fluid inclusions trapped from a mixture of immiscible fluids in the system H$_2$O-CO$_2$-NaCl at 740°C and 2 kbar are shown in Fig. 26. One type of inclusion contains liquid H$_2$O and a relatively large volume percent of liquid and vapor CO$_2$. The second type contains an aqueous phase, a vapor bubble and a halite daughter mineral. These two inclusion types represent the two coexisting immiscible fluids that

---

*It should be noted that the chalcopyrite phase does indeed dissolve when the inclusion is heated, and reappears when cooled. To our knowledge, this behavior has never been observed with any naturally-occurring chalcopyrite-bearing inclusions. This behavior suggests to us that failure to dissolve chalcopyrite in natural inclusions is not a result of kinetic factors and is not a result of trapping a solid phase, but rather may be a result of post-depositional changes in the inclusion chemistry, possibly from diffusional loss of hydrogen through the inclusion walls.
workers have reported that they may not (BARNES during sample preparation or laboratory testing, or determine under what conditions inclusions stretch although our results suggest that inclusions trap rep-

inclusion geothermobarometry is based is that the reconciling this apparent contradiction.

A third example of fluid inclusions trapped from immiscible fluids at 600°C and 3 kbar is shown in Fig. 27. These inclusions have compositions in the Na-C-O-H system and represent a sodium carbonate-rich liquid ("melt") with minor amounts of dissolved CH₄ and H₂O, in equilibrium with a CO₂- and CH₄-rich aqueous vapor phase. As noted in the previous examples of inclusions formed from immiscible fluids, the phase ratios of each of the two types of inclusions shown are remarkably uniform. However, unlike the two examples above, inclusions which appear to have trapped mixtures are extremely rare throughout the entire sample.

POTENTIAL APPLICATIONS OF SYNTHETIC FLUID INCLUSIONS

Synthetic fluid inclusions provide a means of investigating numerous problems related not only to fluid inclusion research, but also to other areas of experimental geochemistry and petrology. The most obvious application of synthetic fluid inclusions is in advancing our understanding of the processes involved in the formation of natural inclusions. For example, although our results suggest that inclusions trap representative samples of the parent solution, other workers have reported that they may not (BARNES et al., 1969); synthetic inclusions provide a means of reconciling this apparent contradiction.

One of the basic assumptions upon which fluid inclusion geothermobarometry is based is that the inclusion volume and composition remain constant after trapping. However, it is known that some inclusions do not maintain constant volume and/or composition as a result of mechanical stresses introduced during sample preparation or laboratory testing, or by temperature and pressure changes in nature (cf. BODNAR and BETHELKE, 1984; PECHER, 1981; WILKINS and BARKAS, 1978). Synthetic fluid inclusions of known density and composition may be used to determine under what conditions inclusions stretch or decrepitate, either in the laboratory or during experimentally-simulated conditions in nature.

Perhaps the most important application of synthetic inclusions will be in the calibration of various instruments used to study natural fluid inclusions. Thus, synthetic inclusions may be used to calibrate fluid inclusion heating-freezing stages, as well as other analytical apparatus used in fluid inclusion research, such as the laser Raman microprobe, laser probe mass spectrometer, and thermal decrepitation gas chromatographs, etc.

In addition to the application of synthetic fluid inclusions to studying problems directly related to fluid inclusion research, these 'miniature autoclaves' provide a means of investigating various chemical systems at conditions that are not easily attainable with currently available experimental techniques. A major limiting factor in many high temperature, high pressure experiments is the inability to satisfactorily sample the fluid at experimental conditions. However, because synthetic fluid inclusions apparently trap a representative sample of the fluid present at run conditions, and preserve this fluid during quenching to ambient conditions, the sampling problem is eliminated, or at least minimized.

As an example, phase equilibria, solubility and PVT relations in the system H₂O-NaCl have been determined using synthetic fluid inclusions and the results compared with published data. The solubility of sodium chloride in vapor-saturated water has previously been determined up to 600°C using standard techniques (POTTER et al., 1977); these data indicate that at 400°C, the solubility of NaCl is 46.1 wt.%. The temperature of dissolution of halite in a synthetic inclusion formed from a 46.1 wt.% solution is ~395°C, which is in close agreement with the predicted value and within experimental error.

The properties of many geologic fluids may be approximated by H₂O-NaCl. In particular, data for the system H₂O-NaCl have been used to model vapor exsolution from cooling, rising magma bodies. This phenomenon is often the triggering mechanism of explosive volcanic eruptions, such as that which occurred at Mt. St. Helens in May 1980, and calculations of the amount of energy generated by vapor-phase separation, or second "boiling", requires knowledge of the density and physical state of the exsolved fluid. Such data are presently not known at magmatic temperatures and pressures, but may be determined relatively easily using synthetic fluid inclusions. For example, at 700°C, the one phase-two phase boundary for a 5 wt.% NaCl solution is at ~1100 bars (SOURIRAJAN and KENNEDY, 1962). At pressures higher than this, a homogeneous fluid with a composition of 5 wt.% NaCl is stable; at lower pressures the fluid will split into two immiscible fluids. Thus, at a pressure of 1000 bars, two fluids, with compositions of ~3.8 and ~56 wt.% NaCl, are in equilibrium (SOURIRAJAN and KENNEDY, 1962). Fluid inclusions trapped at >1100 bars will all have the same composition (5 wt.% NaCl) and the same phase ratios at room temperature. Fluid inclusions formed at 700°C and 1000 bars in the presence of a fluid with a bulk composition of 5 wt.% NaCl will be of two types at room temperature—a two-phase, vapor-rich type with a composition of 3.8 wt.% NaCl and a three-phase, liquid-rich type with a composition...
of 56 wt.% NaCl containing an NaCl daughter mineral. Therefore simple optical examination of synthetic fluid inclusions trapped at various temperatures and pressures will reveal the position of the phase boundary, and heating and freezing tests on inclusions trapped in the two-phase field will provide the compositions of the coexisting phases.

Volumetric (PVT) data are required to interpret the results of heating/freezing tests on fluid inclusions, but such data are available only for a few fluids of geologic interest and for only a limited range of PTX conditions. These data are, however, easily obtainable using synthetic fluid inclusions because inclusions represent, to a first approximation, constant volume systems. For example, an H₂O-NaCl fluid inclusion grown at 600°C and 3 kbar and containing 10 wt.% NaCl homogenizes at 323°C; the vapor pressure in the inclusion at the homogenization temperature is 110 bars (HAAS, 1976). Because isochore lines may be approximated by straight lines, a line connecting the P and T at homogenization (110 bars, 323°C) with the P and T of formation (3 kbar, 600°C) defines an isodensity line for a 10 wt.% solution. The densities of H₂O-NaCl solutions along the liquid-vapor curve are known (HAAS, 1976), providing a value of 0.781 g · cm⁻³ for the projected isochore. If density data along the liquid-vapor curve were not available, the density could have been estimated from the liquid-to-vapor ratio at room temperature (assuming a density of 1.0 g · cm⁻³ for the liquid phase, the vapor bubble would occupy ~22 volume percent of the inclusion at room temperature).

Solubilities of slightly or moderately soluble phases, such as ore metals, may be determined using synthetic inclusions. Thus, the solubility of chalcopyrite in chloride solutions at magmatic conditions, a concern of those interested in the genesis of porphyry copper deposits, can be estimated by measuring the size of the chalcopyrite daughter mineral in synthetic fluid inclusions such as that shown in Fig. 24. Then, the total inclusion volume may be determined from the vapor bubble volume and fluid density at the homogenization temperature (BODNAR, 1983) and used to calculate the total amount of chalcopyrite (or copper) in the inclusion. Alternatively, solubilities can be determined by measuring the dissolution temperature of a daughter mineral present in an inclusion formed from a solution of known composition. Similarly, recent advances in the ability to analyze for dissolved species in individual inclusions may permit determination of the solubilities of species which do not precipitate a daughter mineral upon cooling.

**SUMMARY**

Synthetic fluid inclusions representing many of the various compositional types found in nature have been formed by healing fractures in inclusion-free natural quartz. Observed phase ratios at room temperature and temperatures of various phase transitions indicate that the inclusions trap fluids representative of the parent solution. Therefore, synthetic fluid inclusions may be used to investigate numerous problems related to fluid inclusion research and experimental geochemistry, including: (1) mechanisms of trapping of inclusions and changes that might occur following inclusion formation, (2) calibration of equipment used to analyze natural inclusions thermometrically or chemically, and (3) determination of PVT, phase equilibria and solubility properties of various fluids of geologic interest.

**Acknowledgements**—Discussions with and reviews of earlier versions of this manuscript by D. M. Kerrick, C. W. Burnham, E. Roedder, P. M. Bethke, C. A. Kuehn, T. J. Reynolds, C. J. Kaiser, and J. Touret have been extremely helpful. In addition, we wish to express our appreciation to T. J. Reynolds for assistance with microthermometric analysis, to J. D. Pasteris for providing Raman microprobe analyses of several samples, and D. M. Kerrick and C. W. Burnham for making their laboratory facilities available to us. Finally, we acknowledge M. Frank for expertly typing numerous versions of this manuscript.

**REFERENCES**


