Temporal and Spatial Variations in Hydrothermal Fluid Characteristics during Vein Filling in Preore Cover Overlying Deeply Buried Porphyry Copper-Type Mineralization at Red Mountain, Arizona

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Abstract
Alteration and lithologic characteristics suggest that Red Mountain, Arizona, represents the upper level lithocap region of a porphyry copper system, and this interpretation is reinforced by recent disclosure of deeply buried porphyry copper-type mineralization at this locality. Heating/freezing tests on 1,131 fluid inclusions in sulfide-bearing quartz veins from drill core samples and surface outcrops indicate that two fluids, distinctly different in their physicochemical properties, attended alteration-mineralization at Red Mountain. The early fluids had salinities of 10 ± 5 equiv. wt percent NaCl and boiled at ∼375°–425°C. Based on these inclusions, a geothermal gradient of ∼25°C/km and pressures of 275 ± 75 bars prevailed during this early stage of vein filling. With passing time, boiling ceased and the fluids cooled to ∼300°C. A later fluid with temperatures of ∼375°–250°C and salinities of ∼30–50 equiv. wt percent NaCl was responsible for deposition of chalcopyrite. Atomic K/Na ratios of these later hydrothermal fluids, as determined from sylvite and halite dissolution temperatures, ranged from 0.52 to 1.76. The time-temperature-salinity relationships observed from fluid inclusion studies at Red Mountain are consistent with those predicted for similar geologic environments by numerical simulation and suggest that the earliest vein-filling fluids at Red Mountain had sources in the nearby volcanic wall rock and that later, higher salinity fluids originated in more distant wall rocks or in an as yet unseen intrusion at depth.

Introduction
Fluid flow models and geologic observations indicate that intrusive rocks with which porphyry copper deposits are associated produced convective circulation of fluids of diverse origin in permeable wall rocks. Numerical simulations predict that these convecting fluids served to transfer heat from the hot intrusive body into overlying rocks, resulting in a broad vertical zone of moderate geothermal gradient in preintrusive cover (Norton and Knight, 1977). Such circulation would also have been accompanied by the transfer of large amounts of dissolved material producing attendant alteration in preore cover above the buried heat source (Knight, 1977).

Most known porphyry copper deposits in the southwestern United States have been eroded to the extent that the original cover into which the central pluton was emplaced has been removed, leaving alteration characteristics in such overburden largely open to speculation. However, based on studies of South American deposits, Sillitoe (1973) has suggested that a calc-alkaline stratovolcanic pile is commonly associated with, and genetically related to, shallow plutons exhibiting porphyry copper-type mineralization, and that these volcanic rocks are typically altered to a characteristic assemblage of clay minerals, pyrite, alunite, gypsum, and fine-grained silica. These geologic observations correspond closely to alteration patterns predicted, from thermochemical considerations, for ascending and cooling fluids originally equilibrated with sulfur-rich intrusive rocks at depth (Knight, 1977). Alteration and lithologic characteristics suggest that Red Mountain, Arizona, represents a dissected portion of the stratovolcano thought to form the upper levels of some porphyry copper systems, and such an interpretation is reinforced by recent disclosure of deeply buried porphyry copper-type mineralization at this locality (Corns, 1975).

The purpose of this study was to examine hydrothermally altered rocks over a presumed subsurface pluton at Red Mountain, Arizona, to evaluate tem-
Fig. 1. Location map, general geology (left), and surface expression of alteration zoning (right) of the Red Mountain, Arizona, porphyry copper prospect. Also shown are the locations of drill holes and surface outcrop from which samples were obtained. Geology and alteration zoning modified after Corn (1975).

Summary of Geologic Relations

Red Mountain is located approximately 80 km southeast of Tucson, Arizona, at the northern end of the Patagonia Mountains (Fig. 1), in an area exhibiting extensive intrusive activity and widespread mineralization. The general geology of Red Mountain and the immediate surroundings is summarized here from more detailed descriptions by Schrader (1915), Drewes (1972), Simons (1972), and Corn (1975). The latter describes Red Mountain as "a center of Laramide explosive volcanism and sub-volcanic intrusive activity, set within a geologic terrain dominated by Mesozoic and early Tertiary volcanics and volcanic sediments" (p. 1439). An arcuate zone of dikes, intrusive breccias, and subsidence structures suggests that the volcanic and intrusive rocks are localized within a collapse caldera, the northwest portion of which has been cut and down-dropped, along with the adjacent Sonoita Valley, by the Patagonia fault (Fig. 1).

Red Mountain is formed from an erosionally resistant sequence of highly altered latitic to trachytic tuffaceous rocks referred to locally as the Red Mountain Volcanics which Drewes (1972) correlates with the neighboring Gringo Gulch volcanics of approximately 60 m.y. age. Drill hole 138 from which the 18 samples used in this study were obtained penetrates through nearly 500 m of these tuffs and then encounters approximately 500 m of andesite which is thought to be correlative with the trachyandesite of Meadow Valley of about 72 m.y. age (Simons, 1972). Finally, the drill hole passes through approximately 500 m of interlayered andesite, felsite, and banded hornfels, the latter unit pos-
Table 1. Vertical Distribution, Abundance, and Mode of Occurrence of Alteration Minerals in Drill Hole 138 at Red Mountain, Arizona

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Depth range (m)</th>
<th>Mode of occurrence and abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>0-1,500</td>
<td>Veins and wall rocks; most abundant (50-60%) in upper 500 m.</td>
</tr>
<tr>
<td>Muscovite</td>
<td>0-1,500</td>
<td>Fine grained; upper: replaces all rock-forming minerals except quartz (20-30%); lower: in and directly adjacent to quartz-sulfide veins, rare in wall rock (&lt;5%).</td>
</tr>
<tr>
<td>Pyrite</td>
<td>0-1,500</td>
<td>In veins and wall rock; commonly associated with chlorite; upper: 4-6%; lower: ~1%.</td>
</tr>
<tr>
<td>Apatite</td>
<td>0-1,500</td>
<td>Veins and wall rock; uncommon.</td>
</tr>
<tr>
<td>Calcite</td>
<td>0-1,500</td>
<td>Mostly veins, minor wall rock after Ca-plagioclase; upper: very minor (&lt;1%); lower: ~5% of vein, associated with anhydrite.</td>
</tr>
<tr>
<td>Hematite</td>
<td>0-1,500</td>
<td>Veins and wall rock; very common in upper part of drill hole.</td>
</tr>
<tr>
<td>Chalcocite</td>
<td>0-150</td>
<td>Rims on pyrite; supergene.</td>
</tr>
<tr>
<td>Alunite</td>
<td>0-300</td>
<td>In veins and wall rocks (10-15%), both K and Na varieties.</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>0-300</td>
<td>In veins and wall rock (10-20%), uniformly distributed; possibly supergene.</td>
</tr>
<tr>
<td>Biotite</td>
<td>572</td>
<td>Original in rock (10-20%); altered to chlorite immediately adjacent to vein.</td>
</tr>
<tr>
<td>Chlorite</td>
<td>600-1,500</td>
<td>Replaces earlier biotite, accompanied by rutile; Fe/Mg ~1.0 based on optical properties [Albee, 1962]; commonly intergrown with sulfides in vein; upper: in and directly adjacent to quartz-sulfide veins (&lt;5%); lower: in wall rocks and veins (10-20%).</td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td>878-1,500</td>
<td>Mostly in veins as overgrowths on pyrite, minor wall rock; commonly associated with chlorite (~1%); very rare in upper part of drill hole.</td>
</tr>
<tr>
<td>K-feldspar</td>
<td>1,000-1,500</td>
<td>Replaces plagioclase in wall rock; upper: coarser grained along quartz-sulfide veins, minor in wall rock accompanying/muscovite; lower: very fine grained, completely pervades wall rock.</td>
</tr>
<tr>
<td>Illite(?)</td>
<td>1,000-1,500</td>
<td>Very fine grained disseminations in wall rock.</td>
</tr>
<tr>
<td>Anhydrite</td>
<td>1,100-1,500</td>
<td>Exclusively in veins (~5% of vein).</td>
</tr>
<tr>
<td>Magnetite</td>
<td>1,500</td>
<td>Very minor.</td>
</tr>
</tbody>
</table>

Abundance in volume percent. Depth range in meters below surface. Upper and lower refer to upper and lower portions of the drill hole.

sibly representing a former Cretaceous (Bisbee Formation?) siltstone (Corn, 1975). This entire sequence is intruded by sills and dikes of monzonite and quartz monzonite porphyry which in deep drill holes within the mineralized area amount to 25 to 30 percent of the rock intersected beneath the tuffaceous volcanics (Corn, 1975). No large continuous intrusive body was intersected at depth in this particular drill hole.

According to Corn (1975), both the metallization and the hydrothermal alteration at Red Mountain exhibit concentric zoning patterns centered on the area of monzonite porphyry and quartz monzonite porphyry intrusions, suggesting that intrusive activity, alteration, and mineralization are interdependent. Surface exposures of the central zone (Fig. 1) exhibit extensive alteration of trachyte (Red Mountain Volcanics) to sericite, quartz, and abundant disseminated pyrite (phyllite alteration of Lowell and Guilbert, 1970). A zone of pyrite-alunite-clay alteration (advanced argillic of Meyer and Hemley, 1967) surrounds this central zone and is generally coincident with the area occupied by dikes, intrusive breccias, and subsidence features which define the limits of the suggested caldera structure. Peripheral alteration consists primarily of epidote and chlorite, with minor amounts of pyrite, calcite, and clay minerals (propylitic alteration).

Petrographic studies of eighteen samples covering a vertical distance of greater than 1,500 m in one drill hole (drill hole 138, Fig. 1) revealed gradual but systematic variations in alteration mineralogy with increasing depth. Mineral distributions and abundances in this drill hole, as determined by petrographic, X-ray diffraction, and electron microprobe analyses, are listed in Table 1 and are consistent with the results reported by Corn (1975) for this same drill hole (DDH138), except that no alteration biotite was observed in the present study.

In summary, alteration mineralogy changes gradually from quartz + muscovite (sericite) + kaolinite + alunite + pyrite at shallow depths progressively through the assemblages quartz + sericite + pyrite, and quartz + sericite + chlorite + pyrite to quartz + K-feldspar + chlorite + lesser amounts of anhydrite, sericite, illite (?), chalcopyrite, and pyrite. Calcite, apatite, and hematite occur in very minor amounts over the entire depth of the drill hole. The kaolinite and alunite observed in the upper portion of the drill hole extend to slightly greater depths than
supergene chalcocite and may be either of supergene or hypogene origin.

**Fluid Inclusion Studies**

**Methodology**

**Equipment:** Phase changes in fluid inclusions during heating and freezing tests were measured on dual-purpose heating/freezing stages in laboratories at the University of Arizona and the U.S. Geological Survey. The design of the stages used in this study allows one to freeze and homogenize the same inclusion without having to remove the sample from the stage between measurements, thus making it possible to collect both homogenization and salinity data on individual inclusions with relative ease. Detailed descriptions of both stages have been presented elsewhere (Bodnar, 1978; Werre et al., 1979) and will not be repeated here.

Both heating/freezing stages were calibrated using melting point standards. The Arizona stage had a precision and accuracy of ±0.5° and ±5.0°C, respectively, at 350°C, with a positive thermal gradient of approximately 10°C from the center to the wall of the sample chamber (1.25 cm) at this same temperature (Bodnar, 1978). Errors resulting from sample position in the stage were minimized by using small sample chips (<0.5 cm diam) and always locating the sample in approximately the same position near the center of the chamber. The data were not corrected for sample position in the stage. Temperatures of phase changes in individual inclusions during heating tests were generally reproducible to within 0.1 to 0.2°C if the stage setup was not altered between heating runs. Freezing temperature measurements in this same stage have a precision of ±0.1°C; the accuracy of these data was difficult to determine owing to the lack of suitable standards, but is believed to be on the order of ±1.0°C.

The stage used in the USGS laboratories has a precision and accuracy of better than ±0.1° and ±1.0°C, respectively, up to 300°C with a thermal gradient of approximately 1.0°C over 75 percent of the viewing area of the 2 cm diam sample chamber. Freezing temperature measurements have a precision and accuracy of ±0.1°C, calibrated to −10°C. In both the Arizona and USGS stages, a chromel-alumel thermocouple was positioned adjacent to the inclusion(s) under observation to minimize errors owing to thermal gradients within the sample chambers.

The precisions and accuracies reported above are those obtained using melting standards under nearly ideal conditions. In practice, however, the temperatures of phase changes in fluid inclusions may have considerably poorer precision and accuracy owing to several factors. The sample chips were not all of the same thickness, shape, or size and were not always positioned in exactly the same place in the sample chamber, nor was the junction of the thermocouple always in the same position relative to the inclusion being measured. Also, the small size of the inclusions examined, generally in the range 5 to 30 μm in diameter in this study, precludes the visual determination of temperatures of phase changes with a high degree of precision or accuracy.

**Procedure:** Doubly polished sections approximately 100 to 1,000 μm thick were examined on a petrographic microscope and areas containing fluid inclusions suitable for freezing and/or heating tests were located. The phases in the inclusions chosen for study were identified and, at lower magnifications, the relationship of these inclusions to other inclusions and vein-filling minerals was determined. These areas were then removed from the polished section either by simply breaking the sample by hand or by cutting out the appropriate area with a dental drill. The samples were then placed in the heating/freezing stage and temperatures of phase changes within these inclusions were measured.

After all tests had been completed on the previously chosen inclusions, any additional inclusions in the field of view which had not yet homogenized were heated further and the appropriate data recorded. Because nearly every sample studied exhibited a wide range in homogenization temperatures of fluid inclusions (see below), many of the lower temperature inclusions leaked or decrepitated at the higher temperatures required to homogenize all suitable inclusions in a given field of view. Even though many fluid inclusions were destroyed during these subsequent heating tests, the procedure used allowed data to be obtained from those inclusions most optically suited for heating/freezing tests. Random choice of sample areas for inclusion study and continuous monitoring of the behavior of all inclusions within the field of view during each heating test until the last inclusion had homogenized insured that maximum information concerning the history of vein filling, as recorded by the fluid inclusions, was determined.

In single crystal studies of vein RM11, the above procedure was slightly modified. Starting at the tip of a quartz crystal, inclusions were located and homogenized, then the stage was moved one field of view of the microscope closer to the crystal base along the c-axis (approximately 250 μm) and the procedure repeated until temperatures had been studied to the base of the crystal. During the initial traverse of the crystal, the temperature was not allowed to exceed approximately 325°C to insure that lower temperature inclusions elsewhere in the
Fluid Inclusions from Red Mountain

All inclusions are in polished sections of quartz veins (sample numbers given in captions) and photographed in transmitted plain light at room temperature. The bar scale represents 5 micrometers in all figures.
crystal would not decrepitate. A second traverse with a maximum temperature of approximately 360°C and a final traverse homogenizing all observable inclusions were made. Although no inclusions appeared to decrepitate during the initial traverse, a few inclusions which homogenized during the initial low-temperature traverse were observed to decrepitate during subsequent higher temperature traverses.

**Fluid Inclusion Petrology**

Classification of fluid inclusions based on phase relations observable at room temperature: Many schemes have been suggested for the classification of fluid inclusion types. One of the most useful of these is based upon the phase relations observable at room temperature because this classification procedure also provides information concerning the composition of the inclusion and the conditions of trapping. Using a classification scheme similar to that described by Nash (1976), the fluid inclusions at Red Mountain were divided into three types: liquid-rich, vapor-rich, and halite-bearing.

The simplest type of fluid inclusion observed at Red Mountain contains a liquid plus a vapor bubble (V) occupying less than about 50 volume percent of the inclusion (Fig. 2). Overall, this type of moderately saline, liquid-rich inclusion is the most abundant, although some late quartz contains none of this type. Commonly, these liquid-rich inclusions contain one or more opaque daughter minerals that do not dissolve upon heating, even when the inclusion is held at a temperature near that of liquid-vapor homogenization for extended periods of time (several hours). The opaque phase often has a cubic habit and is nonmagnetic (pyrite?) (O, Fig. 3) or has a distinctly triangular shape and brassy-gold color in reflected light (chalcopyrite?) (C, Fig. 4).

Liquid-rich fluid inclusions described above commonly coexist with inclusions containing liquid plus a vapor bubble which occupies more than 50 volume percent of the inclusion. These vapor-rich inclusions also often contain a cubic (O, Fig. 5) or triangular (C, Fig. 6) opaque phase that does not dissolve upon heating, as do presumably coeval liquid-rich inclusions. In a given area of polished section, a larger percentage of liquid-rich inclusions appear to contain an opaque phase(s) than do the coexisting vapor-rich inclusions. However, it is possible that the opaque phase in many vapor-rich inclusions is obscured by the large bubble which in many cases appear to fill completely the inclusion. Where liquid- and vapor-rich inclusions coexist, there appears to be a continuous range in the degree of filling by liquid from approximately 75 to less than 5 volume percent at room temperature. However, these fluid inclusions of apparently variable phase proportions all homogenize at approximately the same temperature, some to the liquid phase and some to the vapor phase. This behavior suggests that the variation in

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Fig. 2. Two-phase liquid-rich inclusion containing a low to moderate salinity liquid and a vapor bubble (V) occupying approximately 30 vol percent. RM11.

Fig. 3. Liquid-rich inclusion with a cubic (?), nonmagnetic opaque mineral (O). Vapor bubble (V) fills approximately 30 vol percent of the inclusion. RM618.

Fig. 4. Liquid-rich inclusion with a triangular opaque mineral (C) that is brassy gold in reflected light and thought to be chalcopyrite. Vapor bubble (V) fills approximately 35 vol percent of inclusion. RM1536.

Fig. 5. Vapor-rich inclusion with a cubic, nonmagnetic opaque mineral (O). Vapor bubble (V) fills approximately 85 vol percent of inclusion. RM618.

Fig. 6. Vapor-rich inclusion with a triangular opaque mineral (C) that is brassy gold in reflected light and thought to be chalcopyrite. Vapor bubble (V) fills approximately 90 vol percent of inclusion. RM572.

Fig. 7. Multiphase inclusion with a halite daughter mineral (H) and vapor bubble (V). RM788.

Fig. 8. Multiphase inclusion with a halite daughter mineral (H), a reddish hexagonal platelet (S, for specularite) thought to be hematite, and a vapor bubble (V). RM389.

Fig. 9. Multiphase inclusion with a halite daughter mineral (H), a triangular opaque (C) thought to be chalcopyrite, and a vapor bubble (V). RM389.

Fig. 10. Multiphase inclusion with a halite daughter mineral (H), an opaque mineral (O) attached to the halite, and a vapor bubble (V). RM389.

Fig. 11. Multiphase inclusion with a halite daughter mineral (H), a vapor bubble (V), and two opaque phases (O). One opaque has a roughly triangular shape and the other is more rectangular. RM1103.

Fig. 12. Multiphase inclusion containing halite (H) and sylvite (K) daughter minerals. The sylvite is slightly out of focus and partially obscured by the halite and vapor bubble (V). An opaque phase (O) is also present. RM389.

Fig. 13. Multiphase inclusion containing halite (H) and sylvite (K) daughter minerals and a vapor bubble (V). RM389.

Fig. 14. Multiphase inclusion containing halite (H) and sylvite (K) daughter minerals, a triangular opaque (C) thought to be chalcopyrite, and a vapor bubble (V). RM788.

Fig. 15. Multiphase inclusion containing halite (H) and sylvite (K) daughter minerals, a triangular (?) opaque (C), an unidentified opaque (O) attached to the halite, and a vapor bubble (V). RM788.

Fig. 16. Multiphase inclusion containing halite (H), a rod-shaped mineral thought to be anhydrite (A), and a vapor bubble (V). RM618.
degree of filling is apparent and reflects differences in the shapes and orientations of the inclusions.

The third type of fluid inclusion observed at Red Mountain contains, in addition to liquid plus vapor, a halite crystal ± other daughter minerals at room temperature. Of the three types of fluid inclusions observed, the halite-bearing type exhibits the greatest variability of solid phases. The simplest of this type only contains a cube of halite (H) in addition to the liquid and vapor (Fig. 7). Frequently, this type of fluid inclusion also contains a reddish hexagonal platelet of hematite (S for specularite, Fig. 8), a chalcopyrite (?) crystal (C, Fig. 9), or an unidentified opaque phase (O, Fig. 10). Occasionally, two opaque phases occur in this inclusion type (O, Fig. 11). In addition, a cubic phase with a high thermal coefficient of solubility suggestive of sylvite (K, Figs. 12, 13, 14, and 15) or a birefringent, rod-shaped, or rectangular mineral thought to be anhydrite (A, Fig. 16) occur in these halite-bearing inclusions. Several very small (<1 μ) phases were often observed using 100× oil immersion objectives. However, these phases were not identified and in general could not even be seen at lower magnification in the heating/freezing stage.

A fourth type of inclusion reported in porphyry-type deposits contains an aqueous solution plus liquid and gaseous CO₂ at low temperatures (<31.0°C). No CO₂-bearing fluid inclusions were observed at Red Mountain, although crushing studies on one sample (RM1003) showed that the inclusions did contain a noncondensable gas. The identity and quantity of the gaseous phase was not determined, although the vapor bubble did expand upon crushing, indicating that the internal pressure was greater than atmospheric.

**Temporal classification of fluid inclusions:** Fluid inclusions are classified as primary, secondary, or pseudosecondary depending upon when the inclusions were trapped relative to the formation of the bulk of the enclosing mineral. All of the quartz veins examined in this study experienced repeated fracturing in the presence of aqueous fluids as evidenced by the abundant planes of secondary (or pseudosecondary) inclusions observed at low magnification. Generally, the high density of randomly oriented fractures decorated with fluid inclusions made it difficult to determine with confidence whether a given inclusion was along one of these fractures (secondary or pseudosecondary) or was trapped during crystal growth (primary). For this reason, we have not attempted to classify the fluid inclusions as primary, secondary, or pseudosecondary but, rather, have related groups of inclusions to various stages of vein filling.

Two optically distinct varieties of quartz were observed in all veins examined: an early, gray to milky translucent variety and a later transparent type which either engulfs or occurs along microfractures in the milky quartz. Inclusions from the earlier stage (milky) quartz were of the moderately saline liquid-rich sort coexisting, in some cases, with the vapor-rich type. Later clear quartz, filling fractures in the milky quartz, contained predominantly halite-bearing inclusions. Technically, the mode of occurrence of the later halite-bearing inclusions along fractures in the milky quartz would classify them as secondary, but because they could be optically related to a distinct stage of vein filling (i.e., the clear quartz stage), they are considered primary with respect to the clear quartz. Occasionally, a plane of halite-bearing inclusions could be followed through the milky quartz and into the transparent quartz where the plane would abruptly terminate. Other inclusions not obviously along the fracture but in the area where the fracture terminated often provided phase disappearance temperatures similar to those of the inclusions along the fracture. This behavior suggests that the fluid trapped in inclusions along the fracture was the same as that from which the clear quartz at the fracture termination was being deposited. Because these fractures could be traced through the milky quartz, the milky quartz must have preceded both the fluids trapped along the fractures and the clear quartz that was contemporaneous with the fluids.

In all of the samples studied, approximately 90 percent of the vein-filling quartz is of the early, milky variety. When this quartz is examined under the microscope, any given field of view generally contains all of the three types of fluid inclusions previously described, “coexisting” with one another. In most cases, it could not be determined from simple petrographic techniques which, if any, of the many inclusions were coeval because of the abundance of fractures as described above. However, in the volumetrically minor late-stage clear quartz, vapor-rich inclusions were conspicuously absent. Thus, because no vapor-rich inclusions were observed in the late, clear quartz and because the halite-bearing inclusions could be definitely related to this stage of vein filling, it can be reasonably concluded that the vapor-rich and halite-bearing inclusions coexist in space (in the milky quartz) but not in time, i.e., they are not coeval. This assertion is further supported by salinity and temperature data described below.

**Vein filling history**

A sample of trachyte tuff completely altered to quartz + sericite + pyrite and cut by a quartz-sulfide
vein approximately one cm wide was collected from surface outcrop (RM11, Fig. 1). Vein-filling material consisted of milky comb quartz growing from the walls toward the vein center, with massive clear quartz occurring both near the vein center and along fractures in the milky quartz as described above. Pyrite and minor chalcopyrite and galena within the vein were restricted to the later clear quartz and microscopic examination of fluid inclusion types within the vein revealed that halite-bearing inclusions not along obvious fracture surfaces were likewise limited to this stage of vein filling.

As a first attempt to determine time-temperature relationships during vein filling, fluid inclusion homogenization temperatures from vein RM11 were measured as a function of distance from the vein wall. It was found that this method did not provide an accurate representation of temperature variations during vein filling. Close examination of vein morphology revealed that many of the crystals of milky quartz grew at slight angles to the vein wall and a few crystals were seen to have nucleated on earlier crystals and to have grown essentially parallel to the vein wall. Thus, distance from the vein wall and time of fluid inclusion trapping were not correlative. For this reason it was decided to study only single crystals which nucleated at and grew perpendicular to the vein wall.

The results of heating tests on fluid inclusions at various distances from the base of three quartz crystals are shown on Figure 17. All measured inclusions were two phase and homogenized to the liquid phase; vapor-rich inclusions were examined but none were suitable for homogenization tests. The solid lines labeled T.MAX on the diagrams connect the actual maximum homogenization temperature measured at each location along the c-axis of each of the three crystals. For example, in crystal B one inclusion was measured at the base and its homogenization temperature was 361°C, which is also equal to the T.MAX for that location. At a distance of 250 µm from the base, ten inclusions were measured. Three of these had homogenization temperatures between 325° and 349°C and the rest (seven) of the inclusions had homogenization temperatures between 350° and 374°C, as shown by the histogram. The actual temperatures of the seven inclusions in the 350° to 374°C range were 352°, 354°, 355°, 359°, 362°, 364°, and 365°C. Thus, the highest homogenization temperature measured at this location (250 µm from the crystal base) was 365°C, the temperature labeled T.MAX. At a distance of 500 µm from the base of crystal B, two inclusions fall in the range 375° to 399°C and their temperatures were 376° and 394°C. Therefore, at this location, T.MAX is 394°C. Generally, maximum temperatures appear to increase during initial stages of crystal growth, remain fairly constant during intermediate stages, and then decrease as crystallization terminates.

A wide range in temperatures is observed along the entire length of individual milky quartz crystals. Such variations may result in part from the fact that, because of the great abundance of inclusions
in the samples, primary inclusions could not be distinguished from secondary or pseudosecondary inclusions. Thus the single inclusion in the 250° to 275°C range at a distance of 250 μm from the base of crystal C, and possibly all of the inclusions at a distance of 500 μm from the base of this crystal (Fig. 17), may be secondary inclusions formed from the same fluid as was trapped in contemporaneous primary inclusions at the tip of crystal C. This suggestion is supported by the observation that, upon moving away from the vein wall along the c-axis of the crystals, inclusions showing homogenization temperatures comparable to those at the terminus are frequently encountered, whereas the higher temperatures characteristic of the earlier-formed portions of the crystals are not often encountered at the tip of the crystal.

The variations could also reflect, in part, lateral growth effects. Synthesis studies have shown that quartz growth takes place more rapidly in the c-direction than in the a-direction (Hale, 1975), so a given distance in the field of view parallel to the c-axis represents a shorter period of growth time and a narrower range in temperatures than the same distance in the perpendicular direction.

Lateral growth effects were examined using samples cut perpendicular to the c-axis of several milky quartz crystals. When examined in this manner, many crystals show several periods of growth, as evidenced by dark bands of hematite and clay outlining the crystal formed at intermediate stages (Fig. 18). The centers of individual crystals appear gray to milky when examined at low magnification, (Fig. 19) and, at higher magnification, the dark
centers were seen to be caused by abundant vapor-rich and liquid-rich inclusions, indicating boiling during early crystal growth. The same inclusion types would result if the crystal was repeatedly fractured in the presence of a boiling fluid and, because the liquid-rich and vapor-rich inclusions cannot be shown to be primary, this is certainly a possibility. However, even if these inclusions are secondary, they precede the deposition of quartz in the outer growth zones for reasons outlined below. Rarely, a milky quartz crystal was found that lacked the central gray to milky zone (Fig. 20). Examination of the cores of these crystals at high magnification revealed that the crystal also lacked (or contained comparatively few) vapor-rich inclusions, suggesting that these crystals began growing during the waning stages of boiling or after boiling had ceased.

Figure 21 is a schematic diagram of a quartz crystal cut perpendicular to the c-axis, showing an initial milky quartz crystal (A–B), a second stage of milky quartz overgrowth (B–C), and a final enclosing mass of clear quartz containing sulfides.

Crystal growth-zone B is dashed to indicate that many crystals in the vein do not exhibit intermediate growth zones within the milky quartz. Cross section A–D in Figure 21 shows generalized inclusion types and changes in homogenization temperatures along a traverse from the center of the crystal outward into the massive clear quartz. The interiors of crystals contain coexisting liquid- and vapor-rich inclusions, both of which homogenized at 379° to 415°C, suggesting boiling. Outward from the center of a given crystal, homogenization temperatures decreased gradually and vapor-rich inclusions became rare. In the outer milky quartz zone (B–C), only liquid-rich inclusions which homogenized at <370°C were observed. The overgrowth of clear, massive quartz (C–D) was characterized by lower temperature, high salinity (halite-bearing) inclusions. This later quartz also contained disseminated grains of sulfides which were not observed in the earlier milky quartz.

Visual examination of the vein in sample RM11 indicated two stages of quartz deposition, separated by an unknown period of time, from fluids of dis-
cernibly different salinities. Liquid-vapor homogenization temperatures of 354 fluid inclusions from the vein in sample RM11 are shown in histogram form in Figure 22. The boiling, low-salinity fluids are clearly distinguishable from the hypersaline fluids on the basis of thermal criteria, as they were by observation as well. Temperatures of vapor-rich inclusions overlap with the higher temperature region of the histogram for low-salinity liquid-rich inclusions. The lower and upper limits of this range (375° and 425°C, respectively) represent the minimum and maximum temperatures at which boiling may have occurred. Thus, the overlap of the histograms provides a maximum temperature range for boiling. The actual range is probably smaller as suggested by the narrower range in measured homogenization temperatures of vapor-rich inclusions (379°-405°C, 12 measurements) and the highest homogenization temperature of liquid-rich inclusions (415°C). The highest temperatures measured for halite-bearing inclusions coincide with the cooler portion of the low-salinity liquid-rich inclusions. The majority of this latter class, however, homogenized at temperatures intermediate between those of either the vapor-rich or the halite-bearing variety.

**Homogenization data from the drill hole**

Fluid inclusions from eighteen sulfide-bearing quartz veins obtained from approximately 1,500 m of drill core were examined to evaluate temperature variations with depth at Red Mountain. Homogenization temperatures of 706 fluid inclusions distributed among these samples are shown as a function of depth in histogram form in Figure 23 and summarized in Figure 24. The left-hand column of this diagram shows homogenization temperatures of both liquid- and vapor-rich inclusions from the early stage of vein filling, and the right-hand column depicts complete homogenization temperatures for halite-bearing inclusions present in the later stage quartz, i.e., the temperature of disappearance of the vapor bubble or the salt, whichever was higher. Three general observations can be made initially from examination of Figure 23:

1. Boiling, as evidenced by simultaneous homogenization of liquid-rich and vapor-rich inclusions in

   \[\text{In most of the halite-bearing inclusions and in many of the low to moderate salinity liquid-rich and vapor-rich inclusions examined, one or more opaque phases were present that did not dissolve upon heating. Therefore, the temperatures reported are not truly homogenization temperatures.}\]

   \[\text{column shows homogenization temperatures of two-phase inclusions (both liquid- and vapor-rich) and the right-hand column those of halite-bearing inclusions. Sample numbers are depths below surface in the drill hole in meters. The "y" pattern represents inclusions homogenizing to the vapor phase. A summary of all data on this figure is shown in Figure 24.}\]

![Figure 23. Homogenization temperatures of fluid inclusions in eighteen samples from drill hole 138. The left-hand column shows homogenization temperatures of two-phase inclusions (both liquid- and vapor-rich) and the right-hand column those of halite-bearing inclusions. Sample numbers are depths below surface in the drill hole in meters. The "y" pattern represents inclusions homogenizing to the vapor phase. A summary of all data on this figure is shown in Figure 24.](image-url)
close proximity to one another, was not observed below a depth of 1,103 m.2

2. In all samples studied, the peak in the histogram of homogenization temperatures of halite-bearing inclusions is shifted to lower temperatures as compared to that of the two-phase inclusions.

3. Homogenization temperatures of inclusions from both stages of quartz ranged from approximately 200° to 440°C over the entire depth range although, as shown on the summary diagram (Fig. 24), the mean temperature of the halite-bearing inclusions is considerably less than that of the low to moderate salinity inclusions. The only conclusion that can be drawn from the data on Figure 23 regarding temperature variations is that the homogenization temperatures of fluid inclusions showing evidence of boiling (that is, homogenization temperatures of vapor-rich inclusions coexisting with liquid-rich inclusions) increase slightly with greater depth. Below the lower limit of boiling (1,103 m), homogenization temperatures of low-salinity liquid-rich inclusions show a general decrease with increasing depth, but these temperatures are not corrected for pressure. Figure 24 is a histogram of homogenization temperatures for each of the three types of fluid inclusions from all depths in the drill hole.

Fluid salinities

Equivalent salinities of fluid inclusions containing halite as a daughter mineral were obtained from the temperature of salt dissolution upon heating using the NaCl solubility data of Keevil (1942) and Potter et al. (1977), whereas those of inclusions undersaturated at room temperature were determined by measuring the freezing point depression of the liquid as described by Roeder (1962) and referring this value to the data of Potter et al. (1978). Measured salinities and homogenization temperatures of 295 fluid inclusions from various depths in the drill hole are compared in Figure 25, and, as suggested previously from studies of sample RM11, high-salinity (halite-bearing) inclusions generally homogenized at lower temperatures than the less saline variety. There is considerable overlap in temperatures of homogenization for the two types of fluids as was observed in individual veins and shown by cumulative data from the drill hole (Figs. 22, 23, and 24).

Also note that many inclusions having salinities of 35 to 55 equiv. wt percent NaCl lie along a curvilinear trend. This is because approximately 70 percent of these inclusions homogenized by halite dissolution and, therefore, fall along the NaCl saturation curve as shown, assuming that the solubility does not

Fig. 24. Summary of data in Figure 23 showing the relationship between homogenization temperature and inclusion type for all fluid inclusions from drill hole 138.

Fig. 25. Relationship between salinity and homogenization temperature of 295 fluid inclusions from Red Mountain. Inclusions denoted by triangles contained both halite and sylvite and their salinities were determined by summing the weight percents of halite and sylvite given by Figure 26. Salinities of inclusions containing only halite (i.e., those not containing a sylvite daughter mineral at room temperature) were obtained from the temperature of dissolution of halite and data for NaCl solubility given by Potter et al. (1977). Salinities of inclusions undersaturated with respect to NaCl at room temperature were obtained from the melting temperature of the inclusions and data of Potter et al. (1978). At the right side of the diagram is a histogram of salinities determined by the techniques described.

2 Four inclusions in sample RM1506 homogenized to the vapor phase. Their homogenization temperatures were similar to those of liquid-rich inclusions occurring in the same sample (Fig. 23), although an exhaustive search of other polished sections from this same sample failed to locate additional vapor-rich inclusions. It is therefore concluded that these four inclusions represent a rare occurrence of boiling at this location and that, as the other data suggest, boiling to any significant extent did not occur below the depth represented by sample RM1103.
change in the absence of a vapor phase, i.e., at pressures exceeding the vapor pressure of the solution.

At the end of Figure 25 is a histogram of all measured salinities and it is clear that there are two distinct populations with no overlap between the two. No inclusions were observed to have salinities in the range 20 to 30 equiv. wt percent NaCl which bridges halite saturation at 25°C (26.4 wt percent). For several reasons, this gap in salinities is thought to be real and not a result of insufficient sampling or measurement errors. First, of those inclusions not containing halite daughter minerals and whose salinities were determined, 93 percent had salinities of \( \leq 15 \) equiv. wt percent NaCl and none had salinities of 20 to 26 equiv. wt percent NaCl. Also, when it became apparent that there might be a gap in the salinity data, those halite-bearing inclusions appearing to contain the smallest volume percent halite (and presumably having the lowest salinity) were examined on the heating stage. Yet, no halite-bearing inclusions with salinities less than 30.5 equiv. wt percent NaCl were found and, of those halite-bearing inclusions examined, more than 97 percent had salinities exceeding 35 equiv. wt percent NaCl. Finally, the salinities determined from the temperatures of dissolution of halite daughter minerals are minimum salinities because they are based on the system NaCl-H\(_2\)O, whereas the actual fluid contains other cations and anions. Thus, if halite dissolves at 100°C in pure water, the salinity is 28.0 wt percent NaCl. However, if the solution is 6 wt percent CaCl\(_2\) and 6 wt percent KCl instead of pure water, halite saturation is 19.44 wt percent at 100°C, resulting in a solution with a total of 31.44 wt percent salts (Clyne et al., 1980). Therefore, all of the salinities given for halite-bearing inclusions are minimum values.

Approximately 10 percent of the halite-bearing inclusions examined contained a second isotropic daughter mineral. Based on its higher thermal coefficient of solubility and lower index of refraction as compared to halite, this daughter mineral was identified as sylvite (KCl). In most inclusions the sylvite crystal had rounded corners and was smaller than the halite. In all inclusions tested on the heating stages, the sylvite dissolution temperature was below that of halite.

Assuming the inclusion composition is in the NaCl-KCl-H\(_2\)O system, the K/Na ratio of halite-sylvite-bearing inclusions may be calculated using the NaCl-KCl-H\(_2\)O phase diagram. When the data are plotted in this manner, they define three groups (Fig. 26), with the range in KCl and NaCl dissolution temperatures being much narrower within individual groups of inclusions than for the data as a whole. Also, all of the values from an individual sample are restricted to only one of the three groups, except for one inclusion from sample 704 that falls between groups 1 and 2. Thus, all of the data points in group 3, characterized by the lowest KCl dissolution temperatures, are from three samples (704, 878, and 1536), those in groups 2 (intermediate) and 3 (highest KCl dissolution temperatures) are each from a single sample (389 and 618, respectively) where the sample number corresponds to depth in drill hole 138 in meters. Therefore, although there is considerable scatter in halite and sylvite dissolution temperatures over the depth of the drill hole (and presumably over the entire deposit!), at each point in space a much more restricted range is observed.

From the data shown in Figure 26, the atomic ratios K/Na were calculated and are listed in Table 2. The ratios vary from 0.52 to 1.76, with the data obtained from individual samples exhibiting a narrower range. The atomic ratios K/Na at Red Mountain are, in general, higher than those seen with porphyry copper-type mineralization at Bingham, Utah (K/Na = 0.26; Roedder, 1971); Granisle, British Columbia (K/Na = 0.25–0.60; Wilson et al., 1980); Bell, British Columbia (K/Na = 0.22–0.57; Wilson et al., 1980); Santa Rita, New Mexico (K/Na = 0.35; Reynolds and Beane, in prep.); and Panguna, Bougainville, Papua New Guinea (K/Na = 0.17–0.46; Eastoe, 1978).

It is of interest to note that coexisting with the halite- plus sylvite-bearing inclusions were many very small (<10µm in diam) inclusions containing only one isotropic daughter mineral. Upon heating, this one daughter mineral usually dissolved at approximately the same temperature as did the halite.
in those inclusions containing both phases. Also, when the halite- plus sylvite-bearing inclusions were cooled to room temperature after homogenization, many nucleated only a single solid phase. One such sample was placed for a period of two weeks into an oven that continuously cycled through a temperature range of approximately 30° to 50°C. At the end of this time, the inclusions still had not nucleated a second (sylvite) daughter mineral. These results suggest that possibly a larger percentage of the halite-bearing inclusions should also contain sylvite but because of kinetic problems do not.

**Geothermal gradient**

As shown in Figure 23, boiling of the hydrothermal fluids in the upper 1,100 m of the drill hole is indicated by coexisting liquid- and vapor-rich inclusions, both of which homogenize at approximately the same temperature. Because inclusions trapped along the liquid-vapor curve require no pressure correction, homogenization temperatures are the same as trapping temperatures.

Homogenization temperatures of inclusions homogenizing to the vapor phase and coexisting with liquid-rich inclusions homogenizing at approximately the same temperature (except the single inclusion at a depth of 347 m) are plotted versus drill hole depth in Figure 27. At each depth represented by more than one datum point, a wide range in homogenization temperatures is seen. This range could be attributed to: (1) a range of boiling temperatures over a period of time owing to fluctuations in pressure, (2) heterogeneous fluid entrapment resulting in higher homogenization temperatures, (3) observational difficulties during heating tests, (4) a range of boiling temperatures over a period of time owing to salinity variations, (5) necking down, and (6) leakage.

If all inclusions indicative of boiling are assumed to have formed at the same time over the entire 1,100 m in which boiling occurred the magnitude of the prevailing geothermal gradient during early stages of vein filling at Red Mountain may be calculated. The contemporaneity of the inclusions is uncertain. However, all inclusions indicative of boiling

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**Fig. 27.** Homogenization temperatures of 62 vapor-rich fluid inclusions versus depth in drill hole 138. The calculated geothermal gradient during early stages of vein filling at Red Mountain was obtained by linear regression ($r^2 = 0.3596$).
formed early in the vein-filling histories, have low to moderate salinities, and are found in optically similar quartz. A straight line fit through the data points by the method of least squares and shown in Figure 27 provides a calculated geothermal gradient of \(-25^\circ\text{C/km}\). In view of the uncertainties concerning the contemporaneity of the fluid inclusions and the scatter in the data points, this gradient should only be considered a rough approximation of temperature increase with depth during the early stages of vein filling at Red Mountain. However, in spite of the scatter, the data do suggest near isothermal conditions prevailed over a broad vertical interval in the volcanic pile at Red Mountain during this stage of vein filling.

**Pressures during vein filling**

From homogenization and freezing point measurements on inclusions showing evidence of entrapment from a boiling solution, the vapor pressure obtaining can be approximated using the data of Sourirajan and Kennedy (1962) and Urusova (1975). Table 3 lists homogenization temperatures, salinities, and corresponding vapor pressures of twelve liquid-rich fluid inclusions (from 5 different depths) that were coexisting with vapor-rich inclusions. These data indicate that during the early stages of vein-filling the pressure was \(-200\) to \(350\) bars.

During later stages of vein filling associated with hypersaline fluids, no evidence of boiling was observed. Therefore, the pressure must have exceeded the vapor pressure of the solution, defining a minimum value for the pressure conditions attending this period of mineral deposition. Unfortunately, however, the vapor pressures of such highly concentrated solutions are so low that the minimum values do not place severe restrictions on the pressures. For example, the vapor pressure of a 30 wt percent NaCl solution at \(300^\circ\text{C}\) is only \(65\) bars (Haas, 1976); at \(350^\circ\text{C}\) this same solution has a vapor pressure of approximately \(125\) bars (Urusova, 1975). The addition of other cations and anions only serves to lower these minimum pressures.

Of 225 halite-bearing fluid inclusions for which both the vapor bubble disappearance and halite-dissolution temperatures were obtained, more than 75 percent homogenized by halite dissolution. Heating tests of long duration have shown that this phenomenon is not a result of kinetic effects as others have suggested (Eastoe, 1978; Chivas and Wilkins, 1977). In a few cases (\(-5\) percent of those measured), the inclusion may have trapped a solid halite crystal as evidenced by a plane of inclusions exhibiting similar liquid-vapor homogenization temperatures but widely varying temperatures of halite dissolution. This same behavior would result if necking down occurred after halite had precipitated in the inclusion but before a vapor phase had nucleated. In the majority of the inclusions, however, the data suggest that the inclusions trapped homogeneous fluids which became saturated in halite before intersecting the liquid-vapor field boundary. This behavior is commonly interpreted as indicating entrapment at high pressures (Lyakhov, 1975; Kamilli, 1978; Klepsov and Lemmlen, 1959), but recently Roedder and Bodnar (1980) have shown that this interpretation is not necessarily the case. Unfortunately, a rigorous evaluation of pressure conditions attending entrapment of such inclusions must await experimental P-V-T-X data on the appropriate compositions in the liquid-halite field.

**Samples from Other Drill Holes**

In addition to the more detailed studies of sample RM11 and samples from drill hole 138, several fluid inclusions in each of four samples from other drill holes were examined on the heating stage. The locations of the four drill holes are shown in Figure 1 and the results of heating tests are given in Figure 28. The sample from drill hole 134, which is col-lared in phyllic alteration (quartz + sericite + pyrite), contains the three types of inclusions discussed previously, that is, the liquid-rich, vapor-rich, and halite-bearing types. Also, the homogenization temperatures of these inclusions fall in the same range as similar inclusions in sample RM11 and those from drill hole 138, although boiling occurred to a greater depth in this drill hole than in drill hole 138.

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a Recent experimental data (Bodnar, unpub. data) indicate that the isochors in the liquid-halite field between \(300^\circ\) and \(400^\circ\text{C}\) have slopes of approximately \(5\) bars/°C.
Drill holes 140 and 156 are also collared in rocks pervasively altered to quartz + pyrite + sericite, i.e., phyllic alteration (Fig. 1). The samples examined, from depths of 1,350 and 1,492 m, respectively, contain no vapor-rich inclusions and the early, low-salinity fluids appear to have been slightly cooler than those in drill holes 134 and 138 and in sample RM11.

Drill hole 159 is collared in rocks altered to pyrite + alunite + clay minerals (advanced argillic) and is located on the periphery of the Red Mountain system. This sample contains only liquid-rich inclusions which homogenized in the range 325° to 375°C; no vapor-rich or halite-bearing inclusions were observed. The lack of high-salinity inclusions in this peripheral zone is consistent with observations at Bingham, Utah (Moore and Nash, 1974).

**Discussion of Results**

Results of this study indicate that two different fluids, recognized in fluid inclusions by observable as well as measurable characteristics, were associated with alteration and mineralization in preintrusive cover at Red Mountain, Arizona. The earlier of the two fluids deposited crystalline, milky to gray quartz and had low to moderate salinities (~2-18 equiv. wt percent NaCl). The later fluid, on the other hand, was hypersaline (~35-50 equiv. wt percent NaCl) and was associated with deposition of massive clear quartz and chalcopyrite. Inclusions of these two fluid types are clearly distinguishable from one another at room temperature based on the absence or presence, respectively, of halite daughter minerals.

The general thermal pattern indicated by fluid inclusion homogenization studies is one of decreasing temperature with time from early values in the range 400° to 450°C down to approximately 200° to 225°C during later stages of vein filling over a vertical range of approximately 1,500 m. The early low to moderate salinity inclusions are both liquid rich and vapor rich and, based on heating tests, are indicative of boiling. Homogenization temperatures of inclusions trapped from boiling solutions are identical to trapping temperatures and indicate pressures in the range of 200 to 350 bars during early stages of vein filling at Red Mountain (Table 3). Later low to moderate salinity fluids did not boil as indicated by the absence of vapor-rich inclusions in outer growth zones of the milky quartz (B-C, Fig. 21) and thus homogenization temperatures for these inclusions require a pressure correction to obtain trapping temperatures. At a constant pressure (250 bars) and salinity (10 equiv. wt percent NaCl) the magnitude of this pressure correction is on the order of 10° to 25°C, the larger value corresponding to lower homogenization temperatures (Potter, 1977). Therefore, the actual range in trapping temperatures of these low-salinity fluids is probably somewhat less than that of the corresponding homogenization temperatures.

The later high-salinity inclusions have recognizably lower homogenization temperatures, both within individual veins (Figs. 22 and 23) and overall (Fig. 24). These fluids did not boil and hence also require pressure corrections to homogenization temperatures. Corrections to homogenization temperatures of halite-bearing inclusions which homogenized by vapor-bubble disappearance are on the order of 20° to 25°C if the pressure is 250 bars (Lemmllein and Klevtsov, 1961). The pressure necessary to elevate homogenization temperatures of hypersaline inclusions up to those of earlier, low-salinity inclusions (~100°C) is on the order of 1,100 bars (Lemmllein and Klevtsov 1961; Potter, 1977). Thus, in the absence of drastic increase in pressure, the later hypersaline fluids would have been of lower temperature than the earlier low-salinity fluids, indicating an overall decline in temperature of vein filling with time.

Pressure determined from inclusions indicative of boiling may be used to approximate depth of burial. The simplified model given by Haas (1971) for hydrostatic systems boiling to the surface yields initial depths of 2,800 to 5,200 m for the samples from Red Mountain listed in Table 3. Present depths in the drill hole would indicate removal of approximately

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Fig. 28. Homogenization temperatures of fluid inclusions from drill holes 134, 140, 156, and 159 at Red Mountain, Arizona. The number following that of the drill hole on each histogram is the sample depth (m) below the surface.
2,100 to 4,200 m of overburden. The corresponding depths of burial under lithostatic pressure (assuming a pressure gradient of 270 bars/km) would have been on the order of 700 to 1,300 m. This condition is considered unlikely because, if lithostatic conditions prevailed, the present depths below the surface for samples RM1103 and RM1425 are greater than their depths would have been at the time of formation.

The large amount of overburden removal suggested above is in reasonable agreement with geologic observations at Red Mountain. Drewes (1972) has correlated the Paleocene Gringo Gulch volcanics which occur in the Sonora Valley with the Red Mountain Volcanics. Further, Corn (1975) suggests that "This unit [Gringo Gulch volcanics] is 1,500 to 2,000 feet thick and could represent an upper part of the sequence that has been eroded from Red Mountain" and "it appears probable that several thousand feet of tuffaceous volcanics were also eroded from Red Mountain" (p. 1439-1440). Also, a large mass of volcanic rocks occurring north of Red Mountain and referred to as Kunde Mountain on the Mt. Hughes quadrangle map is intensely altered to amorphous silica, pyrophyllite, and kaolinite and may be a slide block that has come from the vicinity of Red Mountain (J. Quinlan, pers. commun.).

Fluid inclusion data covering a 1,500-m interval in preore cover indicate that a broad vertical zone of moderate geothermal gradient prevailed during vein filling at Red Mountain. These results are in good agreement with numerical simulations of thermal regimes in a similar geologic environment (Norton, 1980). Studies of numerous veins within this preore cover each record a range in temperatures commencing at approximately 425°C and evolving through time to approximately 225°C. This again is consistent with time-temperature variations predicted by Norton. Reconnaissance studies further indicate that similar fluid characteristics prevailed over a broad areal extent at Red Mountain. These features are a predictable consequence of large-scale convective circulation of hydrothermal fluids characteristic of porphyry copper systems as evidenced geologically by widespread development of alteration and mineralization.

Fluid inclusion studies of porphyry copper deposits consistently indicate that two fluids of distinctly different salinities are involved in the alteration-mineralization process. Nash (1976), based on data from 36 deposits, states that "all porphyry copper deposits contain moderate salinity inclusions which generally are younger than halite-bearing inclusions" (p. D11). Detailed paragenetic studies at Sierra, Arizona (Preece and Beane, in prep.), and Santa Rita, New Mexico (Reynolds and Beane, in prep.), support Nash's statement. At Red Mountain, the situation is different because, although two fluids are observed, the moderate salinity fluid inclusions are older than the halite-bearing variety in every case. However, samples used for fluid inclusion studies of porphyry copper systems are usually taken from the intrusive stock or from wall rocks in close proximity to the pluton. Conversely, all of the samples examined in the present study were taken from pre-intrusive volcanic cover and, as mentioned previously, no continuous intrusive body was intersected at depth by the drill holes.

Fluid pathlines calculated by Norton (1978, 1980) indicate that the first fluids to flow through a given point within a cooling pluton are endogenous and that later fluids are drawn from surrounding wall rocks. However, in the lithocap region wall rock-derived fluids will be earliest and will be succeeded by fluids originating in, or previously flowing through, the underlying pluton. The inverted order of appearance of dilute versus hypersaline fluids between Red Mountain and the more commonly studied pluton environment is likely a result of the contrasting fluid source regions in the two environments as suggested by Norton. The early fluids at Red Mountain contained considerable amounts of copper as evidenced by the chalcopyrite daughter minerals commonly observed in these low-salinity inclusions, although the deposition of chalcopyrite in the veins was associated with the later high salinity fluids.

In conclusion, fluid inclusion data indicate that the evolutionary path of hydrothermal fluids at Red Mountain is consistent with the geologic environment of formation as predicted by numerical simulations. However, the results of this study also reveal considerable differences in the character of the fluids associated with the shallow volcanic regime at Red Mountain as compared to the more commonly studied pluton environment. It is these differences that provide a potentially important tool for recognizing buried porphyry copper-type systems and for estimating the extent of erosion to which a system has been exposed.

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December 3, 1979; May 13, 1980

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