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Formation of synthetic fluid inclusions in natural quartz

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Abstract

Planes of water-rich fluid inclusions were created in natural quartz by partially annealing laboratory-induced fractures in a hydrothermal apparatus at 600°C and 2 kbar in the presence of water. The size, distribution, and morphology of the synthetic fluid inclusions show a remarkable similarity to fluid inclusions in quartz from metamorphic terranes. Fluid inclusion trains appear to be localized along former fracture-surface step lineations; their size varies proportionally and abundance inversely with the spacing of step lineations on the original fracture surface. Thin island-like inclusions grade to elongate ellipsoids with minimum dimensions considerably greater than the original crack width and appear to have developed at the expense of the immediate crack walls. The surface of the unclosed portion of the crack appears unchanged, suggesting a preferential solution and precipitation phenomenon where the inclusions developed. Fluid density of the inclusions, determined by microthermometric measurement of the homogenization temperature, is in agreement with the fluid density under the experimental annealing conditions. These observations suggest that the total density of the trapped fluid in the inclusions is the same as that of the homogeneous fluid phase present at the time of fluid inclusion formation.

Introduction

Naturally-formed fluid inclusions have been used extensively to deduce the pressure, temperature, and composition of fluid present during various geologic processes (*e.g.* Hollister and Burruss, 1976; Weisbrod *et al.*, 1976; Kreulen, 1977; Walther, 1978; Crawford *et al.*, 1979; Roedder, 1979). The vast majority of these studies has focused on fluid inclusions in quartz, because they are generally abundant and easily observed.

Previous experimental investigations of fluid inclusions (*e.g.* Roedder and Kopp, 1975) have considered the formation of fluid inclusions in synthetic quartz grown under known conditions. Although such studies have found that the synthetic inclusions have trapped a representative sample of the surrounding fluid in terms of density, the fluids, usually metallic hydroxide solutions, are not geologically realistic.

Lemmlein (1929) and Lemmlein and Kliya (1952) found that fluid inclusion growth and morphology could be observed by cracking crystals of water-soluble salts (halite and sodium nitrate) at elevated temperatures and allowing them to heal spontaneously with declining temperature. Their use of time-lapse photography documented necking-down phenomena with decreasing temperature, but their fracture-healing experiments applied only to highly soluble host minerals. The relationship between fluid inclusion size, morphology, composition, and mechanism of formation in less soluble minerals, such as quartz, is still not fully understood.

By fracturing and then annealing natural quartz at 600°C and 2 kbar in the presence of water, we investigated the mechanisms and nature of formation of fluid inclusions under more geologically realistic conditions.

Methods

Rectangular prisms (14 mm by 1.5 mm by 1.5 mm) were cut from a single crystal of optically clear, inclusion-free quartz from an Alpine-type vein. The prisms were then drilled along one of their minor axes and were fractured by compression along their major axes (Fig. 1), using a method similar to that of Martin (1972). The major axes of the prisms correspond to the *c* axis of the quartz crystal from which

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[1] Deceased.

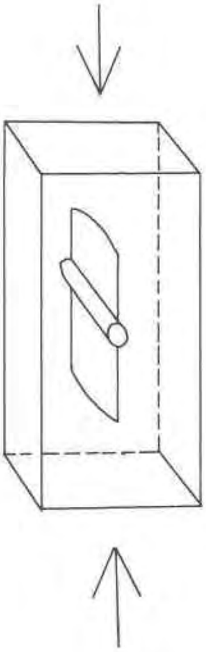

Fig. 1. Schematic diagram of sample geometry, illustrating axial crack radiating from a circular hole. Arrows indicate direction of uniaxial compression and *c* axis of quartz. After Martin (1972).

they were cut. The fractures were then optically examined and the prisms placed in a hydrothermal apparatus at 600°C and 2 kbar water pressure in the presence of water for run durations of 2 and 66 hours.

Hydrothermal treatment times were varied to allow different steps in the quartz annealing and fluid inclusion formation process to be observed. Fluid inclusion population size, distribution, and morphology could then be compared to features of the previously unhealed fractures. A Chaixmeca microscope heating stage (Poty *et al.*, 1976) was used to obtain homogenization temperatures for the synthetic two-phase fluid inclusions.

Results

The size, distribution, and morphology of the synthetic fluid inclusions show a remarkable similarity to natural fluid inclusions in quartz from metamorphic terranes (Roedder, 1962; Touret, 1977). It is apparent that features on the untreated fracture surface affect the subsequent fluid inclusion development and morphology.

Comparison of Figures 2A and 2B suggests that fluid inclusion trains have formed along former fracture-surface step lineations. These step lineations are lines paralleling the direction of maximum compression and are stress-field-dependent. Among the ellipsoidal inclusions, fluid inclusion size varies proportionally and abundance varies inversely with the spacing of step lineations on the original fracture surface. Where step lineations were closely spaced, one to two μm apart, a large number of small (1–2 μm) inclusions develop. Where step lineations were more widely spaced, more than 5 μm apart, a smaller number of larger (5–10 μm) inclusions develop.

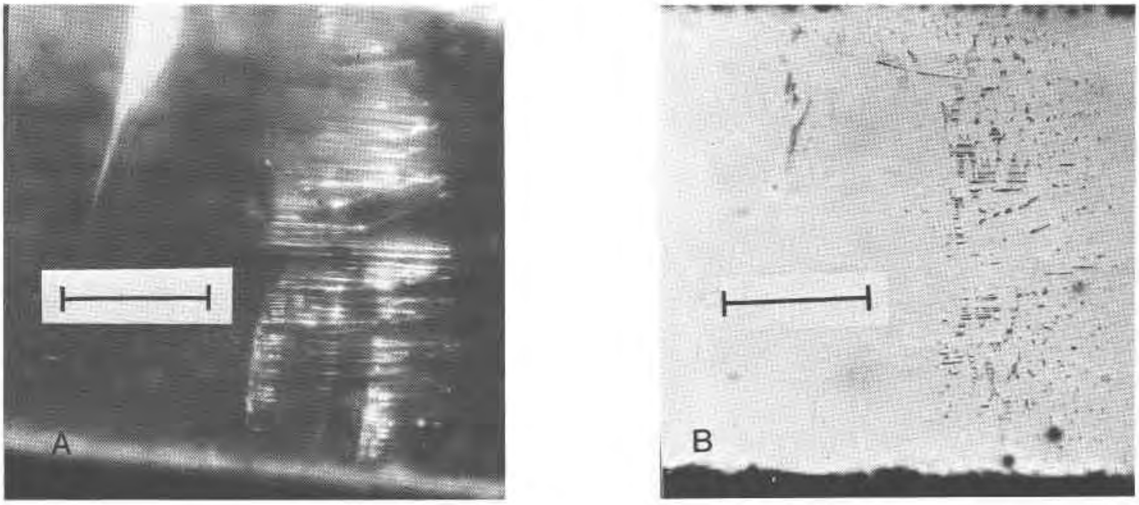

Fig. 2. Laboratory-induced fracture planes in natural quartz. (A) Oblique reflected light photomicrograph of an untreated fracture plane showing variably spaced step lineations. The fracture extends to the right from the hole (not shown). Two faint lineations form a wedge shape at the center of the fracture front. Scale bar = 0.25 mm. (B) Transmitted light photomicrograph of the identical fracture plane after 66 hours of hydrothermal treatment at 600°C and 2 kbar in the presence of water. Fluid inclusion distribution in the synthetic inclusion plane displays a marked similarity to features of the unhealed fracture. Fluid inclusion trains parallel the two former step lineations, making a wedge shape at the center of the fracture front. Scale bar = 0.25 mm.

At 25°C the fluid inclusions consist of two phases, liquid water and a gas bubble. The ratio of gas to liquid volume appears constant among all the inclusions. The inclusions vary from thin island-like inclusions to spheroids and elongate ellipsoids (maximum axes up to three times their minimum axes). The minimum dimensions of the latter are considerably greater than the original crack width of 0.1–0.2 μm, as estimated from interference fringes observed in reflected light. The inclusions show no preferential growth pattern with respect to crystallographic directions. Neither do they display negative quartz crystal forms common to CO_2-rich inclusions (Hollister and Burruss, 1976).

We find a sequential transition occurring in about 100 μm from unhealed fracture to partial annealing of the fracture front into very thin island-like inclusions, to the formation of individual ellipsoidal inclusions (Fig. 3). The ellipsoidal inclusions appear to have developed at the expense of the immediate crack walls, while the surface of the unclosed portion of the crack appears unchanged. This indicates to us that the ellipsoidal fluid inclusions have formed by preferential solution and precipitation of quartz in conjunction with the fracture annealing process. This solution and precipitation mechanism, together with the dimensions of the inclusions, precludes the possibility that the ellipsoidal inclusions are simply trapped between two surfaces. This mechanism is similar to that proposed by several authors (Lemmlein, 1929; Lemmlein and Kliya, 1952; Roedder, 1962). It appears that fluid inclusion development in natural inclusion planes in metamorphic quartz also results from such annealing of natural fractures (Tuttle, 1949).

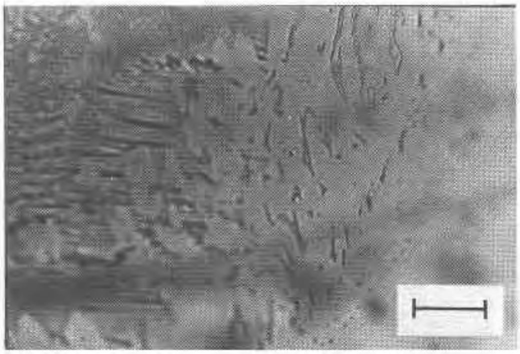

Fig. 3. Transmitted light photomicrograph of transitional development of fluid inclusions in synthetic inclusion plane after 66 hours of hydrothermal treatment at 600°C and 2 kbar in the presence of water. From left to right, unhealed fracture anneals to large island-like inclusions and to individual ellipsoidal fluid inclusions. Scale bar = 0.05 mm.

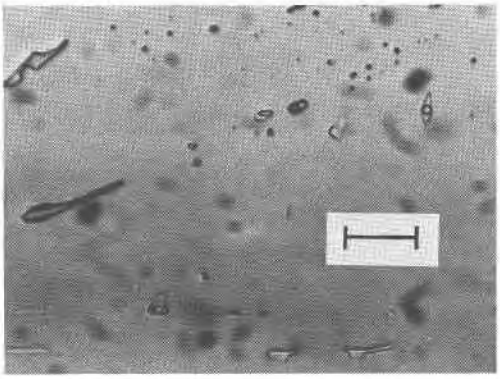

Fig. 4. Transmitted light photomicrograph of trains of synthetic fluid inclusions. Inclusions are two-phase, consisting of liquid water and a gas bubble. They homogenize into the liquid phase at temperatures between 345.5 and 347.0±1.8°C. Scale bar = 0.025 mm.

The densities of the liquid and vapor phases which coexist along the two-phase boundary in the system H_2O are known to be a function of temperature. Therefore, the temperature at which a two-phase H_2O inclusion becomes homogeneous, in either the vapor or liquid phase, determines the total density of the fluid within the inclusion.

The largest ellipsoidal inclusions, 5–10 μm, are ideal for microthermometric study (Fig. 4). Based on 20 measurements, the synthetic two-phase fluid inclusions homogenize into the liquid phase at temperatures between 345.5 and 347.0±1.8°C. These temperatures include a 6.0°C instrumental correction, based on calibration runs on the Chaixmeca stage. The homogenization temperatures correspond to liquid densities between 0.59 and 0.58 along the liquid–vapor equilibrium curve in the pure H_2O system (Burnham *et al.*, 1969). These densities correspond to the densities of supercritical H_2O fluid at 2 kbar and 598 to 602±4°C (Burnham *et al.*, 1969; Schmidt, 1969), in agreement with the experimental annealing conditions of 600°C and 2 kbar. Change in the volume of alpha quartz between 346° and 600°C amounts to only 0.65% (Ghiorso *et al.*, 1979), and therefore has no significant effect on the density and therefore homogenization temperature of the inclusions. The run temperature is about 25°C below the alpha–beta quartz transition at 2 kbar (Helgeson *et al.*, 1978).

Conclusions and implications

Variations in ellipsoidal fluid inclusion size and distribution can be directly related to former fracture-surface features. Fluid inclusion size varies proportionally and abundance varies inversely with the spacing of step lineations on the original fracture surface. Fluid is trapped in fractures by annealing of the immediate fracture surface. The annealing process involves the solution and precipitation of quartz, rather than a simple trapping between two surfaces.

Homogenization temperatures of the two-phase inclusions yield fluid densities in agreement with the density of supercritical H_2O under the experimental conditions. This suggests that the total density of trapped fluid in the inclusions is the same as that of the homogeneous fluid phase present at the time of fluid inclusion formation.

Further applications of this experimental technique should address the problems of possible compositional and isotopic fractionations within the fluid phase during fluid inclusion genesis by using mixed volatile fluids, salt solutions, and immiscible liquids of known compositions.

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