GEOLOGICAL AND CHEMICAL CONDITIONS OF FORMATION OF RED BERYL, WAH WAH MOUNTAINS, UTAH

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ABSTRACT

Several geological and chemical factors appear to have contributed to the formation of unique gem-quality red beryl in a topaz rhyolite lava flow in the Wah Wah Mountains, Utah. All beryl crystals in the flow occur exclusively along shrinkage fractures in devitrified rhyolite, rather than in lithophysal pockets, as is often the case for topaz, or in unfractured rock. The flow occupies a graben and perhaps a significant paleo-drainage. Both beryl-bearing fractures and the host rhyolite show an unusual amount of clay alteration compared to other topaz rhyolite flows in the Wah Wah Mountains and elsewhere in the western United States. Hydrothermal alteration does not appear to be associated with volcanic vents, but may be related to incursion of surface water along shrinkage fractures within the cooling flow.

Beryllium was likely transported with fluoride complexes; fluoride concentrations would remain at optimal levels for Be transport only if concentrations of Ca were low. Whole-rock concentrations of CaO within the host rhyolite are very low (<0.01% to 0.18%) compared to other topaz rhyolites while Be concentrations are about average. Beryl growth occurred at temperatures below magmatic values (~300-650°C), but above the temperature of kaolin development (200-300°C) as fluoride-rich vapors, released during devitrification, encountered fractures. If the rhyolite flow was partially bathed in surface water during cooling, a water-rich low-density fluid, or vapor, probably permeated shrinkage fractures during beryl formation. Beryllium-fluoride complexes reacted with alkali feldspar, water, and Fe-Mn oxides along fractures to produce red beryl. Continued equilibration of the flow with surface water at lower temperatures would likely produce a boiling, more acidic fluid capable of producing the kaolin lined fractures and argillic alteration which are commonly present. Consequently, eruption of low-Ca topaz rhyolite lava followed by incursion of surface water into some medial portions of the flow at high temperatures are critical factors that led to formation of beryl in this unique deposit.

No proven mine reserves exist. However, there is no evidence that most or all of the productive fractures have been found and mined. In the main pit, productive fractures occur every few meters. There is no reason to suspect that beryl-bearing fractures of equal gem-quality do not occur within a few meters or tens of meters of the current pit walls or at other locations in the flow. Probable reserves of red beryl may greatly exceed the amount that has been produced.

INTRODUCTION

The only known occurrence, and most-valued variety, of gem-quality red beryl in the world is in the Wah Wah Mountains, Utah (Shigley and Foord, 1984). Red beryl at this locality (essentially "red emerald", although the name emerald is reserved exclusively for green stones) occurs as a vapor-phase mineral in topaz rhyolite and was precipitated by escaping gases after eruption of rhyolite lava. Only a few similar occurrences of rhyolite-hosted beryl have been documented worldwide. These occur in the Thomas Range, Utah (Christiansen and others, 1986,) and in the Black Range, New Mexico (Kimbler and Haynes, 1980), but neither of these has produced crystals suitable for faceting. East Grants Ridge, New Mexico and San Luis Potosi, Mexico also may have similar occurrences of beryl, but these have not been well documented (Ream, 1979). Most of the marketable crystals from the Wah Wah Mountains have been produced from the Violet Mine which has operated on a limited scale since 1976, under the ownership of the Harris family of Delta, Utah. Production figures for the mine from 1989-1993 are 2.3 million dollars with an inventory of 1.1 million dollars of production.

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unsold gems (Rex Harris, written communication). No drilling or other exploration techniques have been used to determine proven or probable reserves of the mine. However, in April of 1994 Kennecott Exploration leased the mine and surrounding claims to determine reserves and feasibility of gem recovery by other mining and milling techniques.

Previous work on the occurrence of rhyolite-hosted red beryl has dealt mainly with crystallographic, chemical, and optical properties of the crystals (Nassau and Wood, 1968; Flamini and others, 1983; Shigley and Foord, 1984; Aurisicchio and others, 1990; Hosaka and others, 1993) with only general descriptions of the geology (Ream, 1979). Recently proposed models of formation for red beryl have modified only slightly the original suggestions of Hillebrand (1905); the unusual conditions needed for formation of red beryl have not been well constrained. It is generally proposed that beryl originates in a manner that is similar to other vapor-phase minerals; namely, by precipitation in fractures and vugs from high-temperature gases as they are released from slowly-cooled rhyolite lava. Dozens of topaz rhyolite flows and domes, similar in composition to the beryl-bearing flow in the Wah Wah Mountains, occur across the western United States (Christiansen and others, 1986). All of these flows, comprising a total area of 100-200 km², devitrified to form vapor-phase topaz and locally other vapor-phase minerals such as bixbyite, garnet, hematite, pseudobrookite, and fluorite, but the occurrence of beryl is exceptionally rare. Even within the rhyolite flow which hosts the red beryl, the productive open pits comprise only 0.02% of the surface area of the flow. Consequently, the conditions that favor the formation of red beryl are apparently rarely achieved -- even within the premier beryl-bearing flow! Clearly, if a better understanding of the conditions of formation could be had, then exploration for additional deposits and new mine reserves would be aided.

This report describes the occurrence of red beryl in the Wah Wah Mountains, Utah and chemical and geological factors which may have favored its formation in this particular rhyolite flow over very similar topaz rhyolite flows which are apparently barren. In addition, it examines the possibility that additional reserves of gem material may exist within the flow. Potential exploration guides are also discussed. Topaz rhyolites are also genetically related to the large bertrandite/phenakite deposits of west-central Utah. Conditions which may favor the formation of beryl rather than bertrandite or phenakite will be discussed.

**GEOLOGIC SETTING**

The rhyolite flow which hosts the red beryl deposit is located along the eastern flank of the Wah Wah Mountains, Utah (figure 1). Pre-volcanic rocks in the Wah Wah Mountains consist of Proterozoic, Paleozoic, and Mesozoic sedimentary rocks that were folded and thrust to the east during the Sevier orogeny (Best and others, 1987b; Abbott and others, 1983; Weaver, 1980). Tertiary volcanism in the area began about 34 Ma and consisted dominantly of large volume dacitic ash flows and lesser volumes of low-silica rhyolite and andesitic lava flows. Beginning about 23 Ma the style and composition of volcanism changed to smaller-volume ash-flow and dome-forming eruptions of high-silica rhyolite and trachyandesitic lava flows. This bimodal magmatism is part of a roughly east-west belt of Miocene igneous rocks and mineral deposits stretching from Pioche, Nevada to Marysvale Utah (figure 1). It has been termed the Pioche-Marysvale igneous belt (Rowley and others, 1979), the Pioche mineral belt (Shawe and Stewart, 1976), the Wah Wah - Tushar belt (Hilpert and Roberts, 1964), and the Blue Ribbon lineament (Rowley and others, 1978).

The Miocene volcanic activity in the belt can be divided into two distinct episodes; the first episode, from 23 to 18 Ma, formed rhyolitic tuffs and domes and trachyandesitic lava flows which have been designated the Blawn Formation (figure 1; Best and others, 1987a). A subsequent episode (12 to 13 Ma) of bimodal magmatism produced the Steamboat Mountain Formation, the rhyolitic part of which is often topaz-bearing.

The character of the early Miocene magmatism is of particular concern here, inasmuch as this episode produced the beryl-bearing rhyolite flow. Abbott and others (1983) report a K-Ar age of 22.1 ± 0.8 Ma for the beryl-bearing flow; stratigraphically, it is the youngest member of the Blawn Formation which is present along the eastern side of the Wah Wah Mountains. The oldest member of the Blawn Formation in the central Wah Wah Mountains is the garnet-bearing tuff member which vented from Pine Grove, about 18 km northwest of the beryl rhyolite (figure 1). The vent at Pine Grove was subsequently filled by rhyolite domes. ^40Ar/^39Ar ages for the garnet-bearing tuff member and subsequent domes range from 22.9 ± 0.3 Ma to 21.7 ± 0.3 Ma (Keith and others, 1986). A well-dated regional ash-flow tuff with an age of 22.74 ± 0.05 Ma (Myron Best, oral communication, 1993), the Bauers Tuff Member of the Condor Canyon Formation, also underlies the beryl rhyolite. This rhyolitic tuff was derived from the Caliente caldera complex 125 km to the southwest. Three other dated occurrences of topaz rhyolite occur in the central Wah Wah Mountains. They are the Tetons emplaced at 18.3 ± 0.7 Ma (Best and others, 1987a), the Staats pluton at 20.2 ± 0.9 (Rowley and others 1978), and the Lou rhyolite at 19.1 ± 0.2 (Keith and others, 1986). These data suggest that the beryl rhyolite is probably the oldest topaz rhyolite flow in the Wah Wah Mountains.

Blawn magmatism is characterized by initial eruptions of rhyolitic tuffs and flows which are high-silica (75-77% SiO₂) but not as strongly enriched in lithophile elements as most topaz rhyolites (Keith and others, 1986). These early Blawn rhyolites do not exhibit conspicuous vapor-phase mineralization and can be classified as calc-alkaline rhyolites (Christiansen and others, 1986) and may have fractionated from dacitic precursors (Keith, 1982). Across the Pioche-Marysvale igneous belt, the youngest rhyolitic volcanism of the Blawn
episode is generally comprised of topaz rhyolites (figure 1). Inasmuch as some deeply eroded flows may not preserve vapor-phase topaz, which often occurs only in the lithophysal upper portion of the flow, topaz rhyolites also can be defined by unusually high contents of most incompatible trace elements (e.g. Rb, U, Th, Ta, Nb, Y, Be, Li, and Cs) as well as high fluorine (Christiansen and others, 1986).
EXPLANATION

- mafic lavas of Brimstone Reservoir Fm (12-13 Ma)
- topaz and red beryl rhyolite of Blawn Fm (22 Ma)
- Tuff member of Blawn Formation (22 Ma)
- inferred Miocene graben
- high-angle fault (bar and ball on downthrown side)
- strike and dip of Tertiary bedded deposits
- strike and dip of Tertiary compaction foliation
- inferred direction of fluvial transport prior to emplacement of red beryl rhyolite

Figure 2. Map showing location of red beryl rhyolite relative to an apparent Miocene graben, high-angle normal faults, the inferred direction of fluvial transport, and overlying and underlying units. Data compiled from Weaver (1980), Abbott and others (1983), Best and others (1987b).

RESULTS

Host Rhyolite

The rhyolite which hosts the red beryl deposit is exposed over an area of 9.1 km² (figure 2). Undoubtedly, some unknown additional portion of the rhyolite is concealed beneath younger mafic lavas of the formation of Brimstone Reservoir and some has been concealed by valley-filling sediments on the eastern side.

Many topaz rhyolites in the Pioche-Marysvale igneous belt, including the red beryl body (figure 2), appear to be flow/dome complexes which overlie non-welded tuff of co-genetic origin. A large portion of the red beryl body of rhyolite has moderate- to gently-dipping flow layering, but a local area of sub-vertical flow layering suggests the location of a possible vent (figure 3). However, flow layering in much of the rhyolite does not dip radially towards this apparent vent as is the case in some viscous rhyolite domes and flows; consequently, multiple vents may have fed this flow.

Both crystal-poor (~ 5% phenocrysts) and crystal-rich (~15% phenocrysts) rhyolite make up the red beryl flow. In some areas near its base, they occur as distinct, intermixed portions of strongly flow-laminated rock. The implication is that two magmas were at least partially mixed during eruption and emplacement. Elsewhere within the flow, no such subdivisions could be made on the basis of phenocryst content. However, two distinct compositions are represented in samples from the base of the flow (Red-1 to Red-3), which contain higher concentrations of K₂O, Sc, Y, and REE than samples from the mid to upper portions of the flow (Red-4 to Red-6; Table 1). These differences are most pronounced for Y and do not appear to be related to alteration (as discussed later). Fractionation of xenotime (YPO₄ with some additional rare earth elements) from some of the magma may have caused this chemical difference. Additionally, these data may imply that the parent magma chamber was zoned with respect to major and trace elements.

Figure 3. Map showing location of argillic alteration, erosional lineaments, and high-angle faults. Recent rangefront faults on the extreme eastern side of the map have been excluded. A vent area for the rhyolite flow is inferred on the basis of sub-vertical flow foliation. Location of high-angle faults compiled from Weaver (1980) and Abbott and others (1983).
Table 1. Major- and trace-element analyses

<table>
<thead>
<tr>
<th>sample #</th>
<th>RED-1</th>
<th>RED-2</th>
<th>RED-3</th>
<th>RED-4</th>
<th>RED-5</th>
<th>RED-6</th>
<th>RED-7</th>
<th>RED-8</th>
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<tr>
<td>descrip.</td>
<td>beryl/clay</td>
<td>fresh gray</td>
<td>topaz/clay</td>
<td>basal vitro</td>
<td>basal alter</td>
<td>basal gray</td>
<td>white clay</td>
<td>pink clay</td>
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<td>wt%</td>
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<td></td>
<td></td>
<td></td>
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<td>SiO2</td>
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<td>99.74</td>
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<td>99.67</td>
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<td>2.16</td>
<td>1.40</td>
<td>14.24</td>
<td>13.33</td>
</tr>
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</table>

ppm

| Li | 105 | 146 | 78 | 13 | 31 | 65 |
| Be | 18.1 | 13.3 | 10.8 | 22.4 | 11.4 | 10.9 |
| F  | 984 | 1911 | 339 | 1700 | 158 | 2694 |
| S  | 102 | 61 | 77 | 30 | 52 | 30 |
| Cl | 107 | 103 | 131 | 1293 | 137 | 137 |
| Sc | <2 | <2 | <2 | 3 | 4 | 3 |
| V  | 4 | <1 | 4 | 10 | 11 | 19 |
| Cr | 10 | 9 | 9 | 10 | 8 | 7 |
| Ni | 3 | 1 | <1 | 4 | 2 | 4 |
| Cu | 1 | <1 | 2 | 5 | 5 | 1 |
| Zn | 69 | 58 | 46 | 75 | 90 | 50 |
| Ga | 24 | 27 | 20 | 25 | 19 | 19 |
| Rb | 728 | 707 | 487 | 883 | 614 | 465 |
| Sr | 11 | 3 | 16 | 2 | 9 | 7 |
| Y  | 11 | 7 | 8 | 105 | 43 | 80 |
| Zr | 157 | 137 | 195 | 207 | 282 | 207 |
| Nb | 112 | 125 | 87 | 102 | 59 | 78 |
| Mo | 2 | 2 | 2 | 2 | 2 | 2 |
| Ba | 27 | 10 | 10 | 10 | 23 | 14 |
| La | 22 | 8 | 25 | 63 | 101 | 79 |
| Ce | 55 | 23 | 36 | 110 | 41 | 137 |
| Nd | 15 | 4 | 7 | 29 | 14 | 42 |
| Sm | 5 | 4 | 3 | 11 | 10 | 11 |
| Pb | 42 | 53 | 40 | 54 | 27 | 35 |
| Th | 40 | 21 | 6 | 31 | 18 | 57 |
| U  | 9 | 9 | 6 | 15 | 4 | 8 |

Major elements are recalculated to 100% (except clay samples; Red-7 and Red-8).
All elements analyzed by XRF methods, except Be and Li by AA.
TOTAL* - analytical total
LOI - Loss on ignition
< - below detection limit
blank - not analyzed
Distribution of Fractures and Alteration

The red beryl crystals apparently occur exclusively along, or adjacent to, sub-vertical fractures in the rhyolite. Not all fractures, nor all portions of a single fracture, contain beryl. Often the productive zone of any single fracture does not exceed 3-4 m in vertical extent and 30-60 m in length (figures 4 and 5). The fracture orientations cluster in two groups with azimuths of approximately 65° and 140°. Most of the productive fractures contain clays and vapor-phase minerals such as bixbyite which serve as reasonably useful exploration guides. Fracture-hosted bulk clay samples vary from a compact white variety that is dominantly kaolin with trace amounts of smectite to a pink or brown clay that is also dominantly kaolin, but contains more mixed-layer clay (~20% illite and ~80% smectite). Both types of bulk clay samples contain a trace of siderite. Other vapor-phase minerals that are present in productive fractures include tridymite, cristobalite, amorphous silica, and rare topaz. Some red beryl crystals (up to 2 cm in length) occur along irregular planes that appear to be tightly healed fractures. In this situation, some bixbyite also occurs along the fractures, but there is no obvious "fracture-filling" material. The healed fractures appear to be slightly grayer than the surrounding host which might imply that the fractures were sealed by deposition of tridymite or cristobalite, but conspicuous clay is not present.

It is not apparent whether the amount of fracturing, devitrification, and clay (argillic) alteration is more or less abundant in beryl-bearing rhyolite than in the beryl-absent portion of the flow. Most of the rhyolite flow is covered by a thin veneer of soil and colluvium; consequently, it is difficult to accurately evaluate which areas are most fractured, devitrified, and altered. However, both the topographic expression of the productive area and our limited observations would indicate that it is moderately devitrified and fractured and weakly argillically altered (figure 3). Fracturing, devitrification, and clay alteration do affect how resistant the rhyolite is to weathering and erosion. With this in mind, the productive area is on the flank of a prominent ridge; in particular, the main pit is excavated in a small drainage gully which is aligned parallel (ENE) to one of the prominent fracture sets (figure 3). Therefore, the general vicinity of the Violet mine is in rhyolite which is more resistant to erosion, but the location of the most productive pit has clearly been more susceptible to Pleistocene and Recent erosion. This may indicate that it is an area of enhanced clay alteration and/or fracturing.

Flow Folation

Another factor which may have a bearing on the development of vapor-phase red beryl is the orientation and persistence of the flow foliation. In the vicinity of the main pit, the flow foliation strikes 58°-75° and dips 25°-40° NW (figure 5). Flow foliation is readily apparent because planes of slippage within the flow cooled quickly and were resistant to devitrification. The intervening rhyolite, between planes of slippage, cooled more slowly whereby devitrification was enhanced. Consequently, the rock consists of alternating gray (less devitrified) and white (more devitrified) layers. The more devitrified layers were likely the source and the transport medium for vapors which formed beryl and other vapor-phase minerals along fractures. By contrast, other portions of the red beryl rhyolite flow, particularly at higher levels in the flow, may not have consistently collected as large a volume of vapor because they are brecciated or do not exhibit a relatively constant flow foliation direction. Examination of other topaz rhyolite flows has also shown that moderately inclined flow foliation is relatively common at medial levels within a flow (beneath a more steeply inclined and brecciated upper zone; Burt and Sheridan, 1987). Perhaps equally important is the observation that the center of the flow (at medial depths) would cool more slowly and be subject to more pervasive devitrification and the correlative release of volatile complexes. These data suggest that paleodepth may be an important control on beryl formation.

Vertical Distribution of Vapor-Phase Minerals

A few observations should be noted concerning vertical changes in the distribution of alteration minerals. The beryl occurs about 170 m below the nearly horizontal (extrapolated) contact between the mafic lavas of the formation of Brimstone Reservoir and the host rhyolite. However, a significant amount of erosion may have occurred between these units because of their disparity in age (13 and 22 Ma, respectively). Some alluvial deposits and conglomerate are present above the red beryl rhyolite and beneath the mafic lavas, but they are not present directly upslope from the Violet mine. We recognize that the actual depth of formation of the red beryl could have been greater (or less because of unpredictable paleotopography) than this amount.

Perhaps the most obvious zonation of alteration minerals is in the abundance of Fe-staining (limonite/goethite) along fractures; Fe-staining is negligible in the uppermost 120 m of the rhyolite; it is conspicuous at the level of red beryl formation and increases in abundance downward. Much of the fracture-hosted Fe-staining originally may have consisted of bixbyite and Mn-hematite which were subsequently changed by weathering, groundwater, or low-temperature alteration. Topaz is dominantly present above the red beryl where it often occurs in lithophysal vugs rather than along fractures.

Chemical Effects of Alteration

In order to evaluate the chemical effects of alteration, the chemical composition of unaltered rhyolite must be defined.
Figure 4. Plan view of beryl-bearing fractures in the Violet mine open pits. Approximate pit boundaries and fracture lengths and orientations are shown to scale. Number indicates measured azimuth of fracture. Additional mining since the date of this mapping (Aug., 1993) has increased size and production of both pits.

Figure 5. High wall map of main pit of the Violet mine as of August 1993. The approximate spacing and orientation of beryl-bearing versus beryl-absent fractures is shown as well as approximate flow-foliation orientation. Fractures appear to be shrinkage cracks rather than tectonic.
For reasons discussed previously, it appears that some of the chemical variations in the rhyolite are magmatic in origin and the parent magma chamber may have been chemically zoned. Consequently, the chemical analyses are divided into two groups (Red-1-2-3 and Red-4-5-6) based on the proximity of sample localities and compositional correlations of less mobile elements.

Chemical changes that may be related to alteration (vapor-phase or hydrothermal) are presented by means of the isocon method (Grant, 1986). This technique is a graphical application of Gresens' (1967) approach. Rock densities are not required, an advantage when comparing dense fresh rocks with low-density clay–altered rocks. The technique is based on a plot of the concentrations of elements in a fresh rock (on the X-axis) against its altered equivalent (on the Y-axis). Individual concentrations can be scaled by multiplication without affecting the results. On such a graph, an isocon is a straight line through the immobile elements and the origin (figure 6). The slope of the isocon defines the mass change that resulted from the alteration, and the deviation of a data point from the isocon defines the concentration change for that element.

Three isocon diagrams are shown for beryl–bearing, topaz–bearing, and argillically altered rhyolites in figure 6. If there is no detectable alteration, the data points define a line with a slope of 1, representing constant mass. In most cases, a linear array is defined by some components (e.g., Al₂O₃, TiO₂, Ga) commonly considered to be relatively immobile during vapor phase or hydrothermal alteration of volcanic rock, which we interpret as the isocon. Isocon slopes are near 1 for the beryl-bearing rock, indicating no change in mass occurred during alteration. However, considerable scatter of element concentrations about the line show that losses and gains of some elements occurred. The patterns of element mobility are quite similar for topaz- and beryl-bearing rocks, with substantial depletions in Na and F, and enrichments in Sr, Y, S, and LOI (loss on ignition at 1000°C, a measure of H₂O content). There are some significant differences between the beryl-bearing and topaz-bearing samples, including marked enrichments in Be, Ba, CaO, and MgO in the beryl-containing rhyolite and perhaps a depletion in MnO in the topaz containing sample. These changes are probably associated with the formation of pink smectite–rich clays and beryl, and the destruction of feldspar. The fresh–argillically altered pair of samples from the base of the rhyolite flow complex, shows a significantly different pattern of alteration. The constant aluminum isocon has a slope of 1.05, indicating a 5% decrease in mass during partial alteration to clay. Depleted elements include F and Na (as in the other samples), but also include Mn and Fe. Iron-manganese oxides such as bixbyite must not have been stable during the alteration of this sample allowing Mn and Fe to be dissolved and flushed away with the fluid.

Another aspect of alteration of these rhyolites can be visualized by comparing the composition of a basal vitrophyre with adjacent fresh, but devitrified rhyolite (Red-4 and Red-2, Cenozoic Geology and Geothermal Systems of Southwestern Utah.

Figure 6. Isocon diagrams for altered rocks from the rhyolite flow that hosts the red beryl mine, plotted after the method of Grant (1986). The bold lines are constant Al₂O₃ isocons. Isocon slopes indicate that little change in rock mass occurred during alteration of Red-1; a 14% change is indicated for Red-3 and a 5% change for Red-5. Lines of constant gain or loss are labelled with percentages as compared to the fresh rock. Concentrations of individual elements have been scaled by arbitrary factors to avoid overlap on the diagram. Beryl-bearing rhyolite experienced about 50% enrichment of Be and many other elements. Significant losses included Li, Na, and F.
beneath and above portions of the red beryl rhyolite. Evidence of lacustrine sediments has not been found.

Pioche-Marysvale belt from 18-22 Ma mark the inception of rhyolite flows in the southern Wah Wah Mountains do not. A prominent stream valley whereas other beryl-absent topaz flow and a thick accumulation of underlying Blawn tuff. Also parallel to the dominant orientation of faults and dikes of Compaction foliation of underlying ash flow tuff units dips as well, but this loss cannot be evaluated quantitatively, because water, and consequently LOI, increases as glassy rocks hydrate by the addition of meteoric water. Coincident with the loss of magmatic volatiles, other elements could be transported complexed in the vapor (or depending on temperature a low-density fluid). For example, Be shows a 50% depletion in the devitrified rock as compared to the vitrophyre.

**DISCUSSION**

**A Genetic Model**

Our data suggest several new facets of a model for the formation of vapor-phase beryl which may have utility in exploration for new beryl deposits in the vicinity of the Violet mine and elsewhere. Most chemical and physical characteristics of the red beryl rhyolite flow are within the norm of other topaz rhyolite flows in the eastern Great Basin (table 1, Christiansen and others, 1986). However, the occurrence of gem-quality red beryl with abundant kaolin and mixed layer smectite-illite clay is unique. The conditions necessary to form beryl may be linked to those which later formed the clay. Both may have formed in response to interaction of the rhyolite flow with larger than normal amounts of surface water during cooling of the flow.

Eruption of topaz rhyolite lava flows across the Pioche-Marysvale belt from 18-22 Ma mark the inception of extensional tectonism in the area (Best and others, 1987a). Our work suggests that the red beryl flow occupies a graben or prominent stream valley whereas other beryl-absent topaz rhyolite flows in the southern Wah Wah Mountains do not. Fluvial sediments occur in the sequence of Blawn tuffs and flows immediately beneath the red beryl flow; NW to SE transport of fluvial material for distances up to 15 km has been documented in the Blawn sedimentary units (Keith and others, 1986; figure 2). These streams may have emptied into a NE-trending graben that is now occupied by the red beryl rhyolite flow and a thick accumulation of underlying Blawn tuff. Compaction foliation of underlying ash flow tuff units dips towards this graben, even if tilting due to recent Basin-and-Range faulting is removed (figure 2). The graben is also parallel to the dominant orientation of faults and dikes of Blawn age (figure 1). Fluvial sediments are present both beneath and above portions of the red beryl rhyolite. Evidence of lacustrine sediments has not been found.

The origin and orientation of fractures which host the beryl crystals may be important in deciphering the depth and timing of beryl formation. Examination of other well exposed rhyolite flows indicates that there are recognizable vertical and horizontal changes in flow foliation and fracturing. For instance, the outer margins of the flow are locally brecciated due to rapid cooling of the outer rind while dome growth or flow continued. The coherent interior of the flow may exhibit widely spaced fractures with a consistent orientation that formed in response to minor down-gradient creep of the flow shortly after the interior had solidified. These fractures are sometimes referred to as shrinkage cracks and also may be related to a volume decrease during cooling. Some workers have noted that columnar jointed glassy rhyolite also overlies the zone dominated by devitrification and shrinkage cracks (Bonnichsen and Kauffman, 1987). Flow foliation of well-preserved topaz rhyolite in the Wah Wah Mountains and elsewhere show consistent lateral and vertical changes. For example, flow foliation becomes steeper or overturned as the upper margin is approached (Burt and Sheridan, 1987). By contrast, laterally away from the vent and towards the base of the flow, the foliation becomes more horizontal. Comparison of the fracturing and flow foliation of the host rhyolite for red beryl with these characteristics indicates that the red beryl formed in the medial zone of the flow and away from a vent (figure 3).

The orientation of shrinkage cracks may not be totally random, but may be parallel and perpendicular to the direction of flow. In addition, shrinkage cracks may serve as the roots of fumaroles which allow collection and transport of exsolved vapors and influent surface water. The welded rhyolitic ash flow at the Valley of Ten Thousand Smokes in Alaska developed fracture fumaroles shortly after eruption which were oriented either parallel or perpendicular to the valley walls (Keith, 1991). Fracture fumaroles which developed along these orthogonal directions are tens of meters long and were sustained largely by influx of surface water into the ash flow tuff.

The red beryl rhyolite flow is analogous to this example. First, if the extrusive rhyolite lava was somewhat influenced in flow direction by graben margins, then the orientation of shrinkage joints may be parallel and perpendicular to the elongated graben or valley. Orthogonal fractures in the Violet mine (figure 4) are parallel and perpendicular to the apparent graben (figure 2). Second, the location of the flow within a valley or graben may have allowed greater than normal interaction of the hot flow with surface waters; this may have enhanced the formation of kaolin, smectite, and possibly beryl.

Burt (1981) has reviewed the general acidity-salinity conditions under which the vapor-phase assemblage minerals of the red beryl rhyolite may be formed, but does not specifically address what conditions might change to remove or add beryl to the assemblage. Experimental work on the stability of beryllium minerals indicates that the stability field of beryl is greatly expanded (relative to other beryllium minerals) in the presence of water (or high fluid pressures) and...
by fluoride complexes are the most likely transporting ligands for Be in topaz-bearing assemblages. Additionally, near neutral pH, with high K ion activities (K-feldspar stable), and very low Ca ion activities, are also required to allow significant Be transport as fluoride complexes.

These observations appear applicable to the red beryl occurrence in the Wah Wah Mountains. The K and F concentrations in the red beryl rhyolite are buffered by the presence of K-feldspar and early-formed topaz. The CaO content of the rhyolite (<0.01 to 0.52%) is very low compared to other topaz rhyolites in western North America (Christiansen and others, 1986). However, the CaO content of fresh and altered rhyolite within and surrounding the Violet mine is particularly low (<0.01 to 0.18%; Table 1); even the small amount of CaO present in the rhyolite may have been introduced by surface or meteoric water during formation of late smectite rather than be a primary magmatic concentration. To reiterate, low Ca activities in the host fluid and rock allow F to complex and transport Be, rather than form fluorite (CaF₂). This factor may be more important to beryl formation than unusually high Be or F concentrations. Be concentrations in the flow range from 11-22 ppm (Table 1) which is, at best, only average for Be concentrations in topaz rhyolites (Christiansen and others, 1986). Consequently, release and transport of Be as fluoride complexes during devitrification of the rhyolite would seem a viable process.

However, the process involved in formation of beryl over a very restricted portion of the rhyolite flow may be more problematic. Some of the causes of deposition of bertrandite and phengite from Be fluoride complexes proposed by Wood (1992) include lowering of fluoride activity due to the presence of a calcareous lithology or fluid (causing formation of fluorite and a reduction of F ligands), a temperature decrease, or a decrease in K-ion activity. None of these seem appropriate for the clay-absent variety of beryl-bearing fractures which are very tight and contain persistent alkali feldspar, no early-formed fluorite, nor any other apparent alteration products.

Nevertheless some change in temperature-pressure-chemical composition (T-P-X) must have occurred along even very minor fractures in the rhyolite to account for their clear control on beryl formation. In some cases, the only evidence of a relict fracture is the tendency of the rock to break along an irregular plane that is otherwise defined only by the occurrence of beryl and bixbyite. Euhedral beryl crystals may be tightly encased by compact, devitrified rhyolite indicative of crystal growth by replacement of rhyolite rather than open-space filling. Beryl exhibits a strong tendency to form euhedral crystals by metasomatic replacement in other settings as well (Beus, 1983). Aurisicchio and others (1990) examined and analyzed inclusions in the red beryl and found corroded grains of quartz, K-feldspar, bixbyite, and Mn-hematite; also there were accompanying compositional gradients in Fe, Mn, Al, and K within the beryl. Wood (1992) hypothesized that a pH decrease could cause the breakdown of Be fluoride complexes. The persistence of alkali feldspar relics within the growing crystals, as well as the walls of the fracture, suggest that the pH of the beryl growth process was buffered by feldspar and topaz (?) and could not have dropped substantially.

Whatever changes in T-P-X occurred as Be-bearing vapors entered minor fractures in the rhyolite, they may have been subtle. Most, but not all, of the beryl-bearing fractures contain abundant kaolin. However, it is not likely that beryl and kaolin formed concurrently as an equilibrium assemblage. Barton (1986) notes that beryl often alters to form kaolinite, but they form together only at low activities of beryl (i.e. pegmatitic beryls that are alkali-rich). The presence of abundant kaolin in the fractures indicates the eventual establishment of a low pH, water-rich environment after formation of beryl. We conclude that beryl growth occurred at temperatures below magmatic values (~650°C), but above the temperature of kaolin development (200-300°C) as fluoride-rich vapors, released during devitrification, encountered fractures. If the rhyolite flow was partially bathed in surface water during cooling, a water-rich fluid probably permeated shrinkage fractures. Because of the initially high temperature of the flow and low pressure along fractures, the aqueous phase would have been a single-phase, very low-density fluid (not a liquid or a vapor, but a supercritical fluid). Such a low-density fluid will not condense to two-phase fluid inclusions after being entrapped in minerals, but will persist as single-phase fluid inclusions. Roedder and Stalder (1986) refer to growth from such vapors as "pneumatolysis" and consider "vapor-phase" red beryl and topaz from rhyolite lava flows to be some of the few bona fide examples of this process. The essentially exclusive presence of single-phase fluid inclusions in red beryl crystals argue that such a fluid was present during growth. Continued equilibration of the flow with surface water at lower temperatures would eventually form a boiling water-rich fluid and the kaolin-lined fractures and argillic alteration which is commonly temporal and probably overprinted on the higher temperature beryl-bearing assemblage.

Despite the fact that red beryl crystals may have formed in equilibrium with a low-density water-rich fluid, they have unusually low H₂O concentrations (Hosaka and others, 1993; Shigley and Foord, 1984; Flamini and others, 1983; Nassau and Wood, 1968). Perhaps during formation of beryl, the fractures may have exhibited only slightly higher H₂O and H⁺ activities than the devitrifying host. But these changes may be critical. Lower pH (higher H⁺ activity) may allow resorption and reaction of feldspar and Fe-Mn oxides to produce beryl; in addition, any beryl forming reaction from beryllium fluoride complexes consumes water as in the following reaction:

\[ 2H₂O + 2(K,Na) AlSi₃O₈ + 3BeF₂ \rightarrow k_r \cdot Be₂Al₂(Si₂O₁₈) + 4HF + 2(K,Na) F \]
due to differences in bond strength with Si and Al. The dominant portions of OH and Cl may be released more quickly (or efficiently) than F during devitrification. (The high Cl/F ratio of perlitic glass samples compared to other non-glassy samples from the same flow also indicate rapid (or efficient) loss of Cl relative to F for most samples.) This may allow early formation of bixbyite and hematite (due to Cl complexing of Fe and Mn) compared to F-complexed vapor-phase minerals such as beryl. During formation of Be fluoride complexes by devitrification, water fugacities within unfractured rhyolite may be very low. Consequently, any increase in H₂O activity along open fractures may help push reaction 1 to the right. Additionally, higher activities of Mn, Fe, and alkalis along such fumarolic root zone fractures may have allowed the stability field of beryl to expand because of solid solution (Barton, 1986).

In summary, beryl formation may have occurred dominantly through replacement of alkali feldspar in the rhyolite groundmass by reaction with beryllium fluoride complexes carried in a low density fluid (Aurisicchio and others, 1990) in response to higher water fugacities and slightly lower pH (figure 7). Beryl formation by this mechanism would be a water-consuming process that would co-produce acid and soluble fluorides. Some fractures were sealed after beryl formation by ubiquitous SiO₂ polymorphs and contain only beryl, bixbyite, (topaz?), and Mn-hematite, but the majority of beryl-bearing fractures also contain abundant kaolin and mixed-layer smectite-illite clays. The eventual formation of a liquid aqueous phase in response to cooling may have terminated formation of beryl and initiated clay formation along most fractures. Some clay-hosted beryl crystals have etched surfaces implying that they began to react to form kaolin, the most common alteration product of beryl (Barton, 1986).

This model of beryl formation is somewhat analogous to that of the world-class bertrandite deposits 140 km to the north at Spor Mountain, Utah (Lindsey, 1977). The topaz rhyolite flows at Spor Mountain are essentially the same age (21 Ma) as the red beryl flow and were emplaced above non-welded rhyolitic tuffs which overlie epiclastic sediments. The bertrandite occurs in the upper portion of the tuff, along with opal and fluorite, where it replaces dolomite clasts. The tuff was probably water-saturated at the time of bertrandite formation; Be fluoride complexes were supplied by vapors from the overlying devitrifying rhyolite (Burt and Sheridan, 1987). The ore horizon may coincide with a water table that fluctuated over the time of devitrification. The ore zone is underlain by a thick zone of Li-bearing (hectorite) clay. Deposition of bertrandite from Be fluoride complexes may be due to a lowering of fluoride activity by formation of fluorite, or as a consequence of temperature decrease or pH decrease (Wood, 1992). Regardless, the bertrandite formed at a lower temperature (200-300°C) than the red beryl (Barton, 1986).

### Exploration Guides

The acidic water which formed kaolin-filled fractures (up to 5 cm wide) also may have converted much of the early-formed specularite (hematite) to limonite and/or goethite which prominently stain clay-filled fractures. Prospect pits that are at higher elevations in the rhyolite progressively show less Fe-staining and pink clay than the productive pits of the Violet Mine. The pink mixed-layer illite-smectite clay that increases in abundance toward the centers of beryl-bearing fractures was probably formed after the peak of kaolin formation by equilibration with less acidic water at lower temperatures -- possibly by equilibration with meteoric water. The small amount of siderite present in clay samples may have formed at the same time.

As previously noted, clay formation along several closely-spaced fractures has apparently resulted in preferential weathering to produce a gully directly through the area now occupied by the Violet mine main pit; this fracture orientation parallels other prominent stream valleys developed on the rhyolite flow (figure 3). Prominent ridges and knobs of rhyolite near the Violet mine main pit are perhaps slightly less devitrified than the rhyolite within the pit and they may have less disseminated clay as well. However, these prominent knobs and ridges do appear to be noticeably less fractured than the beryl-host rhyolite.

These data suggest that the best areas to prospect for new red beryl deposits may be characterized by some or all of the following:

1) Very low (<0.50 %) whole-rock CaO concentrations that may allow extended transport of Be fluoride complexes rather than premature arrest of fluoride to form fluorite (CaF₂).

2) Unbrecciated rhyolite flow with coherent flow foliation that is moderately inclined (25-40°). These features would characterize the site as being away from the vent and at moderate depths within the flow - perhaps an indication of paleodepth critical for beryl formation.

3) Moderate, but persistent, Fe-staining (limonite/goethite?) along fractures along with trace amounts of bixbyite and Mn-hematite. Early-formed Fe- and Mn-oxides may have reacted with Be fluoride vapors (Aurisicchio and others, 1990) to form beryl; without some substitution of Fe and Mn for Be and Al, beryl formation may not have occurred. Observations made during mining indicate that the occurrence of bixbyite is one of the best indicators of potential beryl-bearing fractures.

4) Clay-filled fractures which contain a combination of white kaolin and pink mixed-layer illite-smectite. These minerals may be a lower temperature expression of a productive fracture. Clay formation is also weakly disseminated into the host rhyolite (weak argillic alteration). These characteristics may favor development of a minor gully through productive, beryl-host rhyolite due to differential erosion.
Figure 7. Schematic section showing sequential development of beryl (and other vapor-phase minerals) and clay minerals along a shrinkage crack within flow-foliated rhyolite. A. At shallow depths (60-120 m?) within the devitrifying rhyolite flow or at greater depths during an early stage of devitrification, exsolved Be fluoride complexes escape without reacting with feldspar to produce beryl; other vapor-phase minerals may be deposited in or near the fracture at this time. B. Incursion of meteoric water within or beneath the flow increases $fH_2O$ (the amount of water vapor) along fractures and decreases $T$ and $pH$ only slightly. Only a low-density aqueous phase may be present along the fracture at high temperatures and low pressure, but the vapor phase escaping from the devitrifying rhyolite probably has a lower $fH_2O$. Beryl growth consumes water, feldspar, Fe-Mn-oxides and lowers the $pH$. C. Temperature and $pH$ continue to decrease along the fracture while $fH_2O$ increases until beryl and feldspars become unstable and kaolin is produced; some beryl crystals may become etched by this reaction. At very low temperatures, or when hydrothermal fluids are replaced by groundwater, mixed-layer illite-smectite clay is formed along the central portions of the fractures. Some Mn-hematite may be converted to goethite/limonite during clay formation.
Mine Reserves

The exploration and mining philosophy articulated by owners of the Violet mine has been to "follow red." The implementation of this philosophy has been to follow a beryl-bearing fracture (or a series of parallel fractures) until the gems or fracture end vertically or horizontally and then excavate any gem-bearing cross-fractures to their completion. Mining has also been terminated when it was impractical to continue with a backhoe or unsafe due to pit high-walls. The mine owners have not found it necessary to identify reserves or calculate the mine life, because they have not needed investment capital. Consequently, no proven mine reserves exist. However, there is no evidence that most or all of the productive fractures have been found and mined. In the main pit (figure 4), productive fractures occur every few meters. There is no reason to suspect that beryl-bearing fractures of equal gem-quality do not occur within a few meters or tens of meters of the current pit walls. The soil cover adjacent to the main pit has not been stripped to investigate this possibility. The fracture density within the pit area is perhaps greater than adjacent prominent erosional knobs, but perhaps not greater than adjacent soil-covered slopes or gullies.

SUMMARY

Several geological and chemical factors appear to have contributed to the formation of unique gem-quality red beryl in a topaz rhyolite flow in the Wah Wah Mountains, Utah. All beryl crystals in the flow occur exclusively along shrinkage fractures in devitrified rhyolite, rather than in lithophysal pockets (similar to topaz) or in unfractured rock. The flow occupies a graben and perhaps a significant paleo-drainage (figure 2). Beryl-bearing fractures exhibit two orientations which are generally parallel or perpendicular to the inferred graben (figure 4); these fractures formed simply in response to cooling or down-gradient creep of the rhyolite flow. Both beryl-bearing fractures and the host rhyolite show an unusual amount of argillic alteration compared to other topaz rhyolites while BeO-Al2O3-SiO2-H2O concentrations of Ca were low. Whole-rock concentrations of CaO within the host rhyolite are very low (<0.01% to 0.18%) compared to other topaz rhyolites while Be concentrations are about average. Beryl growth occurred at temperatures below magmatic values (~300-650°C), but above the temperature of kaolin development (200-300°C) as fluoride-rich vapors, released during devitrification, encountered fractures. If the rhyolite flow was partially bathed in surface water during cooling, a water-rich low-density fluid probably permeated shrinkage fractures during beryl formation. Beryllium fluoride complexes reacted with alkali feldspar, water, and Fe-Mn oxides along fractures to produce red beryl. Continued equilibration of the flow with surface water at lower temperatures would likely produce a boiling, more acidic fluid capable of producing the kaolin-lined fractures and argillic alteration which are commonly present. Consequently, eruption of low-Ca topaz rhyolite followed by incursion of surface water into some medial portions of the flow at high temperatures are critical factors that led to beryl formation.

No proven mine reserves exist. However, there is no evidence that most or all of the productive fractures have been found and mined. In the main pit (figure 4), productive fractures occur every few meters. There is no reason to suspect that beryl-bearing fractures of equal gem-quality do not occur within a few meters or tens of meters of the current pit walls or at other locations in the flow. Probable reserves of red beryl may greatly exceed the amount which has been produced.

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