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Origin of gem red beryl in Utah's Wah Wah Mountains

Gem-quality red beryl on white devitrified rhyolite matrix. This sample measures 9 x 26 mm (0.35 x 1 in.). (Photo by Sky Hall.)

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The most valuable gem-quality red beryl comes from the Wah Wah Mountains of southwestern Utah (Fig. 1). Red beryl occurs as a secondary mineral in topaz rhyolite. Marketable crystals from the Wah Wah Mountains have been produced from the Violet Mine, operated on a limited scale since 1976 under the ownership of the Harris family of Delta, UT.

From 1989 to 1995, production from the mine amounted to more than $3 million with an inventory of several million dollars of unsold gems (Harris, 1995). In 1994, Kennecott Exploration leased the mine and surrounding claims to determine reserves and feasibility of gem recovery. Mining and exploration activity are continuing.

Previous work on red beryl has dealt mainly with crystallographic, chemical and optical properties of the crystals (Shigley and Foord, 1984) with only general descriptions of the geology (Ream, 1979). However, the conditions needed for formation of red beryl have not been well constrained. It is generally proposed that beryl originates 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 et al., 1986). All of these flows devitrified to form vapor-phase topaz and locally other vapor-phase minerals such as bixbyite, garnet, hematite, pseudo-brookite and fluorite. But the occurrence of beryl is rare. Even within the rhyolite flow that hosts the red beryl, the productive open pits comprise only a small fraction of the surface area of the flow. Apparently, the conditions that favor the formation of red beryl are rarely achieved.

Geologic setting

The rhyolite flow that hosts the red beryl deposit lies along the eastern flank of the Wah Wah Mountains (Fig. 1). Prevolcanic rocks consist of Proterozoic, Paleozoic and Mesozoic sedimentary rocks that were folded and thrust to the east during the Sevier orogeny. Cenozoic volcanism began about 34 Ma. It consisted mostly 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. These rocks form the Blawn Formation of which the beryl-bearing rhyolite is one member (Best et al., 1987). Abbott et al. (1983) reported a K-Ar age of 22.1 + 0.8 Ma for this flow. It is probably the oldest topaz rhyolite flow in the Wah Wah Mountains. A subsequent episode (12 to 13 Ma) of bimodal magmatism produced the Steamboat Mountain Formation. The rhyolitic part of that is locally topaz-bearing. Displacement on the late Cenozoic extensional faults that formed the north-trending mountain ranges began about 22 Ma.

Geology of the Violet Mine

The rhyolite that hosts the red beryl deposit is part of a flow/dome complex that overlies nonwelded tuff of cogenetic origin. This rhyolite is exposed over an area of about 9 km^2 (3.5 sq miles) (Fig. 1). An unknown additional portion of the rhyolite is concealed beneath

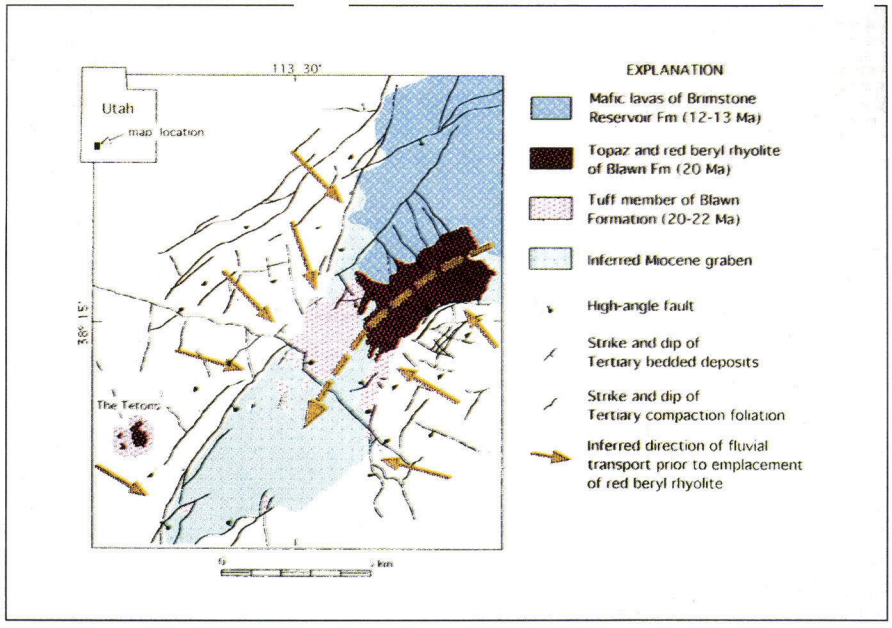


FIG. 1

Map of the rhyolite lava flow that hosts red beryl in the Wah Wah Mountains. The map shows the location of faults, argillic alteration and erosional lineaments.

younger mafic lavas and sediments.

The authors' work suggests that the red beryl flow occupies a northeast-trending graben (Keith et al., 1994). Fluvial sediments are present beneath and above portions of the red beryl rhyolite. Streams may have emptied into the graben. Compaction foliations of underlying ash flow tuff units dip toward the inferred graben. The graben is also parallel to the dominant orientation of faults and dikes of Blawn age (Fig. 1).

The rhyolite has a mineralogy and composition similar to most other topaz rhyolites. It is enriched in incompatible elements like Rb, Nb, Y and Be (about 20 ppm) and depleted in compatible elements like Ti, Sr and Ba. For example, CaO concentrations (<0.01 to 0.52%) are low, even lower than most topaz rhyolites. Phenocrysts of quartz, plagioclase, sanidine and sparse biotite are present. Both crystal-poor (about 5% phenocrysts) and crystal-rich (about 15% phenocrysts) rhyolite make up the red beryl flow. In some areas, the two kinds of lava occur as distinct, intermixed portions of strongly flow-laminated or brecciated rock. Moreover, lavas with two distinctive elemental compositions are present in the complex. Apparently, several magmas were at least partially mixed during eruption and emplacement.

Within the Violet Mine, red beryl crystals occur as well-formed crystals up to several centimeters long. Euhedral beryl crystals are mostly embedded in soft clay. But they may be tightly encased by dense, devitrified rhyolite. This indicates crystal growth by replacement of rhyolite rather than open-space filling. Beryl tends to form euhedral crystals by metasomatic replacement in other settings as well (Beus, 1983). Unlike other localities, the red beryl is not found in lithophysal cavities. Here, beryl crystals appear to occur exclusively along, or adjacent to, subvertical fractures in the rhyolite. Not all fractures, nor all portions of a single fracture, contain beryl. Often, the productive zone of any single fracture is less than 3 to 4 m (10 to 13 ft) high and 30 to 60 m (100 to 200 ft) long. The fracture orientations cluster in two groups with azimuths of about 65° and 140°. Fractures are parallel and perpendicular to the inferred trend of the graben. They may have formed as the flow was channelized by the graben. These shrinkage cracks formed during cooling. They may have served as the roots of fumaroles that allowed collection and transport of exsolved vapors and influent surface water.

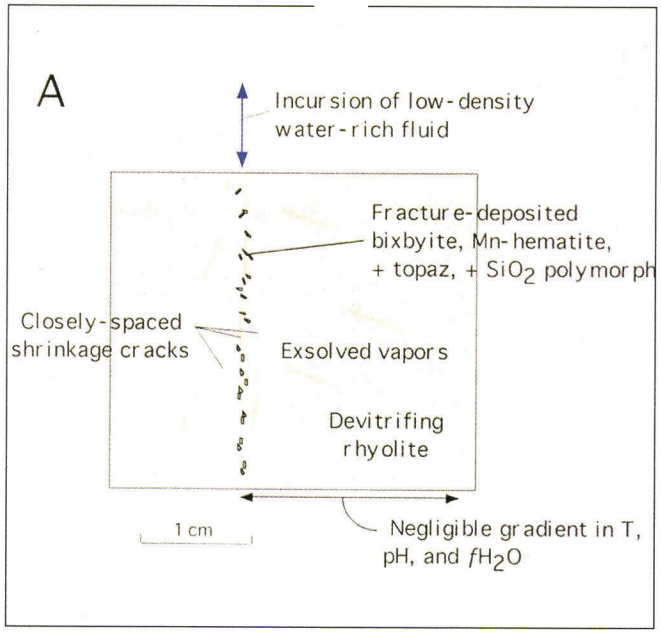
The productive fractures contain vapor-phase minerals such as bixbyite, tridymite, cristobalite and rare topaz. Most have amorphous silica and clay. Fracture-hosted clays are mostly kaolin with trace amounts of smectite or a more mixed-layer clay (about 20% illite and about 80% smectite). Both types of bulk clay contain traces of siderite. Some red beryl crystals occur along irregular planes. These appear to have been once open fractures that were sealed by deposition of tridymite or cristobalilte but clay is not obvious. Bixbyite and Mn-hematite also occur along these sealed fractures.

Most of the beryl-bearing fractures contain abundant kaolin. However, it is unlikely that beryl

Rex Harris, owner of the Violet Mine, works a fracture. Red beryl occurs along iron-stained fractures that are commonly argillized. It is embedded in devitrified rhyolite.

FIG. 2

Schematic of a cross section showing the sequential development of red beryl along a shrinkage fracture within flow-foliated rhyolite. Step A — At shallow depths within the devitrifying rhyolite flow, exsolved Be fluoride complexes escape without reacting with feldspar to produce beryl. Other vapor-phase mineral may be deposited in or near the fracture at this time.



and kaolin formed concurrently as an equilibrium assemblage. Barton (1986) noted that beryl often alters to form kaolinite but they form together only at low activities of beryl (along with pegmatitic beryls that are alkali-rich). The presence of abundant kaolin along many fractures indicates the eventual establishment of a low pH, water-rich environment after beryl formation.

Some details of the mineralization sequence can be established using cross-cutting and inclusion relationships. Bixbyite and topaz were among the earliest vapor-phase minerals. They appear to have cocrystallized with K-feldspar and silica minerals during primary devitrification. Beryl is distinctly later and contains abundant inclusions of quartz, K-feldspar, bixbyite and Mn-hematite, often with textures indicating replacement (Aurisicchio et al., 1990). In addition, bixbyite is one of the best indicators of potential beryl-bearing fractures. The clays found along most of the fractures are not found within the red beryl crystals, but as coatings, suggesting that the clays formed last, perhaps at much lower temperatures than the beryl.

New electron microprobe analyses of Wah Wah beryl — $(K,Na)0\,28Be3A_{1.75}\,(Fe,Mn)0.25(Si6O_18)$ — reveal that many of the unusual major and trace element characteristics may be related to the replacement reaction by which it formed and to the high *f*O2 that prevailed during devitrification and vapor-phase alteration. Red beryl contains significant amounts of transition elements that substitute for Al in the octahedral site of the beryl structure. In many other beryls, cations that substitute for Al have +2 charges. The charge deficiency is compensated for by entry of +l alkalies into channel sites.

However, because of high oxygen fugacities, most of the Fe and Mn in red beryl is probably +3. This eliminates the need for alkalis in channel sites for charge balance. It also explains why red beryl is poor in alkalies compared with most other beryl varieties. This is especially compelling considering that the beryl grew in an alkali-rich environment.

Fluid inclusions in the beryl are one-phase and filled with vapor showing that crystallization was pneumatolytic rather than hydrothermal (Roedder and Stalder, 1986). Similar inclusions are found in topaz from lithophysal cavities in the same flow.

Depth within a lava flow may be an important control on beryl formation. At the Violet Mine, beryl occurs about 170 m (560 ft) below the extrapolated contact with overlying mafic lavas. However, a significant amount of erosion may have occurred before the eruption of the mafic lavas, considering the 9 million years that elapsed. The nature of the flow foliation may also give some indication of depth. In and near the main pit, the flow foliation strikes northeast and dips 25° to 40° northwest. Moderately inclined flow foliation is common at medial levels within rhyolite flows. It is found beneath a more steeply inclined and brecciated upper zone (Burt and Sheridan, 1987). The foliation in the mine is defined by alternating gray (less devitrified) and white (more devitrified) layers. The more devitrified layers were likely the source and the transport medium for vapors from which beryl and other vapor-phase minerals crystallized.

The most obvious zonation of alteration minerals is in the abundance of Fe-staining (limonite/goethite) along fractures. Fe-staining is negligible in the upper 120 m (395 ft) of the rhyolite. It is conspicuous at the level of red beryl formation and increases in abundance downward. Much of the Fe-staining along the fractures may have been derived from destruction of bixbyite and Mn-hematite during weathering or reaction with cool ground water. Topaz is dominantly present above the red beryl. It formed in lithophysal vugs and along fractures that lack any clay alteration.

Red beryl (1.06 carats) from the Violet Mine with brilliant round cut by Tina Nelson. It is valued at $15,000/carat. (Photo by Sky Hall.)

Keith et al. (1994) concluded that the main geochemical changes in the rhyolites that accompanied the formation of beryl included substantial depletions of Na and F and enrichment of Sr, Y, Sc and loss on ignition at 1,000° C (1,830° F), a measure of H_2O content. There are only a few significant differences between beryl-bearing and topaz-bearing samples. These include marked enrichments in Be, Ba, CaO and MgO in the beryl-containing rhyolite. These changes are probably associated with the formation of smectite-rich clays and beryl and the destruction of feldspar in the beryl-bearing samples.

The compositions of vitro-phyres to the flow suggest that before beryl formed, the lavas were modified by simple devitrification and degassing. Crystallization of glass after eruption was apparently associated with substantial losses of several volatile elements including Cl (90%) and F (50% to 95%), and magmatic water as well. The loss of water cannot be evaluated quantitatively because water increases as glassy rocks hydrate by the addition of meteoric water.

Coincident with the release of volatiles, other elements could be transported complexed in the vapor. For example, if a vitrophyre present at the base of the flow exhibits magmatic Be concentrations, then devitrified samples have lost 20% to 65% of their original Be content.

Genetic model

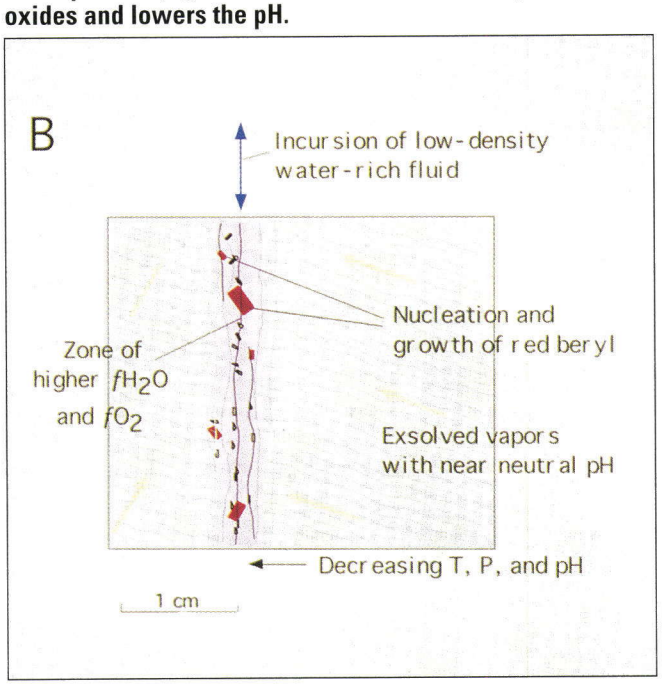
A genetic model for the formation of red beryl at the Violet Mine can be constructed based on the observations described above and limited experimental work.

Crustal extension and the eruption of distinctive topaz rhyolites are obvious prerequisites to the formation of the beryl. Eruptions of topaz rhyolites in the eastern Great Basin from 18 to 22 Ma mark the inception of extensional tectonism in the region. The productive flow probably lies in a northeast-trending graben formed during this episode of extension. 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 enhanced the formation of beryl, kaolin and smectite. Other beryl-absent topaz rhyolite flows in the southern Wah Wah Mountains lack evidence for substantial reaction with surface waters.

The fracturing and flow foliation of the host rhyolite indicates that the red beryl formed in the medial zone of the flow and away from the vent. It may be important that the center of a flow should cool more slowly and be subject to more pervasive devitrification and the correlative release of halogens and complexed metals, such as Be (Fig. 2).

FIG. 3

Step B. Incursion of meteoric water within or beneath the flow increases fH_2O along fractures and slightly decreases T and pH. Beryl growth consumes water, feldspar, Fe-Mn-oxides and lowers the pH.



Red beryl must have grown at temperatures below magmatic values (about 650° C or 1,200° F), but above the temperature of kaolin development (200° to 300° C or 390° to 570° F). Apparently, surface water had access to the interior of the rhyolite flow and a water- and oxygen-rich vapor permeated shrinkage fractures that also served as fumarolic root zones.

Simultaneously, a magmatic vapor — dominantly H_2O and CO_2 with Cl, F and complexed metals — was released from the devitrifying lava and moved along flow foliation. Wood (1992) found that fluoride complexes are the most likely transporting ligands for Be in topaz-bearing assemblages. Additionally, near neutral pH, with high K in activities (K-feldspar stable) and very low Ca ion activities, are also required to allow significant Be transport as fluoride complexes.

The activities of K and F species in the vapors released during devitrification of rhyolite were buffered by the presence of early formed K-feldspar and topaz. The CaO content of the rhyolite in and surrounding the Violet Mine is particularly low (<0.01% to 0.18%). Even this may have been introduced by surface or meteoric water during formation of late smectite.

Low Ca activities in the host fluid and rock should allow F to complex and transport Be, rather than form fluorite (CaF_2). Low Ca may be more important to beryl formation than unusually high Be or F concentrations. Locally, and probably in response to cooling, silica minerals, topaz, bixbyite and hematite crystallized from these vapors, lining the foliation planes, vugs and lithophysae (Fig. 3). Eventually, some of the magmatic vapor also encountered the subvertical shrinkage fractures. The Be-bearing magmatic vapors reacted with surface-water vapor and fracture-hosted minerals to produce red beryl.

In a discussion of bertrandite and phenakite deposition, Wood (1992) proposed that Be-bearing complexes can be broken by lowering the fluoride activity (due to the presence of a calcareous lithology or fluid to produce fluorite), a temperature decrease or a decrease in K-ion activity. The last two changes would be produced if meteoric water mixed with magmatic vapor along the vertical fractures in the rhyolite lava flow. A hypothetical balanced reaction that produces the beryl composition found at the Violet claims illustrates the reaction between water and beryllium fluoride carried in vapors and preexisting bixbyite, feldspar and quartz to form beryl, hydrofluoric acid and soluble alkali fluorides:

$$25.5H_2O + 1.5(Fe,Mn)_2O_3 + 21\,(K,Na)AlSi_3O_8 + 9SiO_2 + 36BeF_2 \longrightarrow 12(K,Na)_{0.28}Be3Al_{1.75}(Fe,Mn)_{0.25}(Si_6O_{18}) + 51HF + 21(K,Na)\,F$$

During formation of Be fluoride complexes by devitrification, water fugacites within nonfractured rhyolite were probably relatively low. Consequently, any increase in H_2O activity as vapor encountered open fractures would push the reaction to the right. 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 alkali containing solutions. Higher activities of Mn, Fe and alkalies may have allowed the stability field of beryl to expand because of solid solution (Barton, 1986).

Some fractures were sealed after beryl formation by ubiquitous SiO_2 polymorphs. They contain only beryl, bixbyite, topaz (?) and Mn-hematite. Most of the beryl-bearing fractures, however, 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 (Fig. 4). The argillic alteration is overprinted on the higher temperature beryl-containing assemblage.

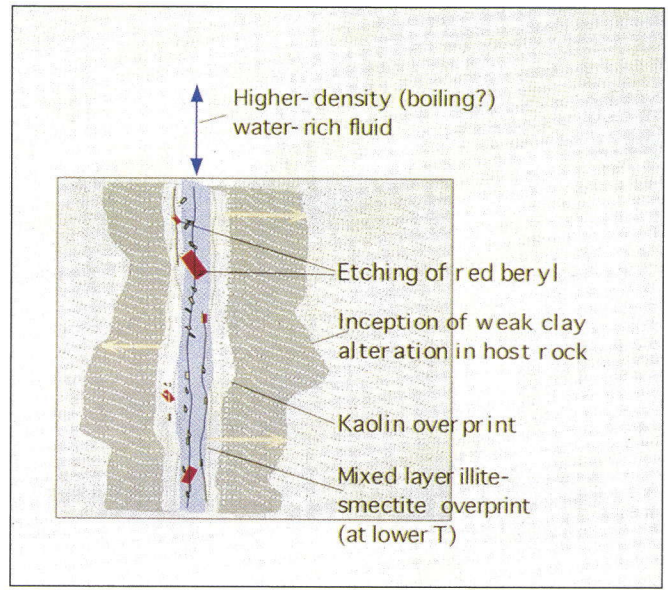
Moreover, some clay-hosted beryl crystals have etched surfaces. This implies that they began to react to form kaolin, the most common alteration product of beryl (Barton, 1986). The acidic water that formed kaolin-filled fractures also may have converted much of the early-formed specular hematite to limonite or goethite that prominently stain the clay-filled fractures.

This model for red beryl formation suggests that the best areas to prospect for deposits may be characterized by some or all of the following:

- High silica rhyolitic lava with vapor phase topaz. Such lavas can be identified geochemically by high concentrations of F (>0.2%) and high concentrations of incompatible elements (Rb >300 ppm; Nb >40 ppm, Be >15 ppm). Moreover, those lava flows that have topaz probably have devitrified sufficiently to release Be from glass (or magma) to a vapor phase. They also have enough fluorine to transport Be as fluoride complexes.
- Very low (<0.5 %) whole-rock CaO concentrations. Low CaO may allow extended transport of Be fluoride complexes rather than promoting precipitation of fluorite (CaF_2).
- Unbrecciated portions of rhyolite flow with coherent flow foliation that is moderately inclined (25° to 40°). These features indicate that a site is distant from a vent and at moderate depths within the flow — perhaps an indication of the modest depth that appears to be critical for beryl formation.
- Moderate, but persistent, Fe-staining along fractures along with trace amounts of vapor-phase bixbyite and Mn-hematite. Early formed Fe and Mn oxides may react with Be fluoride vapors to form beryl. Substitution of Fe and Mn for Be and Al may enhance beryl stability.
- Clay-filled fractures that contain a combination of kaolin and mixed-layer illite-smectite. These minerals may be a lower temperature expression of a productive fracture. ■

FIG. 4

Step C. Temperature and pH continue to decrease along the fracture while fH_2O increases until beryl and feldspars become unstable and kaolinite is produced. Some beryl crystals may become etched by this reaction. At very low temperatures, mixed-layer smectite/illite clay is formed. Some Mn-hematite may be converted to goethite/limonite during clay formation.



Acknowledgments

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References

Abbott, J.T., Best, M.G. and Morris, H.T., 1983, Geologic map of the Pine Grove-Blawn Mountain area, Beaver County, UT, US Geological Survey Miscellaneous Investigations Series Map 1-1479.

Aurisicchio, C., Fioravanti, G. and Grubessi, O., 1990, "Genesis and growth of red beryl from Utah," Rendiconti Fisiche Accademia Lincei ser. 9, Vol. 1, No. 4, pp. 393-404.

Barton, M.D., 1986, "Phase equilibria and thermodynamic properties of minerals in the BeO-$A1_2O3$-SiO_2-H_2O (BASH) system, with petrologic applications," *American Mineralogist, Vol. 71, pp. 277-300.*

Best, M.G., et al., 1987, "Miocene magmatism and tectonism in and near the southern Wah Wah Mountains, southwestern Utah," US Geological Survey Professional Paper 1433-B, pp. 29-47.

Beus, A., 1983, "On the possible mechanism of formation of euhedral crystals in metasomatic processes," *Bulletin of Mineralogy*, Vol. 106, pp. 411 -415.

Burt, D.M. and Sheridan, M.F., 1987, "Types of mineralization related to fluorine-rich silicic lava flows and domes," Geological Society of America Special Paper 212, pp. 103-109.

Christiansen, E.H., Sheridan, M.F. and Burt, D.M., 1986, "The geology and geochemistry of Cenozoic topaz rhyolites from the western United States," Geological Society of America Special Paper 205, 82 pp.

Keith, J.D., Christiansen, E.H. and Tingey, D.G., 1994, "Geological and chemical conditions of formation of red beryl, Wah Wah Mountains, Utah," Utah Geological Association Publication 23, pp. 155-169.

Ream, L.R., 1979 "The Thomas Range, Wah Wah Mountains, and vicinity, western Utah," Mineralogical Record, Vol. 10, pp. 261-278.

Roedder, E. and Stalder H. A., 1986, "Pneumatolysis and fluid inclusion evidence for crystal growth from a vapor," *Memoirs of the Geological Society of India*, Vol. 11, pp. 1-12.

Shigley, J.E. and Foord, E.E., 1984, "Gem-quality red beryl from the Wah Wah Mountains, Utah," *Gems and Gemology*, Vol. 20, pp. 208-221.

Wood, S.A., 1992, "Theoretical prediction of speciation and solubility of beryllium in hydrothermal solution to 300° C at saturated vapor pressure: Application to bertrandite/phenakite deposits," *Ore Geology Reviews,* Vol. 7, pp. 249-278.

Mining law update

Many reforms are being suggested to the Mining Law of 1872. The reforms would impact mines such as Barrick Gold's Betze-Post pit in Nevada, shown here. (Photo courtesy of Barrick Gold.)

Since its passage, the Mining Law of 1872 has been modified several times to meet the changing needs of America's society and economy. Despite the fact that it continues to provide an effective framework for a robust US exploration and mining industry, the mining law continues to be criticized in some quarters as outdated.

Pressure to reform the Mining Law of 1872 has reached new levels in recent years. Many proposals for reform of the law have been introduced during the 1990s. None, though, have been enacted. The issue will not likely disappear and is certain to be raised during the 105th Congress.

To provide a better understanding of the status of current congressional reform proposals, this article presents an overview of the major moments in the history of mining laws in the western United States — from the days before the 1872 mining law and the days following its promulgation, to the current dilemma over mining law reform. The future of the mining law is assessed as are the interests at stake for the modern mining industry.

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Stanley Dempsey

Mining before 1872

No discussion of the Mining Law of 1872 is complete without some historical background to provide an understanding of the origins of this unique law. There was plenty of mining activity on the public lands before the mining law was enacted. At first, the federal government's policy was to allow all miners to work freely on the public lands and to resolve disputes among themselves.

In this "hands off" environment, miners operated according to laws they promulgated. These were based on previous experiences in Europe and Mexico. These "frontier codes" of groups of individual miners took the form