“Pneumatolysis” and fluid-inclusion evidence for crystal growth from a vapor phase

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Abstract

The term pneumatolysis has been used for various geological environments, but the essential feature of most usage has been mineral formation from a hot fluid of low density. As an arbitrary limit, this density is here assumed to be \( \leq 0.1 \text{ g cm}^{-3} \). The best evidence for pneumatolytic conditions is found in the presence of vapor-rich fluid inclusions, but considerable ambiguity remains and hence such evidence must be used with care. Many samples formerly thought to be of pneumatolytic origin were more likely formed from dense solutions that boiled or effervesced, but three examples of presumably valid vapor-phase crystallization in volcanic rocks are given. These are from Summit Rock, Oregon, the Thomas Range, Utah, and the Wah Wah Mountains, Utah. The first consists of brilliant crystals of plagioclase and orthopyroxene projecting into lenticular cavities in an andesite plug; the second and third consist of topaz and red beryl crystals, respectively, in vugs and fractures in rhyolite. All three are believed to have formed by diffusion of their “nonvolatile” constituents through a static low-density vapor phase, and hence are truly pneumatolytic.

PREVIOUS USE OF THE TERM “PNEUMATOLYSIS”

Semantics in science can be a source of endless and sometimes quite sterile arguments that are best avoided. However, in the present paper semantics must be discussed, as they have been the cause of some confusion. Over the years, the term pneumatolysis has been applied to processes occurring in several very disparate geological environments. It was originally introduced by Bunsen for fumarolic alteration of rocks in volcanic areas. It has also been used for all magmatic processes between about 400 and 600°C, under the assumption that such fluids are always supercritical and hence “gaseous”. The term has also been applied almost automatically to most contact metamorphic assemblages, particularly if fluorine or boron was introduced. In general, it has been used for any magmatic process in which the fluid involved was thought to be a “gas”. The exact usage of the term in any given paper is inescapably connected with the implicit or explicit definition adopted by the writer for the terms vapor or gas, and how these two are differentiated from the term liquid. Thus Ermakov (1950) has used the term gas arbitrarily for inclusions that have \(<50\%\) liquid at room temperature, or for inclusions that homogenize in the gas phase.

In a one-component system, for example, \( \text{H}_2\text{O} \) or \( \text{CO}_2 \), the terms liquid and gas can be rigorously defined only along the two phase curve, i.e., when they are in equilibrium with each other. All other fluids in each such system are part of a continuum that can be subdivided only by arbitrary lines that have no physical reality. The semantic problem of gas vs liquid becomes even more difficult as the system considered involves more constituents. Thus, the assumption that a specific
temperature range corresponds to supercritical and hence "gaseous" conditions is inappropriate, as the critical temperatures of natural fluids range widely depending on composition. For this and other reasons, it is most appropriate to use the term _immiscibility_ for _any_ combination of two or more fluid phases that do not mix under specified conditions (See also Roedder and Coombs, 1967, p. 419). If the two fluids differ greatly in density, it is a convenient artifice to call them "liquid" and "vapor" (or "gas"). In the following discussion we shall arbitrarily limit the term pneumatolysis to crystal growth processes involving a fluid of density $\leq 0.1$ g.cm$^{-3}$.

**USE OF FLUID INCLUSIONS TO VERIFY A PNEUMATOLYTIC GROWTH ENVIRONMENT**

Primary fluid inclusions in a mineral are generally assumed to be samples of the fluid from which the crystal grew. If this assumption is valid, one has only to see if the fluid inclusions in a mineral trapped a low-density, volatile-rich phase to prove that the crystallization was indeed pneumatolytic. Unfortunately, the use of fluid inclusions to recognize a pneumatolytic environment is more complex in principle and frequently can yield ambiguous evidence.

**Simplest case—a single homogeneous fluid**

Most fluid inclusions, in most minerals, have indeed been trapped from a single, homogeneous fluid, be it a silicate melt, a dense, water-rich "liquid", or a low-density "vapor". In the last case, the environment can be said to be pneumatolytic, but there remain questions as to the mechanisms whereby the crystallization took place. To explore this problem, let us look at a larger scale of "fluid inclusion"—the vugs, vesicles, veins and mialoritic cavities in rocks. With a few notable exceptions, these almost invariably have leaked and are now full of air, but such cavities _require_ that at the time of their formation, a fluid phase filled the cavity. If the cavity-forming process was relatively near-surface, the fluid would have been at low pressure and could have been low density, but if formed deep, it was more likely under elevated pressure. (The only significant exception to the latter would be vugs formed by shrinkage during crystallization of a dry intrusion; if the cool outer zone supported the overlying rocks, shrinkage in the interior could form vugs filled with an extremely tenuous silicate vapor at a pressure measured in mm or $\mu$m). Examination of the inclusions in crystals lining most such cavities shows that the vugs were filled with a dense water solution which has subsequently been flushed out by groundwater and now has been replaced with air; they are simply fluid inclusions that have leaked, since they were in a porous polycrystalline rock rather than an impermeable single crystal. The largest such "inclusions" are found in the famous cavity or chamber (i.e., "Zanorysh") pegmatites of Volynia and Kazakhstan in the USSR (Ermakov, 1950). In some of these, the central cavity is as large as 200 m$^3$, but there is no real difference between these large cavities and a 1-cm cavity in a mialoritic granite; both may be lined with minerals which grew from the fluid in the cavity.

The central open cavity found in veins in many of the shallower ore deposits is similarly a fluid inclusion that has leaked. The former ore fluid is gone, but crystals that formed from this fluid may line the walls. An important distinction here,
however, is that these crystal linings are generally the result of crystallization from a flowing fluid, not from a static one. Thus, they are not exactly equivalent to the crystals lining an isolated vug or miarolitic cavity, which have formed from an essentially closed system, or to the daughter crystals in a fluid inclusion within a single crystal, which formed from a truly closed system.

The crystals lining a vein have precipitated from a flowing fluid that frequently is found to have changed in composition and/or temperature with time, as has been recorded in many studies of fluid inclusions trapped within various growth stages of these crystals. The amount of crystallization is limited only by the quantity of fluid moving through and the cause of precipitation. However, in a closed system, as in many vugs, vesicles, and miarolitic cavities, two somewhat different processes are involved in the growth of crystals. The first is simple precipitation from the enclosed fluid with decreasing temperature, and the second is transfer from the host rock to the site of crystal growth by diffusion through the static fluid. The amount of crystal growth on the cavity walls from the first is limited by the volume of fluid and the solubility of the crystallizing substance in it; this solubility is probably very small in most low-density fluids. On the other hand, the amount of crystal growth by diffusion from the host rock through a static fluid is limited mainly by time and the specific driving force for the crystallization. Included here may be a reduction of surface energy through the growth of larger crystals from smaller ones, a transfer of material from a glass to the crystals, or the formation of a new and more stable crystal phase.

In each of the above examples, the fluid in the inclusions trapped in the crystals lining the cavity can be assumed to be a sample of the fluid from which the crystal grew, and if this fluid is of very low density, the environment can be considered to be pneumatolytic. The specific process involved in the growth cannot be determined solely from studies of the inclusion fluid, but must include consideration of the evidence for an open vs. closed system, the volume ratio of crystal to fluid, etc. Unfortunately, however, the validity of the basic assumption of a single homogeneous fluid phase is the most difficult to verify.

Two-fluid-phase systems

Geologic environments which have had two coexisting fluid phases (i.e., immiscibility) are common. They include some obvious examples such as gas bubbles (vesicles) in a lava, or in a geothermal fluid, and sulfide globules in a mafic intrusion. Much less obvious, however, are the coexisting “vapor” and “liquid” phases present during the formation of some ore deposits. The fluid inclusions in the minerals formed from such a two-phase system provide the only evidence we have for the former existence of two fluids. Unfortunately, however, the inclusions trapped in crystals forming from two-fluid-phase systems do not always show evidence of this fact. They may (and frequently do) trap only one of the two fluids, and the specific reasons for this behaviour are seldom known, although both nucleation and wetting (i.e., contact angle) phenomena are obviously involved in some cases. Thus, some magmatic minerals contain only gas inclusions, even though they almost certainly grew essentially from a silicate melt, and only trapped gas inclusions because gas bubbles nucleated on the growing crystal surface and were enclosed. Similarly,
crystals growing from a boiling (or effervescing) water solution may trap inclusions of vapor bubbles and few or no inclusions of the liquid phase.

As a result of such problems, much care is needed in the interpretation of vapor-rich inclusions as "evidence" of pneumatolysis. The presence of even a few primary liquid-rich inclusions among the vapor-rich ones signifies that the growth was from, or at least in the presence of a two-phase system. (One caveat here is that if necking down occurs after some condensation of liquid in what were originally all-vapor inclusions, liquid-rich inclusions can be formed even though no liquid was present originally). On the other hand, crystals growing from a vapor phase in the presence of a small amount of condensed liquid could trap inclusions of that liquid.

All too commonly a "pneumatolytic stage" is invoked to explain a zone of vapor-rich inclusions in crystals that otherwise hold only liquid-rich inclusions. Rather than a change of the fluids from liquid to low-density and back, it is much more likely that the zone of vapor-rich inclusions merely represents a stage during which the fluids became saturated with a gaseous phase. This saturation can represent either boiling of the fluid, or effervescence of some more volatile but possibly very minor constituent, for example on a decrease in pressure. In fact, as the bubbles are a dispersed phase that may well nucleate and adhere preferentially on the growing crystals, there is a high probability that they will be trapped. In either case, nucleation and entrapment of bubbles of the low-density phase on the growing crystal surfaces may yield a zone of vapor-rich inclusions that may incorrectly be taken to mean growth of this zone of the crystal from a low-density fluid.

EXAMPLES OF POSSIBLE PNEUMATOLYTIC DEPOSITION

Summit Rock, Oregon

Summit Rock is a small andesitic plug dome in the High Cascades, near Diamond Lake, Oregon. Kleck (1970) described a fascinating set of "cavity minerals" from this plug, and it is these minerals that were examined in the present study. The dome is ≈200 m in diameter, scoriaceous on the exterior and andesite (SiO₂ ≈ 55%) in the interior. In the upper part of the 30 m of exposure, vesicles are spherical and make up as much as 30 volume percent of the rock. The cavities in the lower part are irregular lenticular, subparallel tear vesicles which have two dimensions typically 10 and 100 times the third. Most are < 5 mm in width, and have surfaces coated with sharp euhedral crystals of plagioclase, orthopyroxene and augite, plus a very few crystals of other phases, including ilmenite, apatite, tridymite, magnetite and 8 others. The crystals have clean brilliant faces and protrude into the cavity; most are < 2 mm in length. The tear vesicles make up ≈ 10 volume percent of the rock. Both the plagioclase and the orthopyroxene are zoned, the former from An₇₀ cores to An₁₀, or even An₅ edges and the latter from Fs₂⁷ to Fs₄₅, with the higher iron values at the edges (Kleck, 1970). That author also estimates that cavity minerals compose ≈ 6% of the andesite. The bulk of this figure consists of the granular aggregates of plagioclase etc., lining the cavities, plus a much smaller volume of free standing crystals.

Free standing cavity crystals of plagioclase and orthopyroxene were examined for inclusions by simply breaking them off the cavity walls and mounting in oils. The
very smooth clean crystal faces made polishing unnecessary. Most such crystals were free of visible imperfections, but a few had relatively large rounded inclusions that appeared empty (Fig. 1a, 2a, 3a, b). No film of liquid (or glass) could be seen on the walls, but the rounded shape and the lack of thin reentrant points on the inclusions.

![Figure 1a, b](image1.png) Two rounded vapor inclusions in orthopyroxene crystal from Summit Rock, Oregon, on the crushing stage. The larger one is 41 μm long. 1a—before crushing. 1b—after crushing. An almost invisible fracture has permitted the mounting index oil to flow in and completely fill both cavities. Note that no film of liquid water can be seen on the walls of the opened inclusions, but a tiny opaque grain occurs on the wall of each inclusion. The host crystal rotated during crushing, permitting both inclusions to be in focus simultaneously in Fig. 1b.

![Figure 2a, b](image2.png) A rounded 42-μm-long vapor inclusion in a tabular orthopyroxene crystal from Summit Rock, Oregon, on the crushing stage. 2a—before crushing. 2b—after crushing formed a fracture which intersected the inclusion. Mounting index liquid almost filled the inclusion instantly, leaving a bubble of residual, noncondensible gas (arrow) of about 4% volume percent.

normally make it impossible to see < 10 vol% of such a film. No other type of inclusion was found.

Crushing tests made on a series of such inclusion-bearing crystals, mounted in immersion index oils, showed them to now contain only 0–4% by volume of noncondensible gas, i.e., gases that remain gaseous at room temperature and one atmosphere. This means that they are now better than 95% vacuum (Figs. 1–3). This gas content was established by comparing measurements of the volume of the remaining gas bubble immediately after crushing with those of the entire inclusion before crushing. Such estimates of noncondensible gas volume and pressure are crude at best. Small gas bubbles must be measured quickly, as they dissolve in the mounting oil at increasing rates as their radius diminishes (Roedder, 1970). In addition, there is a large uncertainty in the measurement of the volume of the inclusion before...
crushing, most particularly the third dimension, parallel to the line of sight. As most of the crystals were platy, it was difficult to turn them on their sides, hence the third dimension could only be roughly estimated. On crushing, most of the inclusions filled suddenly with oil, leaving a residual bubble of about 3–4 volume percent which then dissolved more slowly, over a number of seconds. Two inclusions, however, showed no such residue (Fig. 1). As these two were opened with a very tiny fracture, and hence filled more slowly, presumably there was enough time for small amounts of residual noncondensable gas to dissolve during the filling.

**Topaz Mountain, Thomas Range, Utah**

Here a series of rhyolitic domes and lava flows are found over breccias and tuffs (Burt et al., 1982; Christiansen, 1980). The phenocrysts are mainly sanidine, quartz, and plagioclase. The topaz crystals, which are a pale brown or “wine” color, and bleach to colorless in the sun, project into open vugs in the rhyolite, and are accompanied by small amounts of bixbyite, bright red garnet, few thin hematite plates, and rare fluorite. The topaz terminations are brilliantly faceted and gemmy, and generally are devoid of inclusions of any kind. At the attachment with the vug wall, however, the topaz crystals enclose various amounts of tiny crystals of silica and feldspar from the vug lining, and also in part as primary solid inclusions that grew on the surface of the topaz. Among these included crystals, in a very few of the many topazes examined, are large (20–100 μm) rounded fluid inclusions that are
undoubtedly primary and appear empty, i.e., one phase. No two-phase primary inclusion was found, although some crystals show many planes of odd small secondary inclusions that appear to consist of solids plus gas. On crushing in oil, the primary one-phase inclusions behaved very much like those from Summit Rock, as they filled instantly with oil, leaving a bubble of \( \approx 3-6\) vol\% noncondensible gas.

**Wah Wah Mountains, Utah**

In the Wah Wah Mountains in southwestern Utah, red beryl crystals are found in cavities and fractures in a sequence of potassium- and silica-rich trachyandesites and rhyolites (Shigley and Foord, 1984). The rocks are locally rich in fluorine and contain small shows of uranium as well as topaz and beryl. The host for the red beryl is a rhyolite containing 10–20% small phenocrysts of sanidine, plagioclase, quartz and minor biotite in a fine-grained groundmass. Euhehedral, faceted red beryl crystals (mostly \(< 2\) cm) have grown from the wall of miarolitic cavities and fractures. They are associated with bixbyite but not topaz. Christiansen (1980) believes the rhyolites crystallized at 650–800°C, and Shigley and Foord (1984) believe the beryl crystallized from a high-temperature gas or vapor phase released from the cooling rhyolite. Nassau and Wood (1968) studied these red beryls by IR transmission and believe the color is probably caused by Mn\(^{2+}\); most unusual, however, is that, unlike all other beryls examined, they found a complete absence of water in the Wah Wah samples. They attribute this to growth at a very low pressure and high temperature. Flamini et al (1983) described the color zonation and mentioned the presence of fluid inclusions in these beryls.

The numerous beryl crystals examined all contain similar one-phase pseudosecondary, secondary, and probably primary vapor inclusions (Fig. 4), many of which are of negative crystal shape; some have minute solid daughter (?) crystals inside, but no trace of liquid was seen in any of these vapor inclusions. Heating to \(+160°C\) and cooling to \(−170°C\) yielded no visible phase changes in the vapor inclusions in two plates, so they must be filled with low pressure gas. One of the three presumably secondary two-phase inclusions that were found was measured; it was long and irregular, contained a small vapor bubble, and yielded \(\text{Th}=153°C\) and \(\text{Tm}_{\text{ice}}=−0.1°C\).

Crushing tests on a series of vapor inclusions (Fig. 5) showed that they also behaved just like the Summit Rock samples, in that they flow essentially a vacuum with 1–5 vol\% noncondensible gases. These gases were relatively insoluble in the mounting medium, in this case, glycerine.

**DISCUSSION OF THE DATA**

**Nature of the gases present at trapping**

The crushing tests on all three samples prove that at room temperature, these inclusions hold essentially a vacuum, as the total pressure of the noncondensible gases is now \(\approx 0.04\) kg.cm\(^{-2}\) (i.e., \(\approx 0.04\) atm). Presumably the pressure was much higher at the time of trapping, and consisted mainly of condensible gases such as water. The small percentage of noncondensibles probably consist mainly of CO\(_2\), but
Figure 4  Gas inclusions in red beryl from Wah Wah Mountains, Utah. The c axis is horizontal and the largest inclusion (in the center) is 120 μm long. Photo by P. Vollenweider.

Figure 5 a–d  Gas inclusions in red beryl from Wah Wah Mountains, Utah, mounted in glycerine on the crushing stage. Figs. 5a and 5c, before crushing; 5b and 5d, after. The volume of the residual bubbles (arrows) is only a few percent of the inclusion total. The field of view (vertical) is 350 μm in each. Photos by P. Vollenweider.
the numerous analyses of magmatic gases in the literature show that many other gases might also be present, including Ar and He.

Pressure of gases at trapping

The Thomas Range and Wah Wah samples come from what are probably near-surface rhyolite and rhyolitic ash flows, so the pressure was presumably low. At Summit Rock, an upper constraint on the magnitude of the pressure at trapping is provided by the geological occurrence; Kleck (1970) states that the entire outcrop is only 30 m high, and that the top of the plug is mantled with scoria. Tear vesicles as described here occur only in the lower part of this outcrop. It is not known whether these tear vesicles held sufficient gas pressure to support the overlying andesite, or were developed during shrinkage of the core of the plug within a rigid exterior. If the vesicles were a closed system, in the former case, assuming 30 m of andesite of density 2.5 g cm\(^{-3}\), the lithostatic pressure would be 7.5 kg cm\(^{-2}\). In the latter case, the pressure could be any value below this, down to \(\approx 0.04\) kg cm\(^{-2}\). If the vesicles were an open system (i.e., connected to the atmosphere), the pressure within them during crystal growth would have been \(\approx 1\) kg cm\(^{-2}\).

Density of the vapor phase

In order to estimate the density of the vapor phase, both pressure and temperature are needed. Thus saturated steam at 100°C and 1 kg cm\(^{-2}\) would have a density of 0.0006 g cm\(^{-3}\). Higher pressures would increase this density, and higher temperatures at constant pressure would decrease it. From their appearance as tear vesicles, the Summit Rock vesicles presumably opened originally at about the andesite solidus (perhaps 1000°C), but the vesicle crystals could have grown at any time later. Similar reasoning pertains to the two rhyolite occurrences, but there the solidus temperature was probably considerably lower. Almost any geologically reasonable combination of pressure and temperature yields a low density for the vapor phase in these vesicles.

On cooling to room temperature, the bulk of the water in the vapor should condense to a liquid. Where is that liquid in these inclusions? The quantity of such liquid water will be very small at any one of the localities; on a 20 μm spherical inclusion, it would form a layer well under 0.1 μm in thickness, and hence invisible under ordinary observation. Even if the inclusions had a thin réentrant, where this condensed liquid would tend to accumulate by capillarity, it would not be easy to see. Although such films must be thick to be visible in an unopened vapor-rich inclusion, even relatively thin films should be visible once the inclusion is filled with index liquid (e.g., Fig. 1b), but they were not seen. It should be noted, however, that a small grain of a dark or opaque material is present on the walls of each of the inclusions in Fig. 1b, presumably precipitated from the low-density vapor after trapping.

Significance of vapor-rich crystallization

Many examples are known in which low density vapor phases, particularly steam in fumaroles, has deposited a variety of solid substances such as various
chlorides and sulfur. These are open systems, in which large volumes of vapor have passed by a given spot on the wall. Hence the concentration of the precipitated substance in the vapor may be very low and still yield significant crystal growth.

At Wah Wah, deposition of the beryl crystals found in fractures cutting the rhyolite have been credited to a vapor phase streaming through the fracture, but in all three occurrences, however, the vesicles were almost certainly closed or nearly closed systems. How then, with only a relatively small volume of vapor phase to call on, could so much vapor-phase crystallization take place from what was obviously a very low-density vapor? This question is particularly pertinent in view of the low vapor pressures of the constituents of the crystals that precipitated—CaO, MgO, FeO, BeO, Al₂O₃, and SiO₂. The only explanation seems to lie in diffusion through a static vapor phase. In many laboratory studies, and some industrial processes, growth of relatively nonvolatile crystals occurs by this means. The apparent vapor pressure of the oxides in the vesicle fluid, i.e., their “solubility” in the vapor phase, was probably greatly increased by the presence of water, even though of low density. As an example, one may compare the vapor pressure of pure SiO₂ at 500°C with the solubility of SiO₂ in steam at 500°C. Such increased “solubilities” (in terms of mass per unit volume of fluid), although still probably very low compared with those in a liquid phase, apparently permitted dissolution of the constituents at the walls of the vesicle, e.g., from minute groundmass crystals, or from glass, and their transfer to form new crystals projecting into the vug.

Although adequate amounts of appropriate nutrient materials were available from the immediately adjacent vesicle walls at Summit Rock and the Thomas Range, what about the source of the beryllium at Wah Wah? The high concentration of BeO in beryl, and its low concentration in the adjacent rock, would at first seem to preclude a local source by simple diffusion, and, indeed, a through-going flow of magmatic volatiles has usually been called on for such occurrence. Simple mass-balance calculations show, however, that diffusion over relatively short distances, while not proven, is at least adequate to form these beryls. Shigley and Foord (1984) show that the Wah Wah beryls contain about 12.5% BeO, and the host rock about 0.0083%. From these numbers, it is evident that there is adequate BeO in the rock within a radius of 2.8 cm of a vug to form a 5 mm beryl crystal. Even if only half of the BeO is “extracted” to form the beryl, a radius of only 3.6 cm is needed.

Other possible interpretations

The possibility remains that the Summit Rock and Thomas Range vesicle crystals grew from a liquid in a two-phase system, and only bubbles of low-density vapor phase, from boiling or effervescence, were trapped as inclusions. Two features argue against this possibility. First, although many vapor inclusions were found, not even a single small liquid-rich inclusion was found at either locality. As this is only negative evidence, it cannot be accepted as proof. Second, however, these vesicle crystals formed in a very shallow environment. If they formed from the liquid of a two-phase system, the vapor pressure of that liquid would place a limit on the temperature. Thus the vapor pressure of water at 167°C equals the lithostatic pressure from 30 m of andesite; although the composition of such a hypothetical
liquid water solution is unknown, it seems likely that at such temperatures one or more hydrous silicate phases would form from it, rather than plagioclase and orthopyroxene, or topaz.

Kleck (1970, p. 1400) proposed that at Summit Rock "the plagioclase, orthopyroxene, augite, ilmenite, and magnetite have crystallized from a late, residual, interstitial magma which oozed into the cavities and then crystallized. . . . The remaining cavity minerals were deposited from a volatile phase or were deposited because of its presence". He cites several lines of evidence to support his hypothesis, none of which seem adequate to preclude formation by diffusion through a static vapor phase.

In addition to the vapor-phase inclusions in the vesicle crystals, the crystals themselves show one other feature which seems to preclude crystallization from a residual, interstitial magma. This is their occurrence as sharp clean crystals, with brilliant crystal facets. We see no way in which crystals growing from a silicate melt can avoid being coated with residual melt. The possibility that such a coating of glass or crystalline material was present but has since been dissolved away seems unlikely without destroying the lustrous crystal faces and sharp edges.

Similar points may be made about the Wah Wah material, but here Shigley and Foord (1984, p. 208) thought that the red beryl crystallized "from a high-temperature gas or vapor phase released during the latter stages of cooling and crystallization of the rhyolite magma". The fluid inclusions provide some factual verification of that supposition, as long as we assume that the rare liquid-rich inclusions in these beryls are from a later, and presumably much lower-temperature stage in which a dense aqueous liquid bathed the crystals.

CONCLUSIONS

Fluid-inclusion evidence for pneumatolytic crystallization conditions must be used with considerable care, as it can be misleading. Apparently empty, vapor-phase primary inclusions, now holding about 95% vacuum, with no accompanying primary liquid or melt inclusions, prove that at Summit Rock, Oregon, Topaz Mountain, Thomas Range, Utah, and the Wah Wah Mountains, Utah, crystals of plagioclase, orthopyroxene, topaz and beryl have grown in cavities by diffusion transport of their constituents through an essentially static, low-density steam or vapor phase, at temperatures below the solidus for the host volcanic rock. As such, these crystals are examples of the products of pneumatolysis and show the efficacy of even a low density vapor phase as a medium for diffusive transport of what are normally considered nonvolatile rock-forming oxides.

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