BERYLLIUM DEPOSITS IN NEW MEXICO AND ADJACENT AREAS

Virginia T. McLemore, New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro, NM 87801 ginger@gis.nmt.edu

ABSTRACT

Beryllium deposits in Utah, New Mexico, Texas, and Mexico range from small (Apache Warm Springs, 39,063 metric tons Be, grade <0.26% Be) to world-class (Spor Mountain, 7,011,000 metric tons, grade 0.266% Be). Tertiary rhyolites from Iron Mountain, NM (Be-W-Sn-Fe skarn/replacement), Apache Warm Springs, NM (volcanic-epithermal veins), Spor Mountain, UT (rhyolite-hosted) and granites from Victorio Mountains, NM (W-Be-Mo skarn/vein) associated with known beryllium mineralization are predominantly peraluminous to metaluminous, calc-alkalic to alkaline, high-Si (silica-saturated) A-type granites. The rhyolites/syenites associated with contact-metasomatic deposits at Aquachile, Mexico and Round Mountain, TX are peralkaline. Tectonic settings include subduction of lithospheric crust (i.e. volcanic arc) or extensional (i.e. Rio Grande rift, Great Basin). Limited geologic, chemical, and fluid inclusion data of some deposits suggest that these deposits were formed from cooling, mixing, and/or removal of beryllium from variable magmatic-hydrothermal and meteoric fluids. Wall-rock reaction, particularly with limestone, appears to be important.

INTRODUCTION

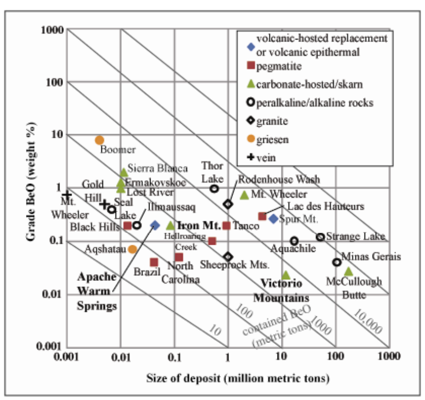
Beryllium (Be) is a strategic element that is becoming more important in our technological society, because it is used in the defense, telecommunications, and nuclear energy industries, as shielding in some of our nuclear, medical, and other equipment, and in many of our electronic devices. Beryllium is used in modules for engine control computers, including in hybrid automobiles. It is used in the solar industry in energy focusing assembly and storage units. IBC Advanced Alloys Corp. and Purdue University are developing a new Be-U mix oxide fuel, which will prevent early cracking of nuclear fuel rods and prevent overheating, both of which will provide a safer and more efficient fuel (Bisetty, 2009).

Beryllium is one of the lightest elements with an atomic number of 4 and atomic weight of 9. It is typically analyzed by induced coupled plasma spectroscopy (ICP). The average concentration of Be in the upper crust is 1.9 ppm (Rudnick and Gao, 2003). The average of stream-sediment samples from the NURE data in New Mexico is 1.63 ppm Be (McLemore, 2010). Beryl is the most common Be mineral and the varieties, emerald and aquamarine, are precious green gemstones. Beryllium is a lithophile element (or element enriched in the crust). However, Be is not always concentrated in easily mined economic deposits and only a few deposits in the world account for current production; Spor Mountain mine in Utah is the largest and most important economic deposit (Barton and Young, 2002; Sabey, 2005; Jaskula, 2009). Thorium (Th), uranium (U), lithium (Li), fluorine (F), REE (rare earth elements), and other elements typically are found with Be and most Be deposits are radioactive because of their Th and U content. Beryllium deposits have been reported and produced from New Mexico (McLemore, 2010), but were not considered important exploration targets in the past because the demand in past years has been met by other deposits in the world. Additional exploration is underway for similar volcanic-hosted beryllium deposits in the Sierra Cuchillo and San Mateo Mountains, Socorro and Sierra Counties, New Mexico.

The purposes of this report are to 1) summarize beryllium in New Mexico and adjacent areas, 2) update earlier compilations of beryllium in New Mexico and adjacent areas (Meeves et al., 1966; Barton and Young, 2002), 3) describe the more important deposits in New Mexico, Texas, Utah, and Mexico for future exploration by incorporating past and recent investigations, and 4) define the tectonic setting and magmatic-hydrothermal evolution of the more important Be deposits.

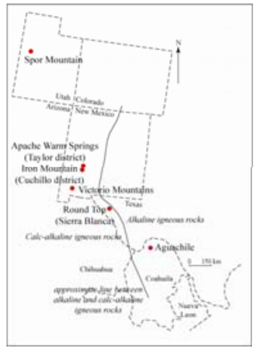
GEOLOGIC SOURCES

Beryllium is found in nature combined with other elements to form minerals. More than 100 minerals contain beryllium, but only a few are economically important (Grew, 2002; Barton and Young, 2002; Sabey, 2005). Only two Be minerals, beryl ($Be_3Al_2Si_6O_{18}$) and bertrandite ($Be_4Si_2O_7(OH)_2$), are of primary commercial importance; bertrandite contains less than 1% Be, and beryl contains approximately 4% Be. Beryl is typically found in pegmatites and transparent forms are gem minerals (green emerald, blue-green aquamarine, yellow heliodor, chrysoberyl, and pink morganite). Bertrandite is the principal Be mineral mined in the U.S., and beryl is the principal mineral produced in the rest of the world. Beryl is found in pegmatites, granites, and rhyolites; whereas bertrandite is found in volcanic tuffs and rhyolites. Helvite ($Mn_8(BeSiO_4)_6S_2$) is a potentially economically important Be mineral commonly found in skarn or carbonate-hosted replacement deposits (such as at Iron Mountain in the Cuchillo district and in the Victorio Mountains in Luna County, New Mexico), but helvite is difficult to separate from the deposit and currently is not of commercial importance (Sabey, 2005). The deposits of economic importance include pegmatites and rhyolite-hosted deposits (i.e. Spor Mountain type; Lindsey, 1981; Lindsey and Shawe, 1986), although other deposits associated with granites and skarns are known (Barton and Young, 2002; Sabey, 2005; Jaskula, 2009). Grade and tonnage of selected deposits from throughout the world are below and summarized in the accompanying table.

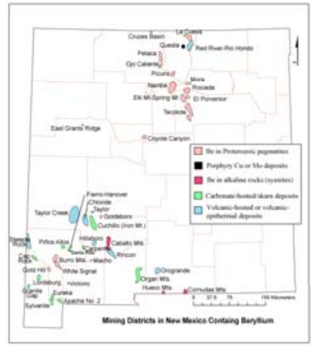


Grade-tonnage of selected beryllium deposits (modified from Barton and Young, 2002 using references in McLemore, 2010). Deposits in bold are located in New Mexico. See Table. Note that size of deposits includes production and reserves/resources and are not always NI 43-101 compliant and subject to change.

BERYLIUM DEPOSITS IN NEW MEXICO AND ADJACENT AREAS



Location of selected beryllium deposits found in southwestern U.S. and Mexico. Approximate line separating the Tertiary alkaline and calc-alkaline igneous rocks is from Price et al. (1987) and McLemore (1996).



Mining districts in New Mexico that contain beryllium (Be). More details are in McLemore (2010).

PRODUCTION AND RESERVES

Year	Bertrandite processed tons	Grade % Be	Proven bertrandite reserves	Grade % Be	Probable bertrandite reserves	Grade % Be
2009	39,000	0.330	6,425,000	0.266	3,519,000	0.232
2008	64,000	0.321	6,454,000	0.266	3,519,000	0.232
2007	52,000	0.321	6,531,000	0.266	3,519,000	0.232
2006	48,000	0.352	6,550,000	0.267	3,519,000	0.232
2005	38,000	0.316	6,601,000	0.268	3,519,000	0.232
2004	39,000	0.248	6,640,000	0.268	3,519,000	0.232
2003	41,000	0.224	6,687,000	0.267	3,519,000	0.232
2002	40,000	0.217	6,730,000	0.267	3,519,000	0.232
2001	48,000	0.224	7,270,000	0.268	3,081,000	0.219
2000	84,000	0.235	7,690,000	0.263	3,166,000	0.217
1999	93,000	0.215				

Production and reserves from the Spor Mountain mine owned by Brush Wellman (metric tons Be content, McNeil, 2004; Brush Wellman, 2004, 2008, 2009).

Beryllium production from Proterozoic pegmatites in New Mexico (Meeves et al., 1966). Additional production in 1963-1969 is withheld. Production from Iron Mountain, NM is unknown.

County	Year	Beryl (pounds)
Rio Arriba	1951-1963	12,748
San Miquel	1951-1963	49,015
Taos (including Harding)	1951-1963	1,678,054
Harding, Taos	1950-1959	1,696,600
TOTAL		1,739,817

SIZE AND GRADE OF SELECTED BERYLLIUM DEPOSITS IN UTAH, NEVADA, NEW MEXICO, TEXAS, AND MEXICO. MORE DEPOSIT SUMMARIES ARE IN BARTON AND YOUNG (2002).

Deposit	Location	Company	Resources tons ore*	Grade % BeO	Other potential commodities	Reference
Volcanic-hosted replacement or volcanic-epithermal vein deposits						
Spor Mountain (currently in production)	Utah, USA	Brush Wellman, Inc.	6,425,000 (>586,000 produced)	0.266	U, F	Brush Wellman (2009)
Apache Warm Springs (Taylor district)	New Mexico, USA	BE Resources Inc.	43,060	0.26	U	McLemore (2010)
Replacement (carbonate-hosted contact metasomatic) and skarn deposits						
McCullough Butte	Nevada, USA		47,000 (175,000,000 total)	0.027		Barton and Young (2002)
Aguachile	Coahila, Mexico		17,000,000	0.1	F, U	McAnulty et al. (1963), Griffitts and Cooley (1978)
Sierra Blanca (Round Top Mountain)	Texas, USA	Standard Silver Corporation	11,300	0.5-1.9	F, U	Standard Silver Corporation (2008)
Iron Mountain (Cuchillo district)	New Mexico, USA	none	84,000	0.2	Fe, Sn, W	Jahns (1944a, b)
Victorio Mountains	New Mexico, USA	Galloway Resources Inc	11,900,000	0.023	Mo, W	Bell (1983), McLemore et al. (2000)
Mt. Wheeler	Nevada, USA		2,000,000	0.75		Barton and Young (2002)
Granite deposits						
Rodenhouse Wash	Utah, USA		1,000,000	0.5		Griffitts (1965), Shawe (1966), Lindsey (1977)
Greisen deposits						
Boomer, Lake George (produced Be 1948-1969)	Colorado, USA	Advanced Alloys Corp.	<1,000 (production 3,000)	2.0-11.2		
Vein deposits						
Gold Hill	Utah, USA		>5000	0.5		Shaw (1966)
Mt. Wheeler	Nevada, USA		<1000	.075		Shaw (1966)

* Not all reserves/resources are NI 43-101 compliant and are subject to change as exploration provides better values.

TYPES OF BERYLLIUM DEPOSITS IN UTAH, NEW MEXICO, TEXAS, AND MEXICO

BERYLLIUM IN PEGMATITE DEPOSITS

Most pegmatites in New Mexico and adjacent areas are associated with the Late Proterozoic granitic plutonism of 1450–1400 Ma, although possibly as young as 1100-1200 Ma. The pegmatites vary in size, but are typically several hundred meters long and several tens of meters wide. Simple pegmatites consist of feldspar, quartz, and mica, whereas complex pegmatites are mineralogically and texturally zoned and consist of a variety of rare minerals. Several commodities have been produced from complex pegmatites in the past; including mica, beryl, Li, U, Th, REE, feldspar, Nb, Ta, W, and gem stones. Additional commodities occur in pegmatites that could be recovered, including quartz, Sb, Rb, and Mo (Jahns, 1946; McLemore et al., 1988a, b, 2010). Typically minerals containing these rare commodities are scattered discontinuously throughout the pegmatite, thereby hampering recovery. Nearly all of the pegmatites in New Mexico are Proterozoic in age and intruded metamorphic and granitic rocks; mid-Tertiary pegmatites are found in the Organ Mountains and Black Range (Carpenter district). Although beryl has been produced from some of the pegmatites, most pegmatites in New Mexico and adjacent states will not constitute an economic resource because of low grade, small size, and the expensive hand-sorting techniques required in order to recover any of the commodities, especially beryl.

PORPHYRY MOLYBDENUM (±TUNGSTEN) DEPOSITS

Porphyry molybdenum (±tungsten) deposits are large, low-grade deposits that contain disseminated and stockwork veinlets of Mo sulfides and are associated with porphyritic intrusions. They occur in three areas in New Mexico (Questa, Rialto stock in Nogal district, Victorio Mountains); the largest Mo deposits are at Questa in Taos County. The deposits consist of thin veinlets, fracture coatings, and disseminations in granitic host rock and ore minerals include molybdenite, powellite, scheelite, beryl, helvite, bismuthinite, and wolframite. The deposits are similar in form to the Laramide porphyry copper deposits (55-75 Ma), but the porphyry Mo deposits in New Mexico are younger (35-25 Ma) and exhibit only minor supergene alteration. Beryl and helvite typically are rare trace minerals found disseminated within the deposit and are associated with the Mo minerals. Beryllium concentrations are uneconomic in New Mexico porphyry Mo deposits.

ALKALINE IGNEOUS ROCKS CONTAINING BERYLLIUM

Some alkaline igneous rocks, typically syenite or alkali-granite composition, have higher concentrations of Be, REE and Zr then other types of igneous rocks. Alkaline rocks are defined as rocks with $Na_2O+K_2O>0.3718(SiO_2)-14.5$ or rocks with mol Na_2O+mol K_2O>mol Al_2O_3 (Shand, 1951). Peralkaline rocks are particularly enriched in Be, heavy REE, Y, and Zr. Some Be, REE and Zr deposits have been found in these rocks, but known Be deposits in these rocks in New Mexico and adjacent areas are low grade and typically uneconomic (Castor, 2008). In these deposits, Be, REE, Zr, Nb, Ta, Y, and other elements are found disseminated within the igneous rock. Alkaline rocks in the Caballo Mountains, Cornudas Mountains, Laughlin Peak, and Gallinas Mountains, NM contain anomalous concentrations of Be; a syenite sample from the Caballo Mountains contained 600 ppm Be. Samples from the Cornudas Mountains assayed as much as 0.2% BeO (Warner et al., 1959). Additional investigations are required.

TIN SKARNS AND TOPAZ RHYOLITES

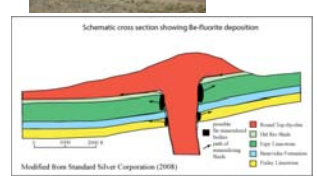
Beryllium minerals are found in tin skarn deposits; but rarely in economic concentrations (Cox and Singer, 1986). Topaz rhyolites are metaluminous to slightly peraluminous, high-silica rhyolites that are enriched in F, Be, Li, Rb, Cs, Ga, Y, Nb, and Ta with flat REE patterns with large Eu anomalies, and high Fe/Mg ratios (Christiansen et al., 1986). They are genetically related to deposits of Be, Mo, F, U, and Sn. Topaz rhyolites erupted contemporaneously with a variety of other igneous rocks, but most typically they form bimodal associations with basalt or basaltic andesite and are unrelated to large collapse calderas.

Rhyolite-hosted tin deposits consist of discontinuous veins and veinlets in rhyolite domes and volcanic centers (Cox and Singer, 1986; Christiansen et al., 1986). The tin deposits occur in the fractured and brecciated outer parts of flow-dome complexes and are hosted by high-silica (>75%), peraluminous rhyolites and/or pyroclastic deposits. Hematitic and argillic alteration is commonly associated with these tin deposits. The deposits are typically small (less than several hundred thousand tons of ore) and low grade (<2% Sn)(Cox and Singer, 1986). These deposits can contain high amounts of Be, among other elements. Four types of tin deposits are found in the altered Oligocene-Miocene rhyolite domes and tuffs in the Taylor Creek district, NM (Maxwell et al., 1986; Eggleston and Norman, 1986): 1) miarolitic cavities within rhyolite, 2) thin veins and veinlets cutting rhyolite, 3) disseminations in rhyolite, and 4) placer deposits in streams and alluvial deposits adjacent to rhyolite domes and flows.

CARBONATE-HOSTED METASOMATIC AND SKARN DEPOSITS

Carbonate-hosted metasomatic-replacement and skarn (Mo-W-Be and F-Be) deposits are found as small veins and replacement lenses within the limestones and dolostones adjacent to or in the vicinity of granitic or rhyolitic intrusions; high silica and topaz rhyolites are particularly favorable. Ore minerals in the Mo-W-Be deposits, such as those in the Victorio Mountains and at Iron Mountain, NM include helvite, wolframite, scheelite-powellite, molybdenite, galena, sphalerite, and beryl in a gangue of pyrite, quartz, calcite, Mn and Fe oxides, and local grossularite, tremolite, phyllite, idocrase, and phlogopite (Holser, 1953; Warner et al., 1959; McLemore et al., 2000). Ore minerals in the F-Be deposits, such as those at Aguachile, Mexico (McAnulty et al., 1963) and Round Top Mountain, Sierra Blanca, TX (Rubin et al., 1990) are predominantly fluorite, bertrandite, quartz, and clay minerals.

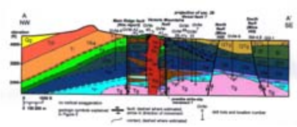
ROUND TOP MOUNTAIN, SIERRA BLANCA, TEXAS

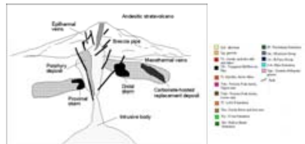


Schematic cross section showing Be-F deposition at Round Top Mountain, Sierra Blanca, Texas (modified from Standard Silver Corporation, 1980). Beryllium is found with fluorite replacing limestone adjacent to rhyolite at Round Top Mountain, one of five rhyolite laccoliths forming the Sierra Blanca complex (Levinson, 1962; Rubin et al., 1990). The Sierra Blanca rhyolite is 36.2±0.6 Ma (K/Ar, Henry et al., 1986) and the other five laccoliths, including Round Top Mountain are believed to be of similar age. Cyprus Beryllium Corporation reported non-NI43-101 compliant resources and reserves of 850,000 metric tons of ore averaging 1.5% BeO (Rubin et al., 1990).

VICTORIO MOUNTAINS, NEW MEXICO

Simplified cross section of the Victorio Mountains, NM (modified from company drill data and unpublished mapping by K. Donahue and V.T. McLemore). Based on field mapping and examination of drill core, three types of mineral deposits have been found: 1) carbonate-hosted Pb-Zn replacement, 2) W-Be-Mo skarn/vein, and 3) porphyry Mo (±W, Be) deposits. The porphyry Mo deposits are not exposed at the surface and found only in drill core in the Victorio Granite and was emplaced at 34.9±0.05 Ma. At the surface, the W-Be-Mo skarn/vein deposits occur as small veins and replacement lenses within the Ordovician limestones and dolostones in the vicinity of rhyolite intrusions. The age of the skarn minerals is similar to the age of the Victorio Granite at 34.9±0.09 to 35.4±0.07 Ma (Donahue, 2002).Samples assayed by Warner et al. (1959) ranged from 0.002 to 0.3% Be and 0.01 to 0.04% W. Open pit resources were estimated as 11,900,000 tons of 0.076% WO_3 and 0.023% Be (Bell, 1983).





IRON MOUNTAIN, CUCHILLO DISTRICT, NEW MEXICO

Two periods of granitic-rhyolitic rocks have intruded the Paleozoic sedimentary section at Iron Mountain, in the Sierra Cuchillo, which are separated by andesite to latite flows and breccias; the older event is >38-36 Ma and the younger is 27-29 Ma and is associated with the Be-W-Sn-Fe skarns (McLemore, 2010). Three types of skarns are found at Iron Mountain; coarse massive andradite with Sn, banded garnet-magnetite with W and F, and ribbon rock with F and Be. Adularia from a scheelite skarn was 27.3±0.6 Ma (Davis, 1986). Ribbon rock is a specific banded alteration with Be.

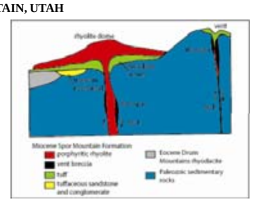
AGUACHILE, MEXICO

The Aguachile Be-F-U deposit, Mexico, is one of the eastern-most of the fluorite deposits in Mexico (Levinson, 1962; McAnulty, 1963; Kesler, 1977; Simpkins, 1983). Aguachile Mountain is a collapse caldera and is surrounded by rhyolite domes that intruded Cretaceous limestones and a plug of microsyenite intruded the rhyolite. Be-U-F veins, breccias, and replacements are found in limestone adjacent to the rhyolites. The major ore body contains 0.1-0.3% BeO. Three periods of fluoritization are recognized (McAnulty, 1963). The ore fluids had a pH of 3-5, Eh of +0.2 to -0.1, and a temperature of above 150°C (Simpkins, 1983).

VOLCANIC-HOSTED REPLACEMENT (SPOR MOUNTAIN BE-F-U DEPOSITS) AND VOLCANIC-EPITHERMAL DEPOSITS

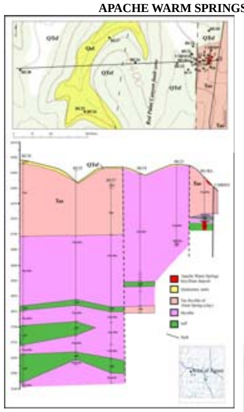
Beryllium deposits are found hosted by volcanic rocks, especially rhyolite, in several areas and are found as volcanic-epithermal veins and/or replacements in volcanic rocks. The Be-F-U deposits at Spor Mountain are the predominant economic nonpegmatite beryllium deposit in the world (Lindsey, 1977; Lindsey and Shawe, 1982; Barton and Young, 2002). The associated rhyolites are high-silica, high-fluorine rhyolites; topaz rhyolites are particularly favorable (Burt et al., 1982), and the rhyolites are enriched in F, Be, Cs, Mn, Nb, Y, U, Th, Mo, Sn, W, and REE (rare earth elements).

SPOR MOUNTAIN, UTAH



At Spor Mountain, beryllium is found replacing layers and lenses within rhyolite flows and tuffs and associated fault breccias that exhibit extensive argillic alteration. At least three stages of rhyolite flows and tuffs are erupted through carbonate rocks along faults forming rhyolite dome complexes and the Be-F-U deposits form along Basin and Range high-angle faults and caldera ring fractures (Lindsey, 1981). The Be deposits and host rhyolites are slightly radioactive and U and F deposits are found in the Spor Mountain area (Griffitts, 1982; Lindsey and Shaw, 1982). The first stage of volcanic activity is the eruption of pyroclastic flows, falls, and surges that were followed by extrusion of rhyolite flows forming domes. The Be, F, and U were in the rhyolite magma and as the lava cools and devitrifies, the lithophile elements differentiates into the outer rind of the lava and low-temperature convection mobilizes them along faults and within permeable tuffs and rhyolites (Burt and Sheridan, 1981).

APACHE WARM SPRINGS, TAYLOR DISTRICT, NEW MEXICO

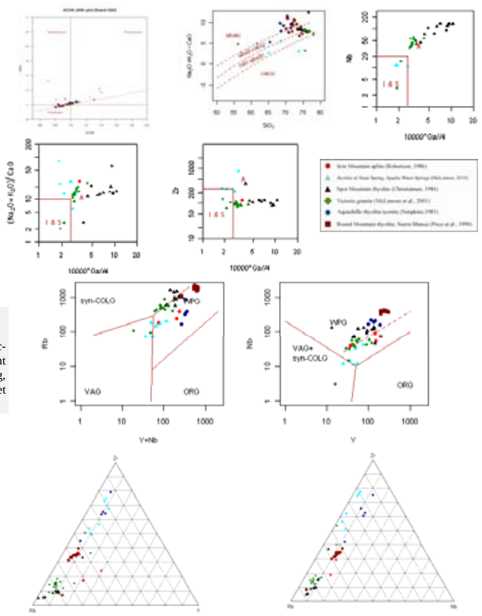


Geologic map and cross section of the Apache Warm Springs beryllium deposit and adjacent area in the Sierra Cucillo (N section 6, T9S, R7W), NM. Interpretations are by the author from examination of drill cuttings, using available drill data, and surface mapping (McLemore, 2010). The deposit consists of volcanic-epithermal beryllium vein and rhyolite-hosted beryllium deposits. Bertrandite is found in small quartz veins and stringers, along fractures with clay minerals, and disseminated within the argillically altered rhyolite and rhyolite ash-flow tuff. The Beryllium Group, LLC controlled the property in 2001-2002, drilled 14 holes, and reported a resource of 39,063 metric ton (43,060 short tons, not NI 43-101 compliant, as reported by Mining Engineering, 2002).

Apache Warm Springs beryllium deposit (Be), as delineated by P and E Mining Consultants, Inc. (2009) as determined from trenching and drilling, looking northeast (N section 6, T9S, R7W).

PETROCHEMISTRY

Rhyolites from Iron Mountain, Apache Warm Springs, Spor Mountain, and granites from Victorio Mountains associated with known beryllium mineralization are predominantly peraluminous (i.e. $Al_2O_3/(CaO + K_2O + Na_2O) > 1.0$) to metaluminous (i.e. $Al_2O_3/(CaO + K_2O + Na_2O) < 1.0$), and high-Si (silica-saturated). The rhyolites/syenites from Aquachille and Round Top Mountain are peralkaline. They are A-type granites (Whalen et al., 1987) found within-plate to syn-collusion granite fields of Pearce et al. (1986) and are similar in chemistry to topaz-bearing rhyolites. The similarity in chemical composition of rocks in these areas to the composition of rocks formed in within-plate tectonic settings infers that the rocks were formed in complex tectonic settings related to the subduction of lithospheric crust (i.e. volcanic arc) and formation of the Rio Grande rift and Great Basin (i.e. extensional tectonic setting). The formation of the rhyolites is consistent with predominantly fractional crystallization (Bobrow, 1984; Rye et al., 1990). The differences in incompatible trace elements, including Be, between the different granitic to rhyolitic rocks are likely related to either differences in the crustal rocks that were assimilated during magmatic differentiation (McMillan, 2004; Chapin et al., 2004; Michelfelder, 2009) or by minor potential contamination from crustal sources and/or magma mixing (Bobrow, 1984). Beryllium and fluorine could be derived from the crustal source and incorporated into the magma.



Chemical plots characterizing granitic and rhyolitic rigneous rocks associated with important Be deposits. A/CNK ($Al_2O_3/(CaO+Na_2O+K_2O)$ verses ANK ($Al_2O_3+Na_2O+K_2O$) from Shand (1943). A (A-type), I (I-type), and S (S-type) granite fields from Whalen et al. (1987). Pearce et al. (1984) tectonic diagrams, showing the samples are similar to within plate to syn-collision granitic granites (San Mateo younger rhyolites) and orogenic granites (older Sierra Cuchillo rocks). Syn-COLG—syn-collusion, VAG—volcanic arc, ORG—orogenic, WPG—within plate granitic fields.

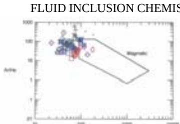
TEMPERATURE AND GEOCHEMISTRY OF MINERALIZING FLUIDS

Fluid inclusion studies in the Victorio Mountains by Donahue (2002) indicate that temperature of the fluids from the porphyry Mo deposit range from 208-315°C, with salinities of 2-11.9 eq wt% NaCl. Fluids from the skarn deposits had temperatures of 180-350°C with salinities of 2-22.5 eq wt% NaCl. Fluids from the late-stage carbonate-hosted replacement deposits had temperatures of 105-289°C with salinities of <2-5 eq wt% NaCl. These fluids were derived in part from a magmatic source, as determined from isotopic and fluid inclusion gas analyses (Donahue, 2002). Boiling, followed by mixing of magmatic-hydrothermal and meteoric waters resulted in a decrease in temperature and salinity, increase in pH, and increase in oxidation. The deposits were formed by episodic brecciation, boiling, fluid mixing, and mineral precipitation.

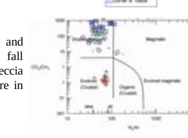
Fluid inclusion studies by Nkambule (1988) at Iron Mountain, NM indicated that the mineralizing fluids were at temperatures between 300 and 385°C, with salinities between 36 and 45 eq. wt% NaCl, probably at shallow depths (~1 km). Late-stage fluorite had lower temperatures of 275-290°C, and lower salinities of 4-12 eq wt% NaCl. The mineralizing fluids were enriched in F, Be (<5000 ppm), Sn, Li, and Fe. Boiling resulted in an increase in salinity due to vapor loss; cooling occurred as magmatic-hydrothermal fluids mixed with meteoric waters.

The mineral assemblage and association with rhyolites at Aguachile, Mexico suggest that the mineralizing fluids were above 150°C, acidic, with a pH between 2 and 6, and oxidizing with a Eh between +0.2 and -0.1 (Simpkins, 1983). At least three stages of fluorite deposition occurred at Aguachile; beryllium was deposited after the first stage.

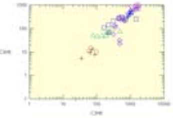
FLUID INCLUSION CHEMISTRY, VICTORIO MOUNTAINS (from Donahue, 2002)



Fluid inclusion gas results at indicate the majority of the gas compositions are meteoric and fall outside the magmatic water box as defined by Norman and Blamey (2002).



Fluid inclusion gas analyses results indicate the skarn and carbonate-hosted replacement deposits gas compositions fall within the shallow meteoric and magmatic fields, while the breccia pipe and a sample from the carbonate-hosted replacement are in the evolved field as defined by Norman et al. (2002).



The fluid inclusion gas analysis showed high concentrations of complex hydrocarbons. The hydrocarbons are most likely coming from the carbonate host rocks. The decrease in concentration from the porphyry to the carbonate-hosted replacement deposits could be due to a decrease in the water/rock ratio or dilution by another fluid.

FORMATION AND AGE OF MINERALIZATION AND ALTERATION

At Spor Mountain, the first stage of eruption was followed by extrusion of rhyolite flows forming domes. The rhyolites were erupted through carbonate sedimentary rocks, which aided in concentration of the beryllium. The beryllium was in the rhyolite magma and as the lava cooled and devitrified, the beryllium differentiated into the outer rind of the lava. Subsequent low-temperature convection mobilizes the beryllium along faults and within permeable tuffs and rhyolites. The rhyolites at Spor Mountain are topaz-bearing, high-fluorine rhyolite lava flows forming domes that are interbedded with tuffs, tuffaceous breccias, and associated fault breccias (Lindsey, 1981; Lindsey and Shawe, 1986). Topaz-bearing rhyolites are compositionally distinct, less common high-silica rhyolites that are enriched in F, Li, Rb, Cs, U, Th, and Be, and are associated with volcanogenic and epithermal deposits of Be, Sn, U, and F (Burt and Sheridan, 1981; Christiansen et al., 1983).

The Apache Warm Springs deposit is a volcanic-epithermal deposit hosted by a rhyolite dome complex (McLemore, 2010), and is similar to the Spor Mountain deposit. A modern analog for the formation of this beryllium mineralization and associated alteration and would be a geothermal system, such as the Norris Geyser Basin in Yellowstone National Park (McLemore, 2010). Deposits at Iron Mountain and Reilly Peak in the northern Cuchillo district (south of the Taylor district), contain Be-W-Sn-Fe skarn deposits that are related to chemically-similar rhyolites as the Apache Warm Springs deposit (McLemore, 2010). The rhyolites in the Iron Mountain area are 29-22 Ma and adularia from a scheelite skarn at Reilly Peak was dated as 27.3±0.6 Ma (Davis, 1986). The Iron Mountain deposit formed from boiling saline fluids rich in Na-K-Ca-Cl salts at temperatures between 300-385°C (as determined by fluid inclusion studies by Nkambule, 1988). The Apache Warms Springs deposits likely formed at the same time by similar fluids and temperatures. The rhyolite of Alum Springs at Apache Warm Springs, and the porphyritic rhyolite and rhyolite aplite at Iron Mountain and Reilly Peak are similar in chemistry to topaz rhyolites; topaz was found in the Iron Mountain rhyolite aplite (Robertson, 1986). Topaz rhyolites appear to be evolved from partial melts of Proterozic lower crust in an extensional tectonic setting, which is consistent with the formation of these rocks.

At the Victorio district, the evidence supports the theory that the three different deposit types found in the district are related and are the product of the magmatic-hydrothermal fluids from the Victorio Granite mixing with meteoric fluids (McLemore et al., 2000; Donahue, 2002). The similar age results for the Victorio Granite and the skarn alteration minerals and the lack of another igneous intrusion in the district indicate that all three mineral deposits formed from one magmatic source at approximately 34.9 Ma. Mineralization likely occurred over an extended period of time with episodic events of brecciation, boiling, fluid mixing, and mineral precipitation. The stable isotope and fluid inclusion gas data point to a magmatic fluid mixing with a meteoric fluid for the skarn and porphyry deposits. Sulfur stable isotopes of minerals from the carbonate-hosted replacement deposits indicate a likely magmatic component to the mineralizing fluid. The mechanisms responsible for the shift in mineralization style between high-temperature porphyry and skarn deposits and lower-temperature carbonate-hosted replacement deposits are most likely boiling and mixing between meteoric and magmatic-hydrothermal waters. Boiling and fluid mixing, as evidenced by fluid inclusion gas and stable isotope data, caused a decrease in temperature and salinity, an increase in pH, and an increase in oxidation state of the mineralizing fluids causing the change from high-temperature porphyry and skarn deposits to lower-temperature carbonate-hosted replacement deposits.

CONCLUSIONS

1. Six areas in Utah, New Mexico, Texas, and Mexico contain Be resources and are associated with rhyolites. Only the Spor Mountain deposit is currently being mined and has enough reserves to meet the current demand.
   - Spor Mountain, UT rhyolite-hosted Be deposit has reported proven reserves amounting to 6,425,000 metric tons of 0.266% Be and produces approximately 40,000-60,000 metric tons Be a year.
   - Epithermal volcanic-hosted Apache Warm Springs deposit (Sierra Cuchillo, NM, Be Resources, Inc.) contains resources in rhyolite amounting to 39,063 metric tons Be grading less than 0.26% Be.
   - Iron Mountain deposit (Sierra Cuchillo, NM) contact metasomatic Be-W-Sn-Fe deposit adjacent to rhyolites contains 76,200 metric tons at a grade of 0.2% BeO.
   - W-Be-Mo skarn/vein deposits in Paleozoic dolostones, limestones, and sandstones in the Victorio Mountains (Luna County, NM, Galway Resources Ltd.) contains open-pit resources estimated as 10,795,500 metric tons of 0.076% WO_3 and 0.023% Be.
   - At Round Top Mountain (Sierra Blanca, TX), the West End skarn contains 272,200 metric tons of 1.9% BeO.
   - Aguachile, Mexico contact-metasomatic deposit contains17,000,000 metric tons of 0.1% Be.
2. Rhyolites from Iron Mountain, Apache Warm Springs, Spor Mountain, and granites from Victorio Mountains associated with known beryllium mineralization are predominantly peraluminous to metaluminous, calc-alkalic to alkaline and high-Si (silica-saturated) A-type granites. The rhyolites/syenites from Aquachille (Mexico) and Round Top Mountain (Sierra Blanca, Texas) are peralkaline.
3. The similarity in chemical composition of rocks in these areas to the composition of rocks formed in within-plate tectonic settings infers that the rocks were formed in complex tectonic settings related to the subduction of lithospheric crust (i.e. volcanic arc) and extensional tectonic settings (i.e. the Rio Grande rift or Great Basin). The formation of the rhyolites is consistent with predominantly fractional crystallization. The differences in incompatible trace elements, including Be, between the different granitic to rhyolite rocks are likely related to either differences in the crustal rocks that were assimilated during magmatic differentiation or by minor potential contamination from crustal sources and/or magma mixing.
4. Limited geologic, chemical, and fluid inclusion data of some deposits suggest that these deposits were formed from cooling, mixing, and/or removal of fluorine from variable magmatic-hydrothermal and meteoric fluids. Wall-rock reaction, particularly with limestone, appears to be important.

ACKNOWLEDGEMENTS

This report is part of on-going studies of mineral resources and the geology of mineral deposits in New Mexico, supported by the New Mexico Bureau of Geology and Mineral Resources, Peter Scholle, Director and State Geologist. I would like to thank many colleagues who contributed to and reviewed manuscripts over the years much of this work is based upon. Sam Nunoo and Haruna Salifu provided technical assistance and their help is greatly appreciated. Chris McKee (NMBMMR) analyzed many rock samples by X-ray-fluorescence using the Phillips PW 2400 instrument purchased with funds from NSF grant EAR-9316467. Lynn Brandvold (NMBMGR) analyzed other samples by atomic-absorption spectrometry and induced coupled plasma spectrometry methods. Other chemical analyses were obtained as part of other projects as cited. Matt Heizler, Lisa Peters, and Rich Esser carried out the mineral separations and $^{40}Ar/^{39}Ar$ age determinations at the New Mexico Geochronology Laboratory at the NMBGMR over the years and their help in understanding the temporal relationships of the mineral deposits is appreciated.

REFERENCES

Barton, M.D. and Young, S., 2002, Non-pegmatitic deposits of beryllium: mineralogy, geology, phase equilibria and origin: Reviews in Mineralogy and Geochemistry, v. 50, p. 591-691.
Bell, A. R., 1983, Victorio Mountains molybdenum/tungsten project, Luna County, New Mexico; Gulf Mineral Resources Co., American Heritage Center, University of Wyoming, No. 43303.01, 150 p.
Bisetty, K., 2009, Rare mineral fuelling nuclear ambitions for local investors: Business in Vancouver, p. 3, http://www.ibcadvancedalloys.com/i/pdf/BusinessinVancouver2009-06.pdf (accessed on Feb. 3, 2010).
Bobrow, D.J., 1984, Geochemistry and petrology of Miocene silicic lavas in the Socorro-Magdalena area of New Mexico: M.S. thesis, New Mexico Institute of Mining and Technology, Socorro, 458 p.
Brush Engineered Materials, Inc., 2004, 2004 Annual Report: Annual Report, 58 p., http://files.shareholder.com/downloads/BW/925738805x0x148985/4FC74957-DBBA-4253-A598-87498FDC4012/2004_ar.pdf, accessed May 27, 2010.
Brush Engineered Materials, Inc., 2008, Strength in challenging times: Annual Report, 120 p., http://files.shareholder.com/downloads/BW/925738805x0x282828/1DAE2328-3DA9-47F3-8754-28193BB952B9/Brush_AR_Website.pdf
Brush Engineered Materials, Inc., 2009, Transforming our world and yours: Annual report, 122 p., http://files.shareholder.com/downloads/BW/925738805x0x368575/A9F177AF-D3E5-4546-8707-73F26F14E146/bw2009ar.pdf
Brush Resources, 2010, Introducing beryllium: presentation, 12 p., http://www.brushresources.com/, accessed May 27, 2010.
Burt, D.M. and Sheridan, M.F., 1981, Model for the formation of uranium/lithpphile element deposits in fluorine-rich volcanic rocks: American Association of Petroluem Geologists, Studies in Geology No. 13, p. 99-109.
Burt, D.M., Sheridan, M.F., Bikun, J.V., and Christiansen, E.H., 1982, Topaz rhyolites—distribution, origin, and significance for exploration: Economic Geology, v. 77, p. 1818-1836.
Castor, S.B., 2008, The Mountain Pass rare-earth carbonatite and associated ultrapotassic rocks, California: The Canadian Mineralogist, v. 46, p. 779-806.
Chapin, C.E., Wilks, M., and McIntosh, W.C., 2004, Space-time patterns of Late Cretaceous to present magmatism in New Mexico; comparison with Andean volcanism and potential for future volcanism: New Mexico Bureau of Geology and Minerals Resources, Bulletin 160, p. 13-40.
Christiansen, E.H., Burt, D.M., Sheridan, M.F., and Wilson, R.T., 1983, The petrogenesis of topaz rhyolites from the western United States: Contributions Mineralogy and Petrology, v. 83, p. 16-30.
Cox, D.P., and Singer, D.A., 1986, Mineral deposit models, U.S. Geological Survey, Bulletin 1693, 379 p.
Davis, L.L., 1986, The petrology and geochemistry of the intrusive rocks and associated iron-rich polymetallic skarn at Reilly Peak, New Mexico: M.S. thesis, University of Georgia, Athens, 108 p.
Donahue, K.M., 2002, Geochemistry, geology and geochronology of the Victorio mining district, Luna County, New Mexico: Linking skarn and Porphyry systems to carbonate-hosted lead-zinc replacement Deposits: M.S. thesis, New Mexico Institute of Mining and Technology, 195 p.
Eggleston, T. L. and Norman, D. I., 1983, Taylor Creek tin district: stratigraphy, structure, and timing of mineralization: New Mexico Geology, v. 5, no. 1, pp. 1-4.
Grew, E.S., 2002, Mineralogy, petrology and geochemistry of beryllium: an introduction and list of beryllium minerals: Reviews in Mineralogy and Geochemistry, v. 50, p. 1-*.
Griffitts, W. R., 1965, Beryllium; *in* Mineral and water resources of New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 87, p. 196-200.
Griffitts, W.R. and Cooley, E.F., 1978, A beryllium-fluorite survey at Aquachile Mountain, Coahuila, Mexico: Journal of Geochemical Exploration, v. 9, p. 137-147.
Henry, C.D., McDowell, F.W., Price, J.G., and Smyth, R.C., 1986, Compilation of potassium-argon ages of Tertiary igneous rocks, Trans Pecos Texas: University of Texas at Austin, Bureau of Economic Geology, Geologic Circular 86-2, 34 p.
Holser, W. T., 1953, Beryllium minerals in the Victorio Mountains, Luna County, New Mexico: American Mineralogist, v. 38, p. 599-611.
Jahns, R.H., 1944a, Beryllium and tungsten deposits of the Iron Mountain district, Sierra and Socorro Counties, New Mexico: U.S. Geological Survey, Bulletin 945-C, p. 45-79.
Jahns, R.H., 1944b, "Ribbon rock," an unusual beryllium-bearing tactite: Economic Geology, v. 39, p. 175-205.
Jahns, R.H., 1946, Mica deposits of the Petaca district, Rio Arriba County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 25, 294 p.
Jaskula, B.W., 2009, Beryllium: U.S. Geological Survey, Mineral Commodity Reports, 7 p., http://minerals.usgs.gov/minerals/pubs/commodity/beryllium/myb1-2007-beryl.pdf
Levinson, A.A., 1962, Beryllium-fluorine mineralization at Aquachile Mountains, Coahuilia, Mexico: American Mineralogist, v. 47, p. 67-74.
Lindsey, D.A., 1977, Epithermal beryllium deposits in water-laid tuff, western Utah: Economic Geology, v. 72, p. 219-232.
Lindsey, D.A., 1981, Volcanism and uranium mineralization at Spor Mountain, Utah: American Association of Petroluem Geologists, Studies in Geology No. 13, p. 89-98.
Lindsey, D.A. and Shawe, D.R., 1986, Spur Mountain Be-F-U deposits; *in* R.L. Erickson, Characteristics of mineral deposit occurrences: U.S. Geological Survey, Open-file Report 82-795, p. 67-69.
Maxwell, C. H., Foord, E. E., Oakman, M. R., and Harvey, D. B., 1986, Tin deposits in the Black Range tin district: New Mexico Geological Society, Guidebook 37, pp. 273-281.
McAnulty, W.N., Sewell, C.R., Atkinson, D.R. and Rasberry, J.M., 1963, Aguachile beryllium-bearing fluorspar district, Coahuila, Mexico: Geological Society of America, Bulletin, v. 74, p. 735-743.
McLemore, V. T., 1996, Great Plains Margin (alkalic-related) gold deposits in New Mexico; *in* Cyner, A. R. and Fahey, P. L., eds., Geology and ore deposits of the American Cordillera: Geological Society of Nevada Symposium Proceedings, Reno/Sparks, Nevada, April 1995, pp. 935-950.
McLemore, V.T., 2010, Beryllium resources in New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Report, in preparation.
McLemore, V. T., Dunbar, N. W., Heizler, M., and Donahue, K., 2000, Geology and Mineral deposits of the Victorio Mining District, Luna County, New Mexico: Preliminary observations: New Mexico Geological Society, Guidebook 51, p. 251-263
McLemore, V.T., North, R.M., and Leppert, S., 1988a, Rare-earth elements (REE), niobium and thorium districts and occurrences in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report OF-324, 28 p.
McLemore, V.T., North, R.M., and Leppert, S., 1988b, Rare-earth elements (REE) in New Mexico: New Mexico Geology, v. 10, p. 33-38.
McNeil, D. 2004, Beryllium: Roskill Mineral Services report, 6 p., http://www.mmta.co.uk/uploaded_files/BerylliumMJ.pdf, accessed May 27, 2010.
Meeves, H.C., Harrer, C.M., Salsbury, M.H., Konselman, A.S., and Shannon, S.S., Jr., 1966, Reconnaissance of beryllium-bearing pegmatite deposits in six western states: Arizona, Colorado, New Mexico, South Dakota, Utah, and Wyoming: U.S. Bureau of Mines, Information Circular 8298, 39 p.
Mining Engineering, 2002, News briefs, The Beryllium Group: Mining Engineering, February, p. 14.
Michelfelder, G.S., 2009, Petrology and geochemistry of the Upper Eocene Sierra Cuchillo laccolith, Sierra County, New Mexico: M.S. thesis, New Mexico State University, Las Cruces, 186 p.
Nkambule, M.V., 1988, Skarn mineralization at Iron Mountain, New Mexico, in light of fluid inclusion studies: M.S. thesis, New Mexico Institute of Mining and Technology, Socorro, 60 p.
Norman, D. I., and Moore, J. N., 1997, Gaseous species in fluid inclusions: A tracer of fluids and indicator of fluid processes, *in* Proceedings of the XIVth European current research on Fluid inclusions, v. 14, p. 243-244.
Norman, D. I., Blamey, N., and Moore, J. N., 2002, Interpreting geothermal processes and fluid sources from fluid inclusion organic compounds and CO2/N2 ratios, *in* Proceedings from the Twenty-seventh Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 28-30, 2002, p. 234-242.
P and E Mining Consultants Inc., 2009, Technical report on the Warm Springs beryllium property, Socorro, County, New Mexico USA: unpublished report for BE Resources Inc., 52 p.
Pearce, J.A., Harris, N.B.W. and Tindle, A.G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks: Journal of Petrology, v. 24, p. 956–983.
Price, J.G., Rubin, J.N,, Henry, C.D., Pinkston, T.L., Tweedy, S.W. and Koppenaal, D.W., 1990, Rare-metal enriched peraluminous rhyolites in a continental arc, Sierra Blanca area, Trans-Pecos Texas; chemical modification by vapor-phase crystallization; *in* H.J. Stein and Hannah, J.L., Ore-bearing granite systems; Petrogenesis and mineralizing processes: Geological Society of America, Special Paper 246, p. 103-120.
Robertson, D.E., 1986, Skarn mineralization at Iron Mountain, New Mexico: M.S. thesis, Arizona State University, 76 p.
Rubin, J.N., Price, J.G., Henry, C.D. and Kyle, J.R., 1990, Geology of the beryllium-rare earth element deposits at Sierra Blanca, west Texas: Society of Economic Geologists, Guidebook 8, p. 191-203.
Rudnick, R.L. and Gao, C., 2005, Composition of the continental crust; in R.L. Rudnick, ed., The Crust: Treatise on Geochemistry, v. 3, Elsevier, San Diego, California, p. 1-64.
Rye, R.O., Lufkin, J.L., and Wasserman, M.D., 1990, Genesis of the rhyolite-hosted tin occurrences in the Black Range, New Mexico, as indicated by stable isotope studies; in H.J. Stein and J.L, Hannah, Ore-bearing granite systems; Petrogenesis and mineralizing processes: Geological Society of America, Special Paper 246, p. 233-250.
Sabey, P., 2005, Beryllium minerals; *in* Kogel, J.E, Trivedi, N.C., Barker, J.M., and Krukowski, S.T., ed., Industrial Minerals volume, 7th edition: Society for Mining, Metallurgy, and Exploration, Littleton, Colorado, p. 263-274.
Shand, S.J., 1943, The eruptive rocks: 2nd edition, John Wiley, New York, 444 p.
Shaw, D.R., 1966, Arizona-New Mexico and Utah-Nevada beryllium belts: U.S. Professional Paper 550-C, p. C206-213.
Simkins, T.H., 1983, Geology and geochemistry of the Aguachile Mountain fluorspar-beryllium mining district, northern Coahuila, Mexico: M.S. thesis, Sul Ross State University, Alpine, TX, 137 p.
Standard Silver Corporation, 2008, Round Top beryllium, uranium, rare earth project: unpublished company report, 34 p., http://www.standardsilvercorp.com/main-sect/uploads/08/round_top_presentation.pdf, accessed February 3, 2010.
Warner, L.A., Holser, W.T., Wilmarth, V.R., and Cameron, E.N., 1959, Occurrence of nonpegmatite beryllium in the United States: U.S. Geological Survey, Professional Paper, v. 318, 198 p.
Whalen, J.B., Currie, K.L., and Chappell, B.W., 1987, A-type granites: geochemical characteristics, discrimination and petrogenesis: Contributions to Mineralogy and Petrology, v. 95, p. 40-418.