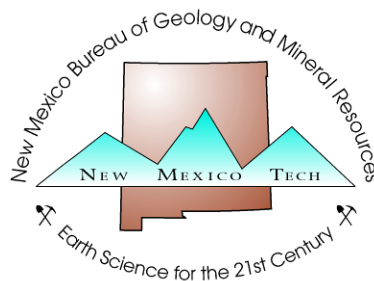# BERYLLIUM RESOURCES IN NEW MEXICO AND ADJACENT AREAS

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ABSTRACT

Beryllium (Be) is a strategic element that is becoming more important in our technological society, because it is six times stronger than steel, has a high melting point, a high heat capacity, is non-sparking, is transparent to X-rays, and when alloyed with other metals it prevents metal fatigue failure. Beryllium is used in the defense, aerospace, automotive, medical, and electronics industries, in the cooling systems for nuclear reactors and as a shield in nuclear reactors. 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). In New Mexico, past production of beryl has been from pegmatites in Taos, Rio Arriba, Mora, San Miguel, and Grant Counties, with the majority of the beryl production from the Harding pegmatite, Taos County. Current drilling in the Apache Warm Springs deposit in the Sierra Cuchillo by BE Resources, Inc. has identified mineralized zones in altered rhyolite. The deposit is classified as volcanogenic beryllium deposit, also known as Spor Mountain Be-U-F or epithermal volcanic-hosted deposit. The Iron Mountain deposit, also in the Sierra Cuchillo south of the Apache Warm Springs deposit, is a contact metasomatic W-Be-Sn-Fe deposit in limestones adjacent to Tertiary rhyolites and granite. Additional exploration is underway for similar volcanic-hosted beryllium deposits in the Sierra Cuchillo and San Mateo Mountains, Socorro and Sierra Counties by BE Resources, Inc. W-Mo-Be skarn/vein deposits in Paleozoic dolostones, limestones, and sandstones were discovered in the Victorio Mountains, Luna County in the early 1900s. Gulf Minerals Resources, Inc. drilled 71 holes in 1977-1983 and delineated a porphyry Mo and W-Mo-Be skarn deposits northwest of Mine Hill and south of Middle Hills. At a cut-off grade of 0.02% WO_3, resources were estimated as 57,703,000 tons of 0.129% Mo and 0.142% WO_3. Open pit resources were estimated as 11,900,000 tons of 0.076% WO_3 and 0.023% Be. Galway Resources Ltd. acquired the Victorio Mountains deposit in the late 1990s. Beryllium also is found in the nepheline syenite at Wind Mountain, Otero County and in the molybdenum porphyry deposit at Questa, Taos County, although not in economic concentrations. Tertiary rhyolites from Iron Mountain (Be-W-Sn-Fe skarn/replacement), Apache Warm Springs (volcanogenic Be deposit), Spor Mountain, UT (volcanogenic Be deposit) and granites from Victorio Mountains (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 Aquachille, 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 or dolomite, appears to be important. Future production of beryllium from New Mexico will depend upon an increase in demand, possibly in the nuclear industry or in solar panels. It is unlikely that any of the beryllium deposits in New Mexico will be mined in the near future because the known deposits are small and low grade and the Spor Mountain deposit contains sufficient beryllium reserves to meet the expected demand in the next few years.

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INTRODUCTION

Beryllium (Be) is a strategic element that is becoming more important in our technological society, because it is six times stronger than steel, has a high melting point, a high heat capacity, is non-sparking, is transparent to X-rays, and when alloyed with other metals it prevents metal fatigue failure. Beryllium is used in the defense 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 a lithophile element (or element enriched in the crust). However, beryllium 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 deposit. Thorium (Th), uranium (U), lithium (Li), fluorine (F), REE (rare earth elements), and other elements typically are found with beryllium and most beryllium deposits are radioactive because of their Th and U content. Beryllium deposits in Utah, New Mexico, Texas and Mexico (Table 1, Fig. 1) 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). Additional beryllium deposits are found in New Mexico (Fig. 2; Appendix 1), but were not considered important exploration targets because the demand in past years has been met by other deposits in the world. However, with the projected increase in demand, these areas in New Mexico are being re-examined for their beryllium potential. Additional exploration is underway for similar volcanic-hosted beryllium deposits in the Sierra Cuchillo and San Mateo Mountains, Socorro and Sierra Counties, New Mexico.

TABLE 1. Size and grade of selected beryllium deposits from throughout the world. More deposit summaries are in Barton and Young (2002). Deposits in the southwestern U.S and Mexico are located in Figure 1. Not all reserves/resources are NI 43-101 compliant and are subject to change as exploration provides better values.
Web sites: 1— http://www.questuranium.com/strangelakeproject.php,
2— http://www.gov.mb.ca/stem/mrd/info/libmin/gacmac/guidebook_a3.pdf,
3— http://www.bestrocks.ca/Hellroaring_Be_REE_Ta.php,
4— http://www.mrn.gouv.qc.ca/english/publications/mines/potential/pro_2001-09.pdf

Deposit	Location	Company	Resources metric tons ore	Grade % BeO	Other potential commodities	Reference
Pegamatites						
various	North Carolina, USA	–	122,800	0.05	–	Griffitts (1954). Sabey (2005)
Various	Brazil	–	42,000	0.04	–	Soja and Sabin (1986), Sabey (2005)
Black Hills	South Dakota, USA	–	13,000	–	–	Runke et al. (1952), Shearer et

Deposit	Location	Company	Resources metric tons ore	Grade % BeO	Other potential commodities	Reference
						al. (1992)
Tanco	Manitoba, Canada	Cabot Corporation	920,000	0.20	–	Cerný (1982, 2005), web site 2
Hellroaring Creek	Canada	Bestrocks Mineral Services	500,000	0.10	–	Kramer (1994), web site 3
Volcanogenic Be (volcanic-hosted replacement, volcanic-epithermal, and Spor Mountain Be-F-U) deposits						
Spor Mountain (currently in production)	Utah, USA	Brush Wellman, Inc.	7,011,000 (>586,000 produced)	0.76	U, F	Brush Engineered Materials, Inc. (2009)
Apache Warm Springs	New Mexico, USA	BE Resources Inc.	39,063	0.72	U	McLemore (2010a)
Carbonate-hosted replacement and skarn deposits						
McCullough Butte	Nevada, USA	–	47,000 (175,000,000 total)	0.027	–	Barton and Young (2002), Sabey (2005)
Aguachile	Coahila, Mexico	–	17,000,000	0.1	F	McAnulty et al. (1963), Griffitts and Cooley (1978)
Sierra Blanca (Round Top Mountain)	Texas, USA	Standard Silver Corporation	272,000	1.9	F, U	Sabey (2005), Standard Silver Corporation (2008)
Etykinskoye (Ermakovskoe)	Russia	Zabailkalsky GOK	>10,000	1.3	–	Barton and Young (2002)
Lost River	Alaska, USA	–	>10,000	0.3-1.75	–	Barton and Young (2002)
Iron Mountain	New Mexico, USA	none	84,000	0.2	W, F	Jahns (1944a, b)
Victorio Mountains	New Mexico, USA	Galloway Resources Inc	10,800,000	0.06	Mo, W	Bell (1983), McLemore et al. (2000, 2001)
Mt. Wheeler	Nevada, USA	–	2,000,000	0.75	–	Barton and Young (2002)
Alkaline igneous rocks						
Strange Lake, George River	Quebec, Canada	Iron Ore Company of Canada	52,000,000	0.12	REE, Zr, Y, Nb	Sabey (2005), Salvi and William-Jones (2006), Richardson and Birkett (1996), web site 1
Ilimaussaq	Greenland	–	>20,000	–	Zr, Y, REE, Ta, Nb	Barton and Young (2002)
Thor Lake	Northwest Territories, Canada	Avalon Rare Metals Inc.	1,136,101	0.48	REE	Wardrop (2007)
Seal Lake	Canada	–	6,800	0.35-0.4	–	Richardson and Birkett (1996), Sabey (2005)
Minas Gerais	Brazil	–	106,000,000	0.04	–	Barton and Young (2002)
Granite/rhyolites						
Rodenhouse Wash	Utah, USA	–	1,000,000	0.5	–	Griffitts (1965b), Shawe (1966), Lindsey (1977)
Sheeprock	Idaho, USA	–	1,000,000	0.01-0.1	–	Rogers (1990),

Deposit	Location	Company	Resources metric tons ore	Grade % BeO	Other potential commodities	Reference
Mountain						Barton and Young (2002)
Seward Penninsula	Alaska, USA	–	–	–	–	Newberry (1998)
Zealand	New Brunswick	First Narrows Resources Corp	315,000	0.1		Conestoga-Rovers and Associates (2008)
Greisens						
Aqshatau	Kazakhstan	–	16,600	0.03-0.07	–	Barton and Young (2002)
Boomer, Lake George (produced Be 1948-1969)	Colorado, USA	IBC Advanced Alloys Corp.	<1,000 (past production 3,000)	2.0-11.2	–	Hawley (1969), Sabey (2005), Piper (2007)
Veins						
Gold Hill	Utah, USA	–	>5000	0.5	–	Shawe (1966), Sabey (2005)
Mt. Wheeler	Nevada, USA	–	<1000	0.75	–	Shawe (1966), Sabey (2005)
Lac des Hauteurs	Quebec, Canada	–	4,360,000	0.3 (beryl)	–	Web site 4
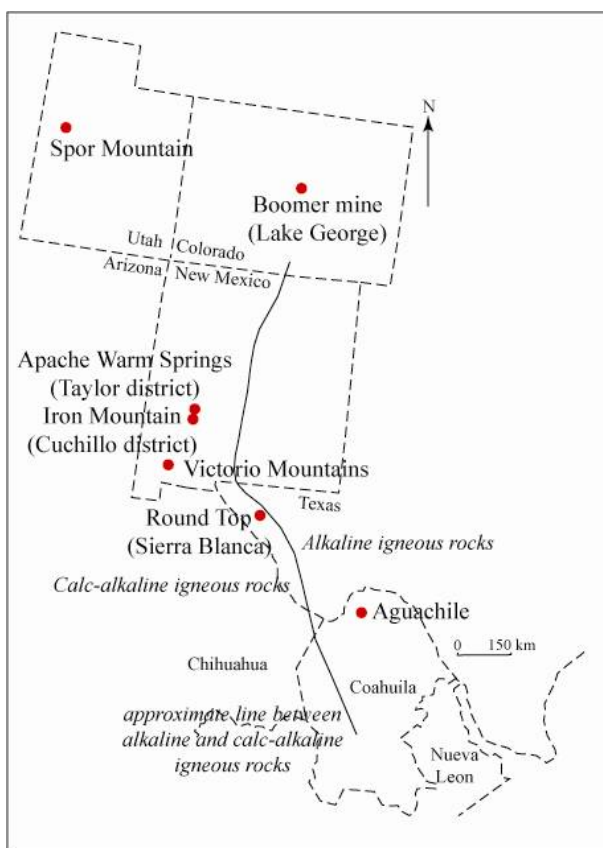
FIGURE 1. Location of selected beryllium deposits with calculated resources found in southwestern U.S. and Mexico. See Table 1 for additional information on these and other

beryllium deposits. Approximate line separating the Tertiary alkaline and calc-alkaline igneous rocks is from Price et al. (1987) and McLemore (1996).
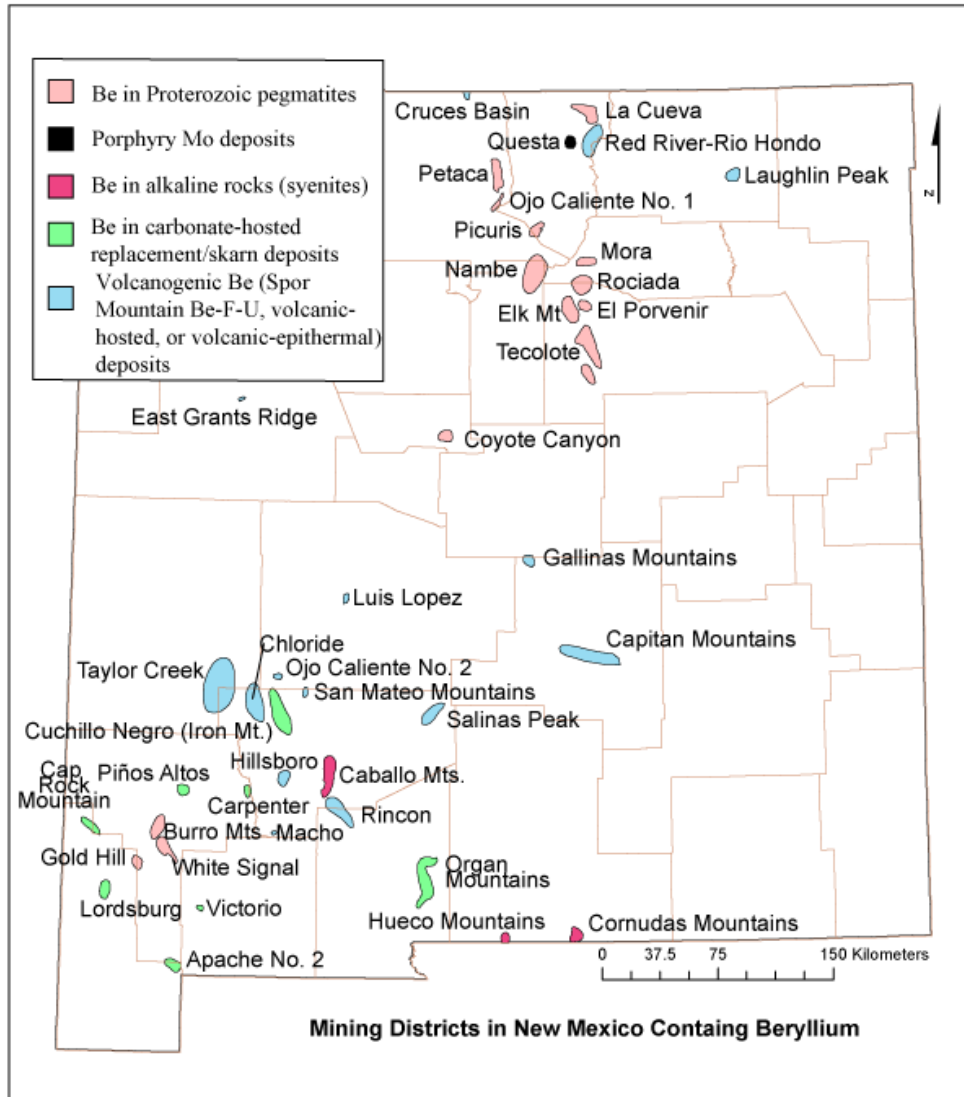
FIGURE 2. Mining districts in New Mexico that contain beryllium (Be). Summary of districts is in Appendix 1.

The purposes of this report are to 1) update earlier compilations of beryllium in New Mexico (Griffitts, 1965a; Meeves, 1966; Meeves et al., 1066; Barton and Young, 2002), 2) describe the more important deposits in New Mexico, Utah, Texas, and Mexico, 3) provide an evaluation of the NURE geochemical stream-sediment data for potential beryllium deposits in New Mexico, and 4) define the tectonic setting and magmatic-hydrothermal evolution of the more important beryllium deposits. For the purposes of this report, a beryllium occurrence is defined as 1) significant quantities of beryllium mineral, 2) whole-rock geochemical analysis of approximately 100 ppm (0.01%) Be or greater, or 3) production of beryllium minerals.

WHAT IS BERYLLIUM?
Description

Beryllium was discovered in 1797 by L. Nicholas Vauquelin as a component of beryl. Beryllium is a hard, silvery-white, very light metallic element (atomic number 4 and atomic weight 9). Beryllium is generally reported as the 44th most abundant element (Sabey, 2005); the earth's crust is estimated to contain an average of 4-6 ppm Be (Cunningham, 2004; Rudnick and Gao, 2005); granitic rocks typically contain 2-40 ppm Be, whereas syenites contain 2-220 ppm Be (Mulligan, 1968). More than 100 minerals contain beryllium, but only a few are economically important (Mulligan, 1968; Grew, 2002). Beryl ($Be_3Al_2Si_6O_{18}$) is typically found in pegmatites and other igneous-related deposits and transparent forms are gem minerals (green emerald, blue-green aquamarine, yellow heliodor, and pink morganite). Chrysoberyl (Al_2BeO_4) also can be a gem mineral. Bertrandite ($Be_4Si_2O_7(OH)_2$), helvite ($Mn_8(BeSiO_4)_6S_2$), and phenakite (penacite; $Be_2(SiO_4)$) are other important beryllium minerals.

Beryllium is nonmagnetic, corrosion resistant, easily transmits X-rays, six times stiffer than steel, one of the lightest of the metals (2/3 the density of aluminum), has a high heat-absorbing capability, has a high melting point (1285°C), has a low thermal neutron adsorption cross-section, and has dimensional stability over a wide range of temperatures (Taylor et al., 2003). Beryllium is the best reflector of electrons and is transparent to X-rays and is used in applications in nuclear reactors. BeO is an excellent refractory material and is used in ceramics.

Uses

The first use of beryllium was as gemstones, such as emeralds and aquamarine. Beryllium can be used as a pure metal, alloyed with other metals, processed as salts that dissolve in water, or processed as oxides or ceramics (Taylor et al., 2003; Jaskula, 2009). Beryllium was first alloyed with copper in the 1920s, which produced a stronger metal (Taylor et al., 2003).

Beryllium is used in the defense, aerospace, automotive electronics (modules for engine control computers, motors), medical, computers, telecommunications industries, in the cooling systems for nuclear reactors, and as a shield in nuclear reactors. Beryllium also is used in appliances, telecommunications (i.e. cell phones, pagers, wireless PDAs), ceramics, computer components, nuclear devices, satellites, missile systems, radar systems, computer components, connectors for fiber optics, magnetics and other applications (Committee on Beryllium Alloy Exposures, 2007). It is used in aircraft bearings and brushings since beryllium can sustain heavy loads. Since beryllium is anti-sparking, lightweight and strong, it is used as a component in fuel containers for jet and rocket fuel systems, and reentry vehicles. It is used for guidance and gyroscope systems in missiles and rockets. Its antimagnetic properties allow for use in inertial navigation systems. Beryllium is transparent to X-rays and is used for low energy, high resolution X-ray imaging for soft tissue, such as mammograms. 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). It even has been used in bicycles and golf clubs!

Beryllium is used in photovoltaic solar panels as a substrate (Brush Engineered Materials, Inc., 2009).

The largest usage is as alloys with Cu and Al since beryllium provides resistance to fatigue and failure to spring and stressed functions. Copper-beryllium alloys exhibit high electrical and thermal conductivity, high strength and hardness, good formability, and excellent resistance to corrosion, wear, and fatigue. These alloys, sold in strip and bulk product form, are ideal choices for demanding applications in computers, telecommunications, automotive electronics, aerospace, oil exploration, undersea fiber optic cables, and plastic mold tooling. Beryllium-copper alloys resist corrosion, are excellent conductors of electricity, and are used for electrical contacts and connectors where extremes of temperature and high corrosion are expected, such as in the automatic windows of many car doors. Beryllium metal is elastic and used in the manufacture of springs, gears and other machine components that need a degree of elasticity. Beryllium is used in radiation widows for X-ray tubes because it has a low absorption for X-rays.

Beryllium ceramics are used in computer chips, radio tubes, microwave guides, and electrical insulators. Also, beryllium is used in medical diagnostic equipment and heart implants. One of the most recent uses has been for the mirrors in telescopes, because beryllium has high reflectivity and light weight. Beryllium isotopes provide a means to date materials.

Production

Production statistics for beryllium are available since 1935 (Fig. 3). Before 1969, beryl from pegmatites was the primary source of beryllium. In 1968, the first bertrandite mine was opened in Spor Mountain, Utah and the mill opened in 1969 (Brush Resources, 2010). Spor Mountain contains some of the world's largest reserves (Table 3). Only six countries currently produce beryllium: United States (Brush Resources Inc. at their Spor Mountain mine), China, Mozambique, Portugal, Madagascar, and Brazil (Table 2; Jaskula, 2009). Other countries may have produced beryl ore, but information is not available to determine production; these include Uganda, Kazakhstan, Nigeria, and Russia (Jaskula, 2009). The price for beryllium in 2009 was $120/pound contained Be (U.S. Geological Survey, 2010).

TABLE 2. World mine production of beryllium, in metric tons (Jaskula, 2009; U.S. Geological Survey, 2004-2010). U.S. production includes bertrandite ore, calculated as equivalent to beryl containing 11% BeO. Price from U.S. Geological Survey (2004-2010). Other countries include Portugal, Madagascar, and Brazil. These figures do not include possible production from other countries, such as Kazakhstan, Nigeria, Uganda, and Russia.

Country	2003	2004	2005	2006	2007	2008	2009
U.S.	85	90	110	155	152	176	120
China (estimated)	15	20	20	20	20	20	20
Mozambique	3	3	6	6	6	1	1
Other countries	1	1	1	1	<1	<1	<1
Total	104	114	137	192	179	198	142
Apparent Consumption	57	69	84	226	100	212	120
Price (dollars per pound contained Be)	113	125	99	128	144	159	120
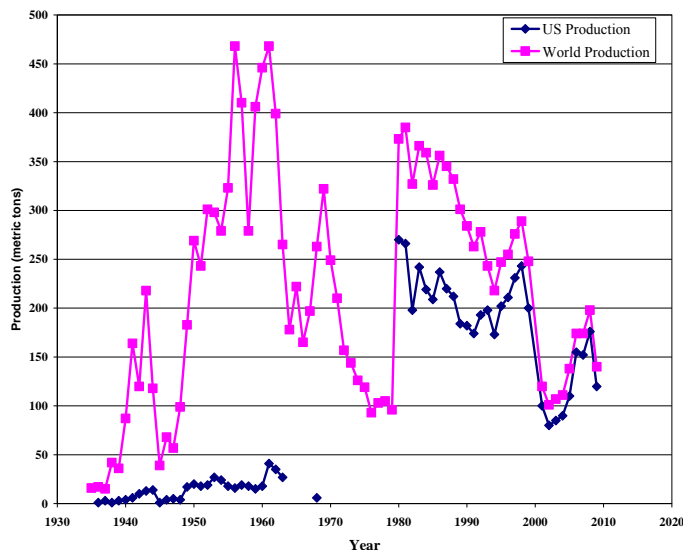
FIGURE 3. World and U.S. Be production 1935-2009 (U.S. Geological Survey, 2009).

TABLE 3. Production and reserves from the Spor Mountain mine owned by Brush Wellman (metric tons Be content, McNeil, 2004; Brush Engineered Materials, Inc., 2004, 2008, 2009).

Year	Bertrandite processed tons	Grade % Be	Proven bertrandite reserves	Grade % Be	Probable bertrandite reserves	Grade % Be
Total 1969-2009	3,000,000	~0.2	–	–	–	–
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 of beryllium in New Mexico

Beryllium occurrences and deposits found in New Mexico are shown in Figure 2 and listed in Appendix 1. Beryl was produced from pegmatites in New Mexico in 1950-1963 (Table 4). There is no production of beryllium in New Mexico currently.

TABLE 4. Beryllium production from Proterozoic pegmatites in New Mexico (Meeves et al., 1966). Additional production in 1963-1969 is withheld. Additional production from Iron Mountain in the Cuchillo Negro district, Santa Fe district, and Mora district is unknown.

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

Processing

Summary flow sheets describing the processing of beryllium are by Sabey (2006) and shown in Figure 4. The beryllium ore is mined from the open-pit mine at Spor Mountain, Utah and shipped to the mill at Delta. At the mill, typical processing techniques are employed: crushing, grinding, adding sulfuric acid, adding thickeners to separate the beryllium, and extracting the beryllium from the solution by solvent extraction (Brush Resources, 2010). Beryl is treated by a similar process at the Brush Wellman facility, except that the beryl ore is melted in a furnace to produce a beryllium glass, which then is ground and dissolved in acid. Beryllium oxide is then shipped from the Delta mill in Utah to processing plants in Elmore, Ohio, also owned by Brush Wellman, Inc., where it is used to process metallic beryllium, beryllium alloys, and beryllium ceramics. Brush Wellman, Inc. owns additional processing plants throughout the country and also processes beryl ore from deposits throughout the world.
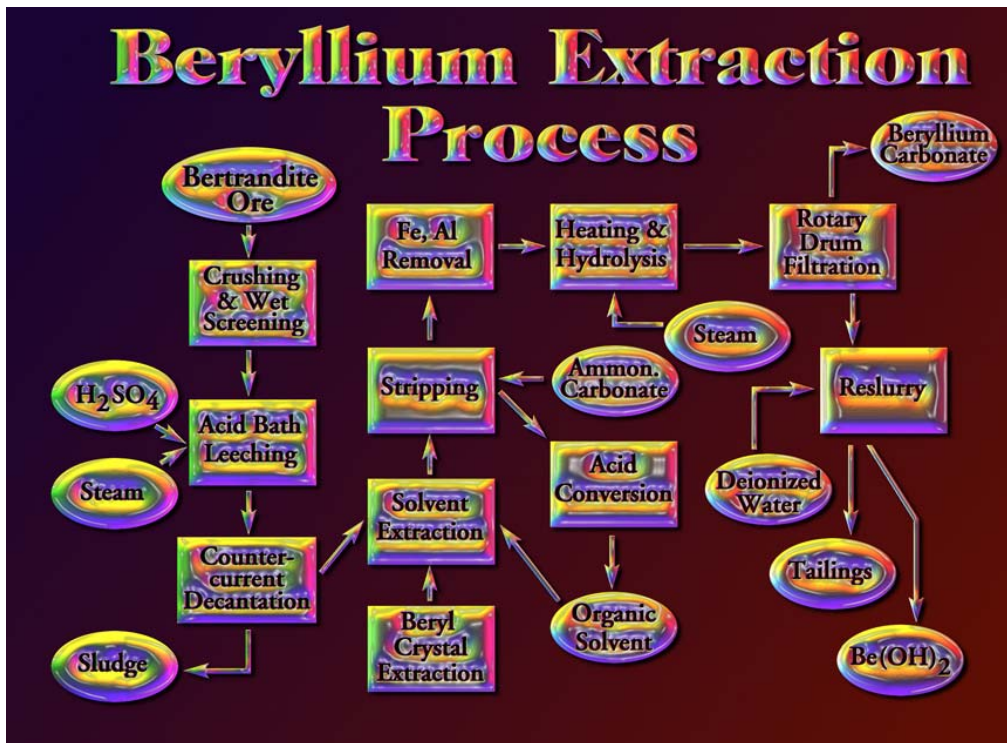
FIGURE 4. Flow chart showing the simplified beryllium extraction process.

Outlook

Beryllium is not a regularly traded commodity and marketing is typically by specific contracts. Brush Engineered Materials dominates the beryllium market, from mine production through manufactured products. The U.S. consumption of beryllium has remained relatively stable; in 2009, consumption was 120 metric tons, valued at $30 million (Table 2; U.S. Geological Survey, 2010). World consumption of beryllium is expected to increase approximately 2% per year and current production and reserves at Spor Mountain are sufficient to meet this demand (Table 3; Jaskula, 2009).

Several beryllium deposits in southwestern U.S and Mexico have calculated resources and are shown in Figure 1 and briefly described in Table 1. The Spor Mountain deposit is currently in production and has reserves at the end of 2009 amounting to 6.425 million metric tons with an average grade of 0.266% Be, or 15,800 metric tons of contained Be, which is sufficient for 100 years at the current production rate (Table 3; Jaskula, 2009; Brush Engineered Materials, Inc., 2009). The Round Top deposit at Sierra Blanca, Texas is acarbonate-hosted replacement beryllium deposit that contains approximately 771,100 metric tons grading 1.5% BeO (historic resource, not NI 43-101 complaint; Standard Silver Corporation, 2010). Deposits in New Mexico include Apache Warm Springs, Iron Mountain, and Victorio Mountains, but development of these deposits for beryllium is not likely in the near future. Exploration is ongoing at the Apache Warm Springs deposit, but there is no activity at Iron Mountain. The Victorio Mountain project is on hold until economic conditions for Mo or W improve.

World resources are estimated to be more than 80,000 metric tons of Be (U.S. Geological Survey, 2010); major deposits are listed in Table 1. The Thor Lake deposit in the Northwest Territories in Canada is under development for REE, and contains 498,409 metric tons grading 0.98% BeO; the primary mineral is phenakite (Be_2SiO_4), which contains 44% BeO (Paul and Stubens, 2009). The Strange Lake REE deposit in Quebec contains 137,639,000 metric tons of ore grading 0.077% BeO (Daigle and Maunula, 2010). Both of these beryllium projects are on hold at this time because of economic conditions. Etykinskoye rare metals operation in Russia owned by Zabailkalsky GOK could be another important source of beryllium; it is possible that some current production comes from this deposit. In China, the Ningxia Non-ferrous Metals Smeltery is reported to mine beryllium ores. In Brazil, Esmeralda de Conquista, part of the Mineração Badin Group, has reportedly stockpiled its production of beryl since the early 1990s but may have restarted exports in 2001. Piteiras Mineração of Minas Gerais produces beryllium concentrate based on industrial beryl and gems, which is further processed to produce emerald and industrial beryl. Other beryllium deposits are found in other countries, specifically Russia and Brazil (Table 1).

Environmental, health or other issues

Beryllium has been recognized since the 1940s as posing occupational hazards in the manufacture and production stages; these health effects are summarized by Deubner et al. (2001), Taylor et al. (2003), the Committee on Beryllium Alloy Exposures (2007), Stefaniak et al. (2008), and Foley et al. (2010). However, mining of beryllium ore as beryl and bertrandite has not been associated with any adverse health effects and beryllium in solid mineral form and finished products presents no adverse health effects. However,

beryllium in the processing facilities can trigger a debilitating and possibly fatal lung disease, berylliosis, or chronic beryllium disease (CBD).

Since many beryllium deposits are associated with U and/or Th, radioactive waste materials must be specially handled.

Substitutes and alternative sources

Alternative minerals for the use of beryllium are rare. Alternative materials made with aluminum and titanium are less expensive than those with beryllium, but not as efficient. In some metal applications, other copper alloys (i.e. Ni, Si, Sn) can be substitutes for Be-Cu alloys. Aluminum nitride or boron nitride could be substituted for some beryllium oxide applications.

METHODS OF STUDY

Data used in this report have been compiled from a literature review, field examinations, and unpublished data by the author. A summary of the mining districts and mines in New Mexico containing beryllium deposits is in Appendix 1. A summary of the NURE stream-sediment anomalies in New Mexico, ranging from 5 to 38 ppm Be, are in Appendix 2. Locations, available data, and references of chemical analyses are in Appendix 3. The district identification numbers (prefixed by DIS) and mine identification numbers (prefixed by NM) are from the New Mexico Mines Database (McLemore et al., 2005a, b) and refer to the mines and districts in Appendix 1. Names of mining districts are from File and Northrop (1966) and McLemore (2001), where possible. Mining districts, mines, NURE data, and other spatial data were plotted using GIS ArcMap.

It is not easy to determine the chemical composition of beryllium within rocks and so few studies analyzed for beryllium. Because beryllium is transparent to X-rays, it is not detected by X-ray fluorescence spectrometry (XRF) or electron microprobe techniques. Most of the whole-rock geochemical data referred to in this report were determined by XRF, which determines the major oxide elements and some trace elements (Rb, Sr, Ba, V, Nb, Zr, Y, Ni, and Cr), but not beryllium. Additional trace elements in some samples were analyzed by inductively-coupled plasma optical emission spectrometry (ICP-OES; Be, Sr, Ba, V, Zr, Y, Sc, Cr, Ni) or by instrumental neutron activation analysis (INNA; Hf, Ta, U, Th, REEs, but not Be). Beryllium is analyzed by atomic absorption spectroscopy (AAS), ICP-OES, and inductively-coupled plasma mass spectrometry (ICP-MS).

Numerous statistical packages were utilized in this report to summarize, analyze and interpret the chemical rock and NURE data obtained. Some of these programs include Excel, WinStat, SigmaStat, SigmaPlot, ProStat, Rockware, and PSPlot. All of these computer programs utilize the same fundamental statistical mathematics and include documentation. Statistics are mathematical tools used to describe, summarize, analyze, interpret and present data and, if the data are robust enough, also can be used to make predictions of resource potential (Cheeney, 1983; Wellmer, 1998; Schreuder et al., 2004). Descriptive statistics are mathematical tools that summarize or reduce the data sets to as small a subset of numbers as possible using indicators such as the mean, median, mode, standard deviation, coefficient of variation, etc. The mean or arithmetic average is the sum of the values divided by the number of values. The median is the middle value of a list ranged from lowest to largest. The mode is the value of a variable that occurs most

frequently. The frequency distribution or the frequency of occurrence is typically illustrated by a histogram (a bar or line graph of values where the length of the line shows the frequency of that value), cumulative frequency or density function plots. A normal distribution or bell curve is a density function plot where the curve is regularly shaped; other distributions of data are likely (Schreuder et al., 2004). The standard deviation is a measure of how much the data deviates from the mean.

       Several additional statistical tools were utilized in this report. Regression analysis is the process used to determine the best fit of a line or curve to a set of data consisting of dependent and independent variables; linear regression is used to describe how well the trend fits along a line. A correlation is used to define the linear relationship between two variables. Pierson correlation is obtained by dividing the covariance of the two variables by the product of their standard deviations. A correlation coefficient of 0.8 is generally a good correlation, although in some cases lower correlation coefficients (i.e. 0.5) could be acceptable. The term trend is used when the data indicate a relationship, but not a strong linear or curvilinear correlation.

       Relationships, trends, and correlations of the geological, geochemical, mineralogical, and geotechnical data were examined using these statistical methods. Outliers are the sample points that appear to be inconsistent with the remainder of the collected data (Iglewicz and Hoeglin, 1993). Possible sources of outliers are recording and measurement errors, incorrect distribution assumption, unknown data structure, or novel phenomenon (i.e. geochemical anomalies). Numerous techniques can be used to statistically identify outliers. Wellmer (1998) and Schreuder et al. (2004) summarize the mathematical theory behind most of the statistics used in this report.

GEOLOGY OF BERYLLIUM DEPOSITS

       Beryllium deposits are found in volcanic rocks as replacements and epithermal veins (volcanogenic Be), skarns, contact-metasomatic deposits, greisen-bordered veins, and pegmatites (Table 5; Burt et al., 1982; Kramer, 1994; Barton and Young, 2002; Foley et al., 2010). Associated igneous rocks include topaz-bearing rhyolites (Burt et al., 1982) and high-silica rhyolites (Levinson, 1962; McAnulty et al., 1963; McAnulty, 1980). Beryllium also is found associated with alkaline to peralkaline plutonic rocks (Warner et al., 1956, 1959; Holser, 1953; Mutschler et al., 1985, 1991). Many high-silica rhyolites and granites are associated with deposits of Be, U, F, Sn, and other lithophile elements. These include topaz rhyolites, tin-bearing rhyolites and granites, and A-type granites. Grade and tonnage for selected deposits is shown in Figure 6 and summarized in Table 1.
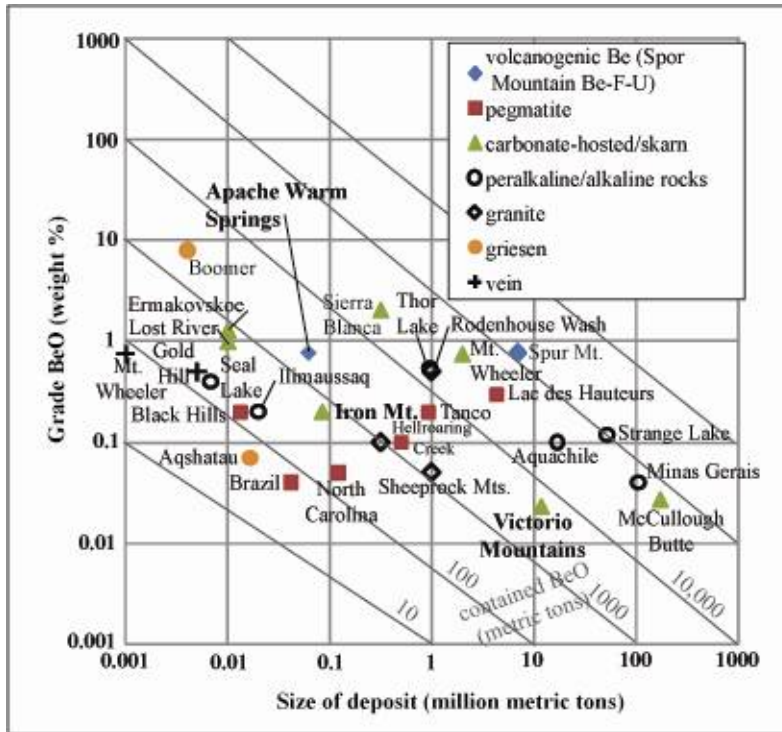
FIGURE 5. Grade and tonnage of selected beryllium deposits (modified from Barton and Young, 2002 using references in Table 1). Deposits in bold are located in New Mexico. See Table 1. Note that size of deposits includes production and reserves/resources and are not always NI 43-101 compliant and subject to change.

TABLE 5. Types of beryllium deposits (Beus, 1966; Barton and Young, 2002; Sabey, 2006). USGS Classification after Cox and Singer (1986), Ludington and Plumlee (2009), and Foley et al. (2010).

Type of Be deposit	USGS Classification	Example
Pegmatites	13	Tanco, Canada
Volcanogenic Be (volcanic-hosted replacement, volcanic-epithermal, Spor Mountain Be-F-U deposits)	Volcanogenic Be deposits	Spor Mountain, Utah
Carbonate-hosted replacement and skarn (Mo-W-Be, F-Be, Fe-Mn)	14a	Ermakovskoe, Russia
Alkaline igneous rocks (disseminations and veins in peralkaline rocks and fenites)	11	Strange Lake, Canada
Granite/rhyolites (topaz rhyolites)	25h	Taylor Creek, NM
Tin skarns	15c, 14b, 14c	Lost River, Ak
Greisens	Mo-W greisens, 15c	Boomer, Colorado
Veins	–	Columbia black shale
Porphyry molybdenum (±copper, tungsten)	16, 21a, 21b	Questa, NM
Metamorphic (schist)	31c	Regal Ridge, Yukon, Canada
Placer (mostly beryl and babefphite)	–	–
Coal	–	–

Mineralogy

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 beryllium 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 beryllium 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 Negro 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).

Geochemistry of beryllium

The average igneous rock contains approximately 3 ppm Be, with granites containing an average of 6 ppm and feldspathoidal rocks containing 8 ppm Be (Shawe and Bernold, 1966). Natural concentration of beryllium in soils in the world is variable, ranging from 0.1 to 40 ppm Be (Taylor et al., 2003). In New Mexico, ground water sampled during the NURE (National Uranium Resource Evaluation) program in the 1970s and early 1980s averaged 3 µg/L Be (108 samples) and stream sediments averaged 1.6 ppm Be (20,266 samples) (U.S. Geological Survey, 2001; Taylor et al., 2003). Beryllium is typically found with F, Li, Nb, Ta, REE, W, Sn and U (Barton and Young, 2002).

EVALUATION OF THE NURE STREAM-SEDIMENT DATA
Description

A regional geochemical database, including stream sediments (Fig. 6) and waters exists for the state of New Mexico that was generated from reconnaissance surveys as part of the U.S. Department of Energy's National Uranium Resource Evaluation (NURE) program during 1974-1984 (McLemore and Chamberlin, 1986). Field sampling techniques are detailed in Sharp and Aamodt (1978). The NURE data is typically arranged by 1x2-degree quadrangles, although a few areas were sampled and evaluated in greater detail (Estancia Basin, Grants uranium district, and San Andres and Oscura Mountains area). Total number of stream sediment samples in the state analyzed was 27,798 and 12,383 water samples were analyzed. Chemical analyses for New Mexico were performed at two national laboratories (Los Alamos and Oak Ridge) and each laboratory utilized different analytical techniques and analyzed sediments for different elements (Hansel and Martell, 1977; Cagle 1977; Aredt et al., 1979). Only the stream sediments were examined for this report.
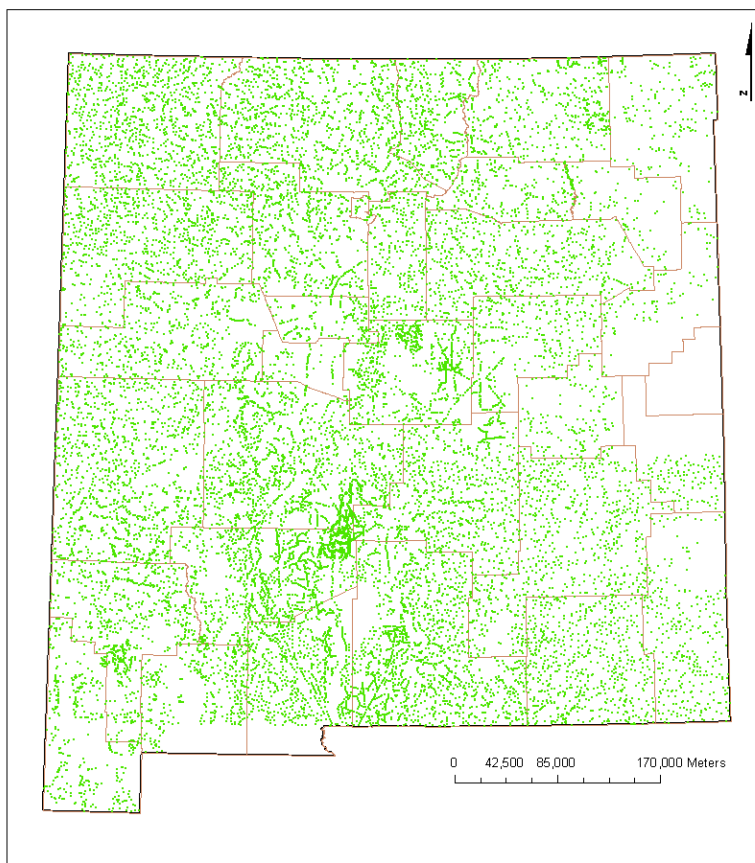
FIGURE 6. Distribution of NURE stream sediment samples in New Mexico (data from Smith, 1997).

Some of the NURE data are problematic (Haxel, 2002) and the entire data set should be used with caution. Some of the recognized problems of the NURE data include inconsistent sampling techniques, variability in density of sampling, different size fractions used for analysis, different laboratories and different analytical techniques and analytical errors, and different analytical detection limits. Methods of evaluating the validity of NURE data in New Mexico, include examining histograms, comparing the NURE data with average upper crustal values, comparing data for pairs of statistically similar elements, such as Zr-Hf, Th-U, and La-Ce (Haxel, 2002), comparing descriptive statistics and histograms for different laboratories, and examining the descriptive statistics between the 1x2-degree quadrangles. In addition, there are several areas in New Mexico where subsequent stream-sediment surveys have been completed and show similar geochemical patterns as the with the NURE data (Ellinger, 1988; Ellinger and Cepeda, 1991; Watrus, 1998; New Mexico Bureau of Mines and Minerals Resources et al., 1998). Some NURE samples have been re-analyzed by the U.S. Geological Survey and most samples compare well.

The main purposes of the NURE program were to provide an assessment of the nation's uranium resources and to identify areas favorable for uranium mineralization. The NURE data were not designed to reveal uranium or other mineral deposits, but if the NURE data are used with caution, the data can be used to identify areas of potential

geochemical interest for further study. Ultimately, field examination of these identified areas must be conducted.

Elemental geochemical patterns in stream-sediment and water samples can be used in environmental studies to detect areas of anomalously high concentrations of elements and perhaps to distinguish between natural background and possible contamination from mining and other anthropogenic inputs (Schreck et al., 2005; McLemore, 2010b), as well as identify areas for potential economic mineral resources. Numerous studies have utilized the NURE data for New Mexico to evaluate mineral resource potential (Laughlin et al., 1985; Bartsch-Winkler and Donatich, 1995; Bartsch-Winkler, 1997; New Mexico Bureau of Mines and Mineral Resources et al., 1998; McLemore et al., 2001). Zumlot (2006) presented an evaluation of the NURE data for the entire state and used slightly different statistical techniques then used in this report and presented much of the data analysis on a web site (https://webspace.utexas.edu/howarifm/www/NURE/1nm.htm/).

Methods of Study

The NURE data for New Mexico were downloaded from Smith (1997). Below detection values (i.e. concentrations of 0 and negative values) were eliminated from the data set to form a processed data set. Statistical analysis was performed on the processed data. The processed NURE data were entered into GIS ArcMap, along with mining districts, mines from the New Mexico Mines Database (McLemore et al., 2005a, b), and the state geologic map (New Mexico Bureau of Geology and Mineral Resources, 2003). Single element maps were plotted for selected areas using ArcMap. Descriptive statistics, histograms, box plots, scatter plots, and cumulative frequency plots were created using data for the entire state (Table 6); Figure 7 is a histogram of the beryllium geochemical data. Outliers were identified, located (using search in ArcMap), and determined if they were due to analytical error or atypical abundance (i.e. geochemical anomalies). Many times, three or more outliers are found together, as described below. Since the sample density is not very detailed, single outliers could have geochemical significance.

TABLE 6. Descriptive statistics of processed NURE data for New Mexico, using WinStat. Data are in parts per million (ppm). Upper crustal abundance is from Grew (2002) and Rudnick and Gao (2005).

	Be	U	Th	Zr	Li
Number of samples	20266	27351	25033	18369	21132
Mean	1.63	3.35	8.11	123.96	26.32
Variance	0.70	14.25	68.11	34518	138.78
Standard deviation	0.83	3.78	8.25	185.79	11.78
Minimum	1	0.1	0.2	1	1
Maximum	38	445.1	332.5	4689	224
5th Percentile	1	1.72	1.3	7	13
25th Percentile	1	2.4	4	48	19
Median	1	2.9	7	66	24
75th Percentile	2	3.59	9.9	112	31

	Be	U	Th	Zr	Li
Geometric mean	1.48	3.00	6.02	68.87	23.30
Geometric Standard Deviation	1.53	1.50	2.22	3.04	1.48
Abundance in the upper crust (ppm)	2.1	2.7	10.5	193	24

Histogram
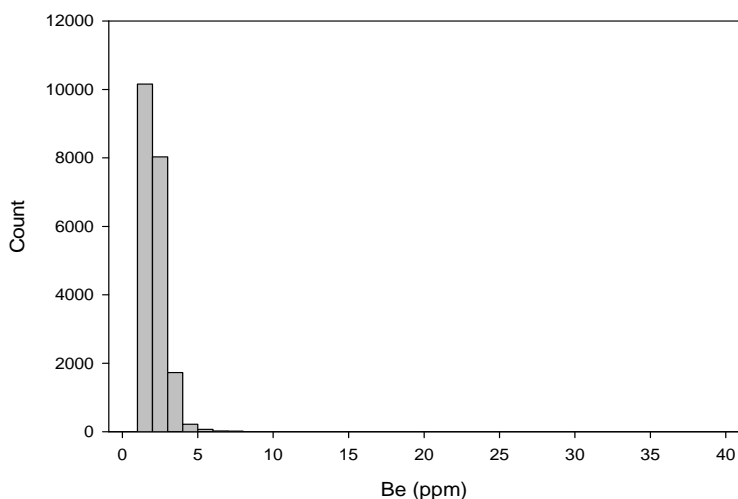
FIGURE 7. Histogram of beryllium in New Mexico NURE stream-sediment samples. Number of samples is 20,266.

Identification of geochemical anomalies and background

Identification of geochemical anomalies (i.e. outliers) and background concentration is not always simple. An orientation or analog study can be performed in a non-mineralized or uncontaminated site to define a local threshold against which anomalies can be judged. Anomalies can be determined by statistical methods such as selecting the upper 2.5% of the data or the mean plus 2σ (standard deviation) as geochemical anomalies (Hawkes and Webb, 1962). However, these statistical methods do not always account for different geochemical processes that form the anomalies nor do they always account for two or more overlapping populations. The geochemical threshold also can be determined by plotting a cumulative frequency plot and the threshold value is at the break in slope (Matschullat et al., 2000). The box plot also can be used to define the upper and lower threshold (Bounessah and Atkin, 2003; Reimann et al., 2002). These later two techniques begin to account for different geochemical processes and for two or more overlapping populations. The data also can be compared to average crustal abundance or other averaged data. Table 7 summarizes the upper threshold for REE and other elements using these techniques.

TABLE 7. Upper concentration thresholds (i.e. outliers) for beryllium calculated by different methods.

Method	Be ppm	U ppm	Th ppm	Zr ppm	Li ppm	Reference
Upper crustal abundance	2.1	2.7	10.5	193	24	Rudnick and Gao (2005)
Mean (entire state)	1.63	3.4	9.5	123.96	26.32	NURE data
Median (entire state)	1	2.9	8.5	66	24	NURE data
Mean + 2σ	3.3	7.4	18.0	–	49.9	Hawkes and Webb (1962)
Box plot	2	3.6	11.0	158	31	Bounessah and Atkin (2003)
Cumulative frequency plot	3	7	20	500	50	–
Anomalous value used in this report	5	12	20	200	30	–

Areas indicated by the NURE data

Evaluation of the NURE stream-sediment data identified 129 geochemical anomalies that were 5-38 ppm. Most of the anomalies are related to rhyolitic complexes, including ignimbrites (i.e. ash flow tuffs); 51 anomalies (5-11 ppm) are related to the outcrop of the Bandelier Tuff in the Jemez Mountains (Appendix 2). A sample from east of East Grants Ridge contained 11 ppm and is likely related to the topaz rhyolites found at East Grants Ridge. A group of three samples containing 5-11 ppm Be in Blue Mountain quadrangle north of San Jose district, San Mateo Mountains is likely related to local ash-flow tuffs or rhyolite domes; riebeckite-bearing rhyolite is found in some rhyolites in the San Mateo Mountains (Deal, 1973; Atwood, 1982). The NURE stream-sediment sample with the highest Be concentration (38 ppm) is from near the Iron Mountain beryllium deposit in the Cuchillo Negro district. Most samples from the Victorio district contain 1-2 ppm Be, but three samples contain 8-9 ppm Be. A sample containing 20 ppm is found southeast of the Laughlin Peak district, and likely related to the alkaline volcanic and intrusive rocks in that district. Samples from other districts with granitic rocks and volcanic-epithermal vein deposits contain anomalously high concentrations of Be, including 12 ppm Mogollon district (12 ppm Be), 4-5 ppm Ladron Mountains (4-5- ppm Be), Little Florida Mountains (9 ppm Be), east of the Steeple Rock district (4-7 ppm Be), east of Gila Hot Springs (4-7 ppm Be), in and east of Taylor Creek district (4-7 ppm Be), Questa (6 ppm Be), and La Cueva district (4-5 ppm Be). A sample containing 14 ppm is from the Mesa Aparejo district in Valencia County, an area known for travertine deposits.

DESCRIPTION OF SELECTED BERYLLIUM DEPOSITS IN NEW MEXICO AND ADJACENT AREAS
Pegmatites in New Mexico

Pegmatites are coarse-grained granitic dikes, lenses, pods, or veins and represent the last and most hydrous phase of crystallizing magmas. Nearly all of the pegmatites in New Mexico and adjacent areas are Proterozoic in age and intruded metamorphic and granitic rocks; mid-Tertiary pegmatites are found in the Organ Mountains and Black Range. 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 feet long and several tens of feet 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 (Table 4), 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; McLemore, 2010d). Typically minerals containing these rare commodities are scattered discontinuously throughout the pegmatite, thereby hampering recovery. 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.

Gold Hill (DIS058), White Signal (DIS068), and Burro Mountains districts (DIS046) Grant and Hidalgo Counties

The Gold Hill, White Signal, and Burro Mountains districts are in the Burro Mountains, which is a northwest-trending range of predominantly Proterozoic Burro Mountains Granite (1550 Ma; Hedlund, 1978), and is surrounded by Quaternary alluvial fans on the west end and by Tertiary volcanic rocks on the east end. Proterozoic pegmatites intruded the Burro Mountain granite (Fig. 2) and some of these pegmatites were prospected in the 1950s for U and Th. The oldest rocks in the mountain range form the Bullard Peak Group of Hewitt (1959) and consist of migmatite, quartz-biotite gneiss, hornblende gneiss, and amphibolites. This intrusive episode was followed by a pervasive retrograde event in which the mafic rocks were chloritized, sericitized, and epidotized. Proterozoic diabase dikes and plugs were subsequently intruded. These rocks are fractured and intruded by basaltic, rhyolite and felsic dikes.

The pegmatites vary in size from pods a few inches across to lens-shaped bodies several hundred feet long and almost as wide. Minerals found in the pegmatites include quartz, albite, microcline, muscovite, biotite, and trace garnet, fluorite, fluorapatite, allanite, euxenite, samarskite, cyrtolite, and beryl (Gillerman, 1964; Hedlund, 1978). Only small amounts of Th, Nb, Ta, U, REE, and Be are present. Many pegmatites are zoned with coarse quartz at the core with small segregations of microcline (Gillerman, 1964). Surrounding the core is a quartz-perthite zone with muscovite and biotite. The next zone out is a quartz-albite-muscovite or quartz-albite-microcline zone. The outermost zone is quartz-microcline.

The largest pegmatite in the three districts is the White Top pegmatite (NMGR0137) in the Gold Hill district. Beryl was found in the shaft and dump at the White Top pegmatite (Meeves et al., 1966; Richter and Lawrence, 1983). At the South Pegmatite (NMGR0058) in the Gold Hill district, massive green fluorite occurs in the quartz-albite-muscovite zone with trace of beryl.

Picuris district (DIS236), Taos County

The Picuris district, in the Picuris Range of the Sangre de Cristo Mountains (Fig. 2), is best known for the Harding pegmatite (NMTA0015), a Proterozoic complex-zoned pegmatite, which has produced substantial amounts of beryl, lepidolite, spodumene, and

tantalum-niobium (microlite) minerals. The pegmatite was discovered about 1910 and mining for lepidolite began in 1919. This was the first of three mining periods at the pegmatite (the Lepidolite period, 1919-1930) (Jahns and Ewing, 1977). Lepidolite, a lithium-bearing mica, is used to manufacture glass. From 1920 to 1930, approximately 12,000 short tons of lepidolite-spodumene ore, averaging 3.5% LiO_2 was produced (Schilling, 1960). Additional production occurred in 1942-1947 (41 short tons of spodumene, 558 tons of lepidolite) and again in 1950-1953 (806 short tons of lepidolite, 249 short tons of spodumene).

The second period of mining, the Microlite period (1942-1947), began in 1942 when Arthur Montgomery began producing microlite, a tantalum-niobium mineral. The Harding pegmatite is one of the few mines in the world to produce microlite. From 1942 to 1947, more than 22,000 pounds of tantalum concentrates, averaging 68% Ta_2O_5 and 7% Nb_2O_5, were produced (Jahns and Ewing, 1977). In addition, 464 pounds of placer tantalite and columbite (43% Ta_2O_5, 36% Cb_2O_5) eroded from the pegmatites were produced.

The third mining period, the Beryl period, occurred between 1950 and 1959. From 1950 to 1959, 848.3 short tons of beryl that averaged 10% BeO were produced from the Harding pegmatite, and from 1950 to 1955 the pegmatite accounted for nearly 20% of the beryl production in the United States (Schilling, 1960). After mining ceased in 1959, the Harding mine was leased to several companies for exploration of additional resources; production, if any, is unknown. Since the early 1970s, the mine was leased and subsequently donated to the University of New Mexico for preservation as a field laboratory.

The Harding pegmatite is actually a series of granitic pegmatites in a well-defined belt 2500 ft long and 150-500 ft wide that consists of numerous pinch-and-swell pegmatite dikes, 5-20 ft thick (Jahns and Ewing, 1977). Most of the beryl was found as large anhedral crystals and aggregates with quartz, apatite, and muscovite in the quartz-rich hanging wall zone. The beryl zone was 0.5-8 ft thick and separated from the contact by an albite border selvage (Jahns et al., 1958). Beryl is found as white, blue, pale rose, pinkish, greenish or yellow-greenish in color. Approximately 1000 pounds of beryl was produced from the Roybal pegmatites, east of the Harding pegmatite.

Ojo Caliente No. 1 (DIS147) and Petaca (DIS148) districts, Rio Arriba County

The predominant mineral deposits found in the Ojo Caliente and Petaca districts in the Tusas Mountains are pegmatites (Fig. 2; Appendix 1). All of the numerous pegmatites in the Ojo Caliente and Petaca districts are Proterozoic in age and intruded metamorphic and granitic rocks. Mica, feldspar, beryl, uranium, and other commodities have been produced from these pegmatites (Table 4; Redmon, 1961; Bingler, 1968; Chenoweth, 1974). Mica production was in excess of 250 short tons and was mostly scrap mica from the pegmatites and Proterozoic micaceous schist. The pegmatites average 410 ft long and 35 ft wide. Beryl is found mostly in the albite-rich zones and in fractures within the quartz cores. Stream-sediment samples collected from the Ojo Caliente drainage basin range from 1 to 10 ppm Be (Wenrich-Verbeek and Suits, 1979).

Nambe district (DIS185), Rio Arriba and Santa Fe Counties

The Nambe district is in the Truchas Range, where several northeast-trending pegmatites intruded the Proterozoic rocks that are a few feet wide and few tens of feet long and consist of quartz, microcline, perthite, plagioclase, muscovite, tourmaline, garnet, magnetite-ilmenite, beryl, and other minerals. Approximately 1500 pounds of beryl was produced from the Fish pegmatite (NMRA0155) in 1957 (Redmond, 1961). The Fish pegmatite is approximately 60 ft long, 10 ft wide, strikes N80°W, dips 80°S, and consists of feldspar, quartz, muscovite, and beryl. Beryl also has been found at the B.A.T. (NMSF0087), Shaw 2 (NMSF0034), Aspen Basin (NMSF0086) and Rocking Chair (NMSF0090) pegmatites (Redmond, 1961).

Rociada district (DIS164), San Miguel County

The Rociada mining district is in the eastern Sangre de Cristo Mountains, east of the Pecos Wilderness Area. The pegmatites intruded amphibolite, are a few inches to more than 20 ft wide and as much as 150 ft long, and consist of quartz, perthite, albite, lepidolite, beryl, and muscovite (Jahns, 1953). Rhabdophanite is reported by Redmond (1961). The Pidlite pegmatite (NMSM0117) was mined for lithium and microlite (Jahns, 1953). The Pidlite pegmatite is 75-200 ft long, 18-30 ft wide, strikes N20ºW, intrudes schist, and consists of quartz, microcline, microlite, lepidolite, beryl and other rare minerals (Jahns, 1953; Northrop, 1996). Beryl and gadolinite are present in the border zone of the pegmatite, which is less than 2 ft thick. Bertrandite was reported from the Pidlite district by DeMark (1992).

El Porvenir district (DIS161), San Miquel County

Several pegmatites intruded Proterozoic granite that intruded metamorphic rocks in the El Porvenir (Hermit Mountain) district, near Young's Canyon, Burro Creek and Gallinas Creek and contain trace amounts of beryl (Harley, 1940; Northrop, 1996).

Elk Mountain district (DIS162), San Miguel County

Elk Mountain mining district is in the southern Sangre de Cristo Mountains, where pegmatites intruded Proterozoic quartz-mica schist (Jahns, 1946; Redmon, 1961). Generally the pegmatites are long, narrow dikes and lense-shaped pods, several hundred feet long and intruded the metamorphic rocks and rarely the tonalite and granite (Klich, 1983). The pegmatites typically consist of quartz, albite, microcline, muscovite, rose muscovite, and lepidolite (Klich, 1983). The Elk Mountain (San Miguel, Kept Man, NMSM0008) pegmatite is approximately 200 ft long and 90 ft wide and consists of microcline, quartz, muscovite, garnet, fluorite, tourmaline, columbite, and trace beryl, gadolinite and REE minerals (Holmquist, 1946; Redmon, 1961; Northrop, 1996). The Sparks-Stone pegmatite is 5-6 ft wide, 50 ft long, and produced 32.27 pounds of U_3O_8 (McLemore, 1983).

Tecolote district (DIS166), San Miguel County

The Tecolote district is in the Rincon Range, where 24 short tons of beryl were produced from the Priest mine (NMSM0122; Harley, 1940; Anderson, 1957; Redmon, 1961). The Priest pegmatite, the largest, intruded Proterozoic schist and gneissic granite, is 400 ft long and 90 ft wide, strikes N70ºE, and consists of quartz, microcline,

columbite, garnet, tourmaline, sericite, tantalite, and beryl. Other pegmatites in the district contain trace amounts of beryl.

La Cueva district (DIS232), Taos County

REE-Th-U veins, veins in Proterozoic rocks (±U, Th, REE, Cu, Au, Zn), and pegmatites (±U, Th, REE, Be, mica) are found in the southern part of the Proterozoic Costilla granitic massif in La Cueva district (also known as Vermejo Park and Costilla Creek district) in the vicinity of Costilla Creek, northern Taos County (Zelenka, 1984; Goodnight and Dexter, 1984; McLemore, 1990; McDonnell, 1992). The Costilla massif consists of granite gneiss, pegmatitc granite, and granite to quartz monzonite. The radioactive pegmatites intruded the granite and both intruded a complex Proterozoic terrain of metamorphic and igneous rocks. The Proterozoic rocks are overlain by Tertiary volcanic and volcaniclastic rocks related to the Questa caldera to the south and the Rio Grande rift. The granitic rocks are subalkaline, metaluminous to peraluminous. Mineralization in the district was discovered in the 1950s during prospecting for radioactive veins and pegmatites (Collins, 1954, 1956), and exploration was carried out in the 1970s and 1980s by Phillips Petroleum Company and Duval Corporation (Reid et al., 1980; Zelenka, 1984; McDonnell, 1992; McLemore, 1990; McLemore and Mullen, 2004). There has been no mineral production from the area.

Mineralized zones containing high concentrations of U, Th, and REE elements are found in fracture zones within the Proterozoic Costilla granite and pegmatites. Radioactive minerals found in La Cueva district include uraninite, thorite, uranothorite, magnetite, zircon, allanite, apatite, sphene, thorogummite, uranophane, uraniferous hematite, trace beryl, and an unknown uranyl silicate (Zelenka, 1984). Pegmatites also contain abundant sheet mica, 3 inches across, and minor beryl and chrysoberyl (McKinlay, 1956; Schilling, 1960; Northrop, 1996). Clay-rich zones at the La Cueva prospect (NMTA0559) contain uranophane and thorogummite and as much as 1522 U, 1643 ppm Th, 625 ppm La, and 1560 ppm Ce in selected samples (Zelenka, 1984). Stream sediments downstream of known prospects contain as much as 202.2 ppm U, 51 ppm Th, 48 ppm La, and 96 ppm Ce (McLemore, 2010b).

Mora district (DIS126), Mora County

Numerous pegmatites are found in the Mora district, but only a few contain rare minerals (Redmond, 1961). Beryl is rare.

Coyote Canyon district (DIS002), Bernalillo County

A pegmatite intruding Proterozoic granite in the Coyote Canyon district contained trace amounts of beryl (Kelly and Northrop, 1975; Northrop, 1996).

Rabb Park, Black Range, Grant County

Small Tertiary pegmatites at Rabb Park in the Black Range, near Emory Pass, intruded rhyolite porphyry (Kelley and Branson, 1947; O'Brient, 1986). The Rabb Park pegmatites are up to 10 ft long, 3 ft wide, and associated with fine-grained aplite. The pegmatites and aplites consist of quartz, sanidine, plagioclase, biotite, magnetite, zircon, apatite, and sphene. Beryllonite was reported (Murphy, 1992; Northrop, 1996). The

pegmatites are 33.8±0.7 Ma (K/Ar date), similar in age as the Kneeling Nun Tuff that erupted from the Emory caldera (O'Brient, 1986).

Volcanogenic Be (volcanic-hosted replacement, volcanic-epithermal, or Spor Mountain Be-F-U) deposits

Volcanogenic beryllium (i.e. Spor Mountain Be-F-U) deposits are hosted by volcanic rocks, especially rhyolite, in several areas and are found as volcanic-epithermal veins and/or replacements in volcanic rocks (Foley et al., 2010). Volcanogenic beryllium deposits form where hydrothermal fluids interact with volcanic rocks, especially topaz-rhyolites and granite porphyry. 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). At Spor Mountain, bertrandite 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 terrain 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 associated rhyolites are high-silica, high-fluorine rhyolites; topaz rhyolites are particularly favorable for beryllium deposits (Burt and Sheridan, 1981; Burt et al., 1982), and the rhyolites are enriched in F, Be, Cs, Mn, Nb, Y, U, Th, Mo, Sn, W, and REE. Beryllium, 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).

The formation of volcanogenic beryllium deposits is related to 1) a high-silica, lithophile-rich magma, 2) magma mixing leading to extrusive volcanic activity, 3) permeable host rock, such as rhyolite tuffs, and 4) convecting hydrothermal fluids enriched in Be, Fe, F, and other lithophile elements.

Spor Mountain, Utah

At Spor Mountain, bertrandite is found replacing layers and lenses, especially carbonate rock fragments, within rhyolite flows and tuffs and associated fault breccias that exhibit extensive argillic alteration characterized by zeolites, clay and late K-feldspar. The deposit is mined by open pit methods since 1969 (Fig. 8). The beryllium deposits and host rhyolites are slightly radioactive and U and F deposits are found in the area (Griffitts, 1982; Lindsey and Shaw, 1982; Park, 2006). 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 (Fig. 9; Lindsey, 1981; 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. 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).

The ore bodies are typically tabular, 5-10 ft thick, 500-1000 ft wide, and 1500-10,000 ft long. Bertradite is disseminated in the porous volcanic tuff, replaces limestone rock fragments, and is associated with fluorite, manganese oxides, silica, lithium, and

uranium. Total production is estimated as 3 million short tons of 0.2% Be or 11 million pounds of recovered Be (Table 3). Spor Mountain contains approximately 7 million tonnes of beryllium at a grade of 0.26% Be (or 18,300 tonnes of contained metal; Cunningham, 2004).

FIGURE 8. View of Spor Mountain open pit.
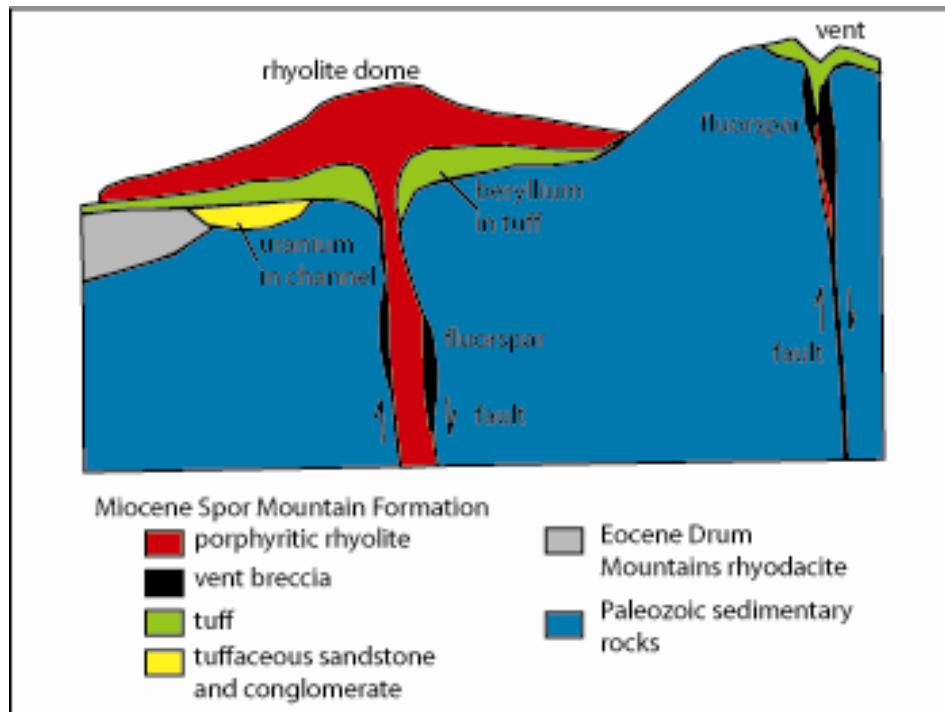
FIGURE 9. Schematic sketch of the Spor Mountain deposit.

Apache Warm Springs, Ojo Caliente No. 2 district (DIS230), Socorro County

The Apache Warm Springs deposit (NMSO0152, also known as the Sullivan Ranch site, McLemore, 2010a) lies in the Montoya Butte quadrangle on the northeastern edge of the Mogollon-Datil volcanic field in the northern Sierra Cuchillo range (Fig. 10) and is similar to the Spur Mountain-type Be-F-U deposits (Lindsey and Shawe, 1986). Only one mine has yielded metals production from this district, the Taylor mine (NMSO0073), a volcanic-epithermal vein deposit, which yielded one car load of Cu, Ag, and Pb ore about 1950. During the uranium boom a small amount of uranium was produced from the Apache Warm Springs deposit, according to Hillard (1967, 1969).

Beryllium, mostly as bertrandite ($H_2Be_4Si_4O_9$), was first noted in Red Paint Canyon about 1961 by M. Howard Milligan (NMBGMR files). Shawe (1966) identified the Apache Warm Springs beryllium deposit as part of the New Mexico-Arizona beryllium belt. Meeves (1966) described the results of field reconnaissance mapping, trenching, and drilling for beryllium by a commercial company under contract to the U.S. Bureau of Mines. Eighteen holes were drilled as part of these early exploration efforts.

The Beryllium Group, LLC controlled the property in 2001-2002, drilled 14 holes, and reported a resource of 43,060 short tons (not NI 43-101 compliant; Mining Engineering, 2002). Great Western Exploration, LLC controlled the property from 2004-2007 (P and E Mining Consultants Inc., 2009). In October 2007, BE Resources Inc. acquired the property and has applied for exploration permits for additional drilling. There has been no beryllium production from the property. Griffitts and Alminas (1968) conducted a stream-sediment reconnaissance of the Monticello Box area for base-metals and found the area to have numerous minor geochemical anomalies; beryllium was not analyzed for.

The Sierra Cuchillo is a north-trending mountain range bounded by the Monticello and Winston grabens (Fig. 10). The predominant structures in this mountain are Basin and Range faulting. The Iron Mountain Be deposits are in the northern Cuchillo Negro district, south of the Ojo Caliente No. 2 district and has similar rocks.

The oldest rocks exposed near the district are marine sedimentary rocks belonging to the Permian Yeso and San Andres Formations. Fault blocks south of the district consist of orange- to reddish-brown, well- to moderately-sorted sandstones and siltstones that are interbedded and overlain by dark gray, fine-grained, massive limestones. These units are as thick as 640 m elsewhere in the Sierra Cuchillo (Jahns et al., 1978). It is likely that these Permian rocks underlie much of the Montoya Butte quadrangle at depth (Jahns et al., 1978; Maldando, 1980). The volcanic rocks consist of the andesite of Monticello Box (the oldest volcanic rocks exposed in the area), lahar, latite of Montoya Butte (36 Ma, McLemore, 2010a), Vicks Peak Tuff (erupted from the Nogal Canyon caldera, 28.4 Ma), rhyolite of Alamosa Canyon (28.4 Ma), rhyolite of Alum Spring, and other younger volcanic rocks (McLemore, 2010a).

The Apache Warm Springs beryllium deposit (Fig. 11, 12) is a volcanogenic beryllium deposit (i.e. Spor Mountain Be-F-U deposit). A geologic map and cross section as interpreted by the author is in Figure 11. Bertrandite is found in small quartz veins and stringers, along fractures with clay minerals, and disseminated with the rhyolite and rhyolite ash-flow tuff. Summary of drilling is in McLemore (2010a). Meeves (1966) reports assays as high as 2.05% BeO in drilling during the U.S. Bureau of Mines drilling program, additional chemical analyses for beryllium are in McLemore (2010a). Only one

hole in the recent drilling, BE18A, contained beryllium analyses higher than 50 ppm, with the highest analysis of 2600 ppm Be (P and E Mining Consultants, Inc., 2009; McLemore, 2010a). It is possible that the beryllium deposit could continue south of the known extent in Red Paint Canyon, as indicated by the magnetic anomalies (McLemore, 2010a).

The Apache Warm Springs beryllium deposit is characterized by intense acid-sulfate alteration (also known as advanced argillic alteration), which produces the multiple shades of white, red, yellow, orange, purple, green, brown, and black that gives Red Paint Canyon its name. The alteration at the Apache Warm Springs beryllium deposit can be differentiated into two zones on the basis of mineralogy, texture, and inferred temperatures as (1) clay zone (Fig. 13) and (2) silicified zone (Fig. 14, 15). Boundaries between the zones are typically gradational and are distinguished by quartz content and texture. The altered areas are characterized by the leaching and replacement of the matrix and primary minerals in the original host rock by kaolinite, illite, quartz, hematite, and locally illite/smectite, pyrite, anatase, alunite, bertrandite, and possibly pyrophyllite. The texture of the original lithologies is typically destroyed and replaced by clay minerals. Stratigraphic position and relict textures suggest that original lithologies were volcaniclastic rocks and rhyolite ash-flow tuffs (rhyolite of Alum Spring), possibly part of a rhyolite dome structure. The intensity of alteration varies and some primary minerals such as quartz, titanite, zircon, and apatite are locally preserved. The alteration is older than the Quaternary-Tertiary sedimentary rocks, which are unaltered and contain boulders and clasts of the altered tuff.

Although, the age of the Apache Warm Springs Be deposit can not be directly determined because of lack of suitable dateable minerals, the age of the mineral deposits can be estimated by stratigraphic position, age of faults, analogy to other deposits, and other geologic evidence, as older than the Turkey Springs Tuff (24.4 Ma), but younger than the latite of Montoya Butte, and likely younger than the Vicks Peak Tuff (28 Ma). Similar relationships are found further south in the Cuchillo Negro district, where the Ag-Cu-Pb-Zn veins and skarns are associated with the older 36-38 Ma granitic-rhyolitic rocks and the Fe-Be-W-Sn skarns are associated with the younger 29-27 Ma rhyolites (Jahns, 1944a, b; Davis, 1986a, b).
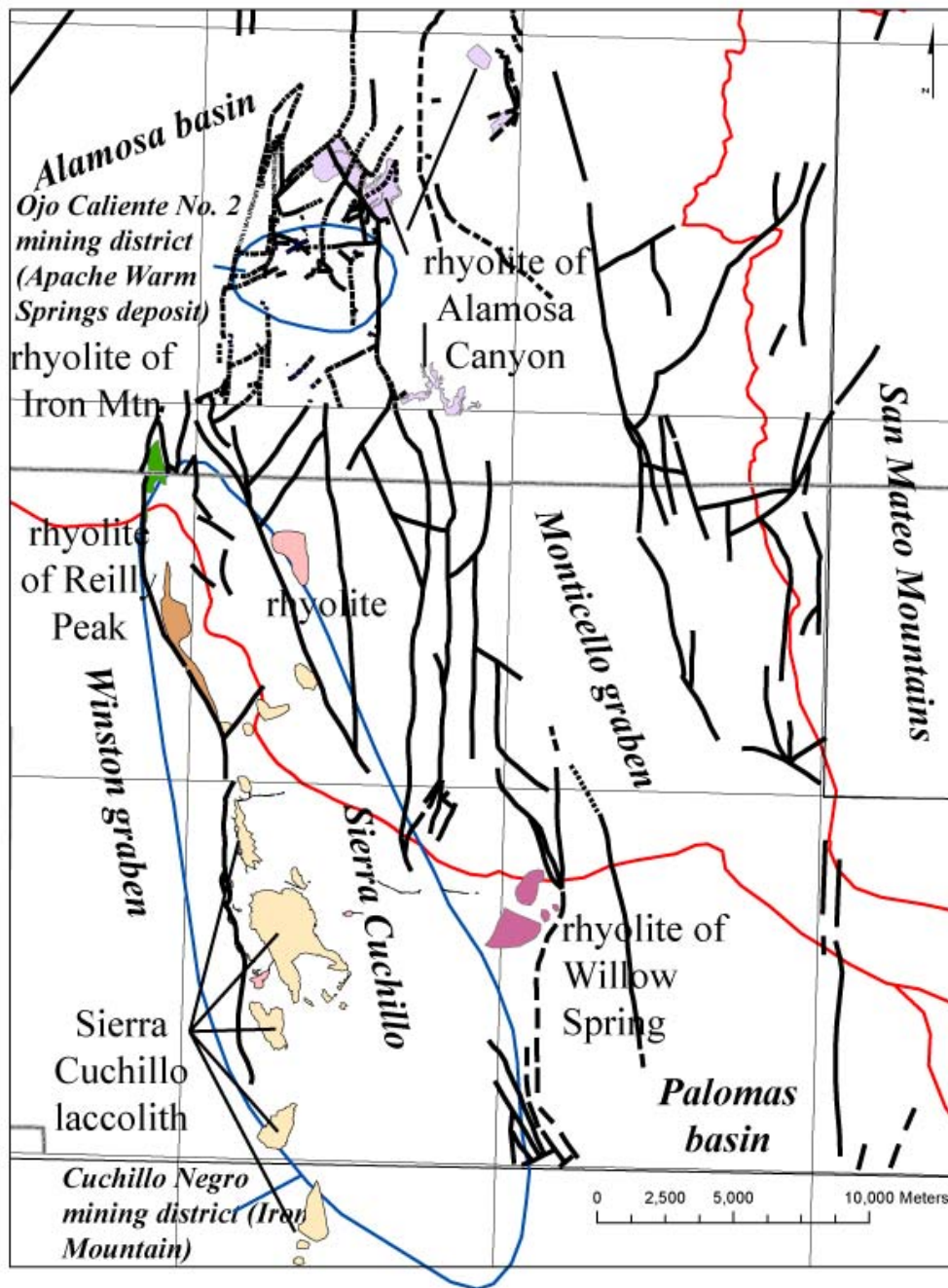
FIGURE 10. Regional structure map of the Sierra Cuchillo-San Mateo area showing the mining districts (blue) in the area (defined by McLemore, 2010a). Red line is boundary of Alamosa basin. Major granitic-rhyolite intrusions are shown in colored polygons and discussed in text. Not all rhyolite intrusions in the San Mateo Mountains are shown. Black lines are faults from Osburn (1984), Harrison (1992), Jahns et al. (2006), Ferguson et al. (2007), and McLemore (2010a).
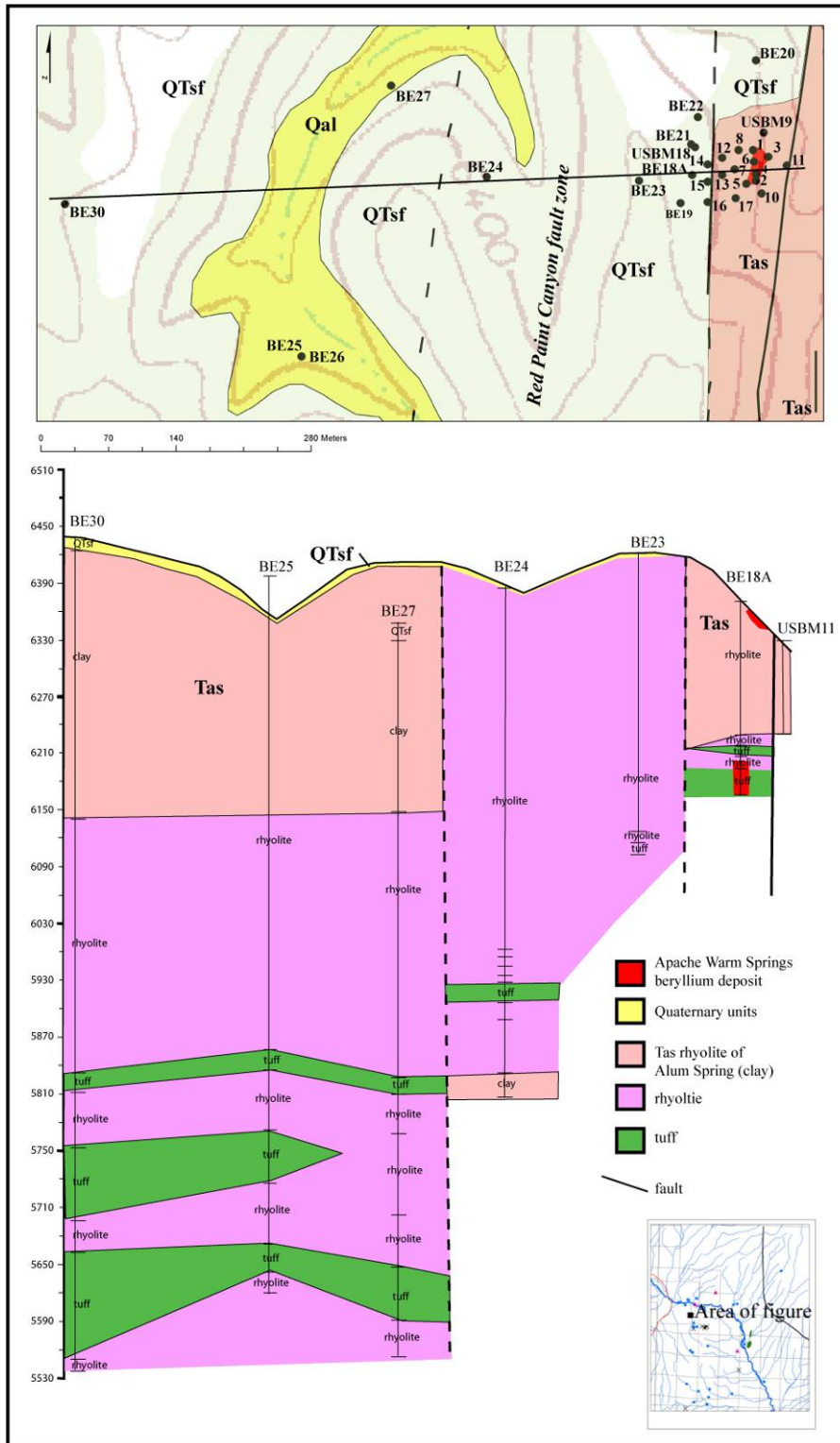
FIGURE 11. Geologic map and cross section of the Apache Warm Springs beryllium deposit and adjacent area (N section 6, T9S, R7W). Interpretations are by the author from examination of drill cuttings, using available drill data (McLemore, 2010a), and surface mapping.

FIGURE 12. 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).

FIGURE 13. Clay zone with red hematite-kaolinite and white kaolinite surrounding the Apache Warm Springs beryllium deposit (N section 6, T9S, R7W). A sample collected from the site shown on the left contains kaolinite, quartz, and hematite (Mont-35, McLemore, 2010a). A sample collected from the white clay shown in the photograph on the right contains quartz, kaolinite, illite, smectite and mixed layered clays (Mont-61, McLemore, 2010a).

FIGURE 14. Silicified zone, looking southwest. The Apache Warm Springs beryllium deposit is to the right (N section 6, T9S, R7W).
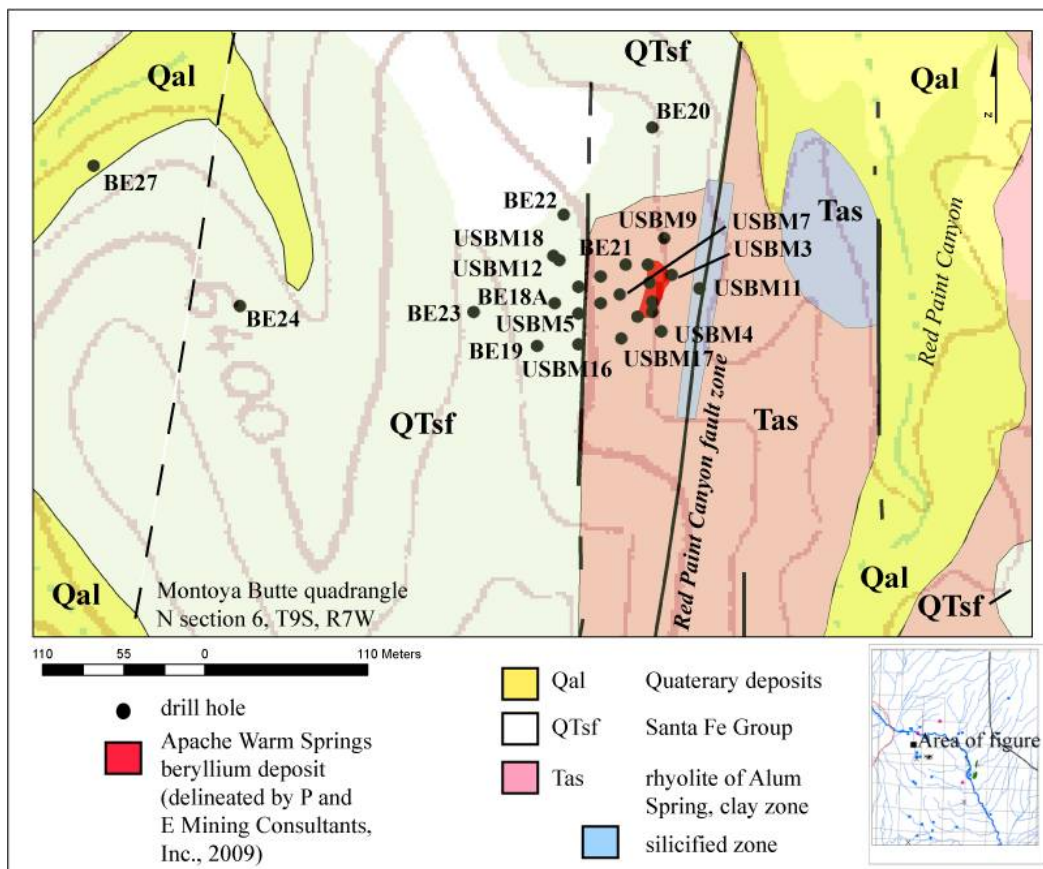
FIGURE 15. Alteration map of the Apache Warm Springs beryllium deposit. The western fault (between BE27 and BE 24) is identified from drilling data (Fig. 11; McLemore, 2010a).

Carbonate-hosted replacement and skarn deposits

Carbonate-hosted replacement and skarn (W-Mo-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 W-Mo-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, pyroxene, idocrase, and phlogopite (Holser, 1953; Warner et al., 1959; McLemore et al., 2000, 2001). Minerals in the F-Be deposits, such as those at Aguachile, Mexico (McAnulty et al., 1963) and Round Top Mountain, Sierra Blanca, Texas (Rubin et al., 1990) are predominantly fluorite, bertrandite, quartz, and clay minerals.

Victorio district (DIS114), Luna County

The Victorio (Mine Hill, Middle Hill) district is west of Deming (Fig. 2, 16) and was discovered in the late 1800s. Production of carbonate-hosted replacement Pb-Zn (Ag, Cu) deposits began about 1880. An estimated 70,000 to 130,000 short tons of ore were mined between 1880 and 1957 and yielded approximately $2.3 million worth of lead, zinc, silver, gold, and copper, including 17.5 million lbs Pb and >60,000 lbs Zn (McLemore and Lueth, 1996). Tungsten was produced during WW II. There has been no Be or Mo production.

Beryllium and tungsten skarn and vein deposits were discovered in the Victorio Mountains in the early 1900s (Griswold, 1961; Holser, 1953; Dale and McKinney, 1959). Tungsten was produced from 1942 to 1944 from the mines at Tungsten Hill (Fig. 16). In 1942, approximately 20,000 short tons of ore containing an average of 1% WO_3 were produced from the Irish Rose claim (NMLU0452), worth nearly $70,000 (Dale and McKinney, 1959). The ore contained mostly scheelite with some galena, smithsonite, and helvite. In addition, 19.6 short tons of 60% WO_3 were produced from the mine in later years.

Exploration since the 1950s has been modest; most companies were exploring for porphyry copper deposits. In 1969-1970, Humble Oil Co. drilled four holes and encountered skarns, but they did not find any significant porphyry copper deposits. Keradamex drilled two holes in 1971 without encountering any significant mineralized zones. Asarco, Rosario Exploration, Southern Union Co., Newmont, Donegan and Donegan, Leonard Resources, and Bethlehem Copper Corp. also examined the area. Gulf Minerals Resources, Inc. drilled 71 holes in 1977–1983 and delineated a porphyry Mo and Mo-Be-W skarn deposit northwest of Mine Hill and south of Middle Hills (Fig. 16). At a cut-off grade of 0.02% WO_3, resources were estimated as 57,703,000 short tons of 0.129% Mo and 0.142% WO_3 (not NI 43-101 compliant). Open pit resources were estimated as 11,900,000 short tons of 0.076% WO_3 and 0.023% Be (Bell, 1983). In 1987-1988, Cominco American Resources examined the district for gold potential and drilled 15 holes on and around Mine Hill, and found minor intercepts of mineralized zones. Santa Fe Pacific Mining, Inc., drilled 18 holes in 1990-1991 and Echo Bay Exploration, Inc., drilled 8 holes in 1993. Gage Mining Co. owns most of the patented claims on Mine Hill and the Middle Hills is mostly federal land.
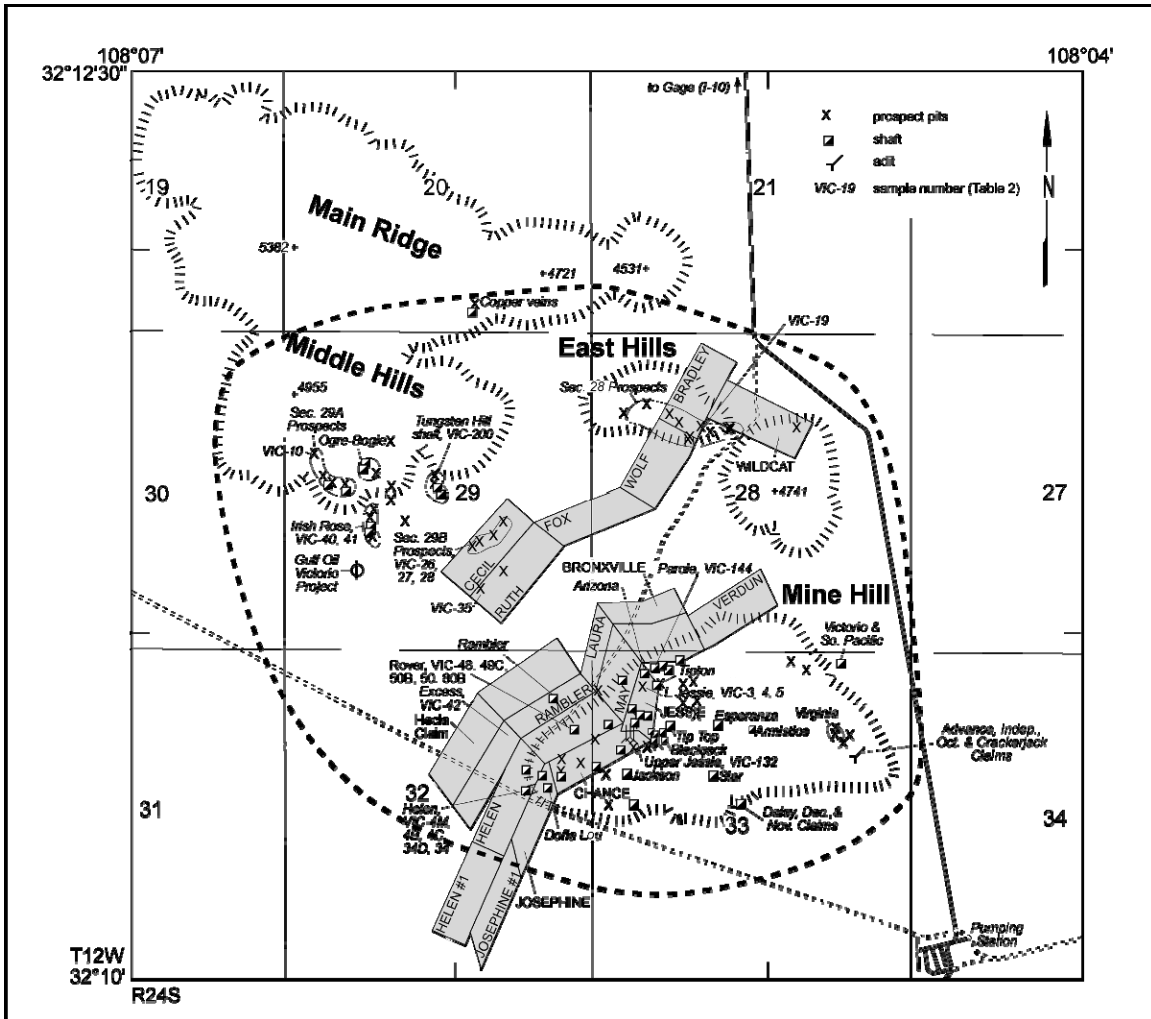
FIGURE 16. Mines and prospects in the Victorio mining district, Luna County.

Proterozoic rocks and the Cambrian-Ordovician Bliss Formation were encountered in drill cores from the Victorio district despite not being exposed at the surface (Fig. 17). Proterozoic rocks consist of quartzo-feldspathic gneiss and amphibolite. In the subsurface, the Bliss Formation is variable in thickness, ranging from 100 to 125 ft (Fig. 18; Heidrick, 1983). The Bliss Formation lies unconformably on Proterozoic basement with a 3-ft-thick basal conglomerate consisting of subangular to subrounded Proterozoic metamorphic rocks and quartz pebbles in a fine sand matrix. The next 12-20 ft is typically a clean orthoquartzite. The upper 75 ft of the Bliss Formation has two distinct lithologies, a silty quartzite unit and a limey to dolomitic siltstone. In drill core, both of these lithologies host significant W-Mo-Be skarn/vein deposits.

The oldest rocks exposed at the surface in the area are Ordovician thin- to medium-bedded limestones, dolostones, and calcarenites with chert interbeds of the El Paso Group (Figs. 17, 18; Kottlowski, 1960; Thorman and Drewes, 1980). Locally the El Paso Group unconformably overlies the Bliss Formation in the subsurface and is conformably overlain by the Montoya Group. The Fusselman Formation lies

conformably on the Montoya Group and consists of 30-900 ft of fine- to coarse-grained dolostone.
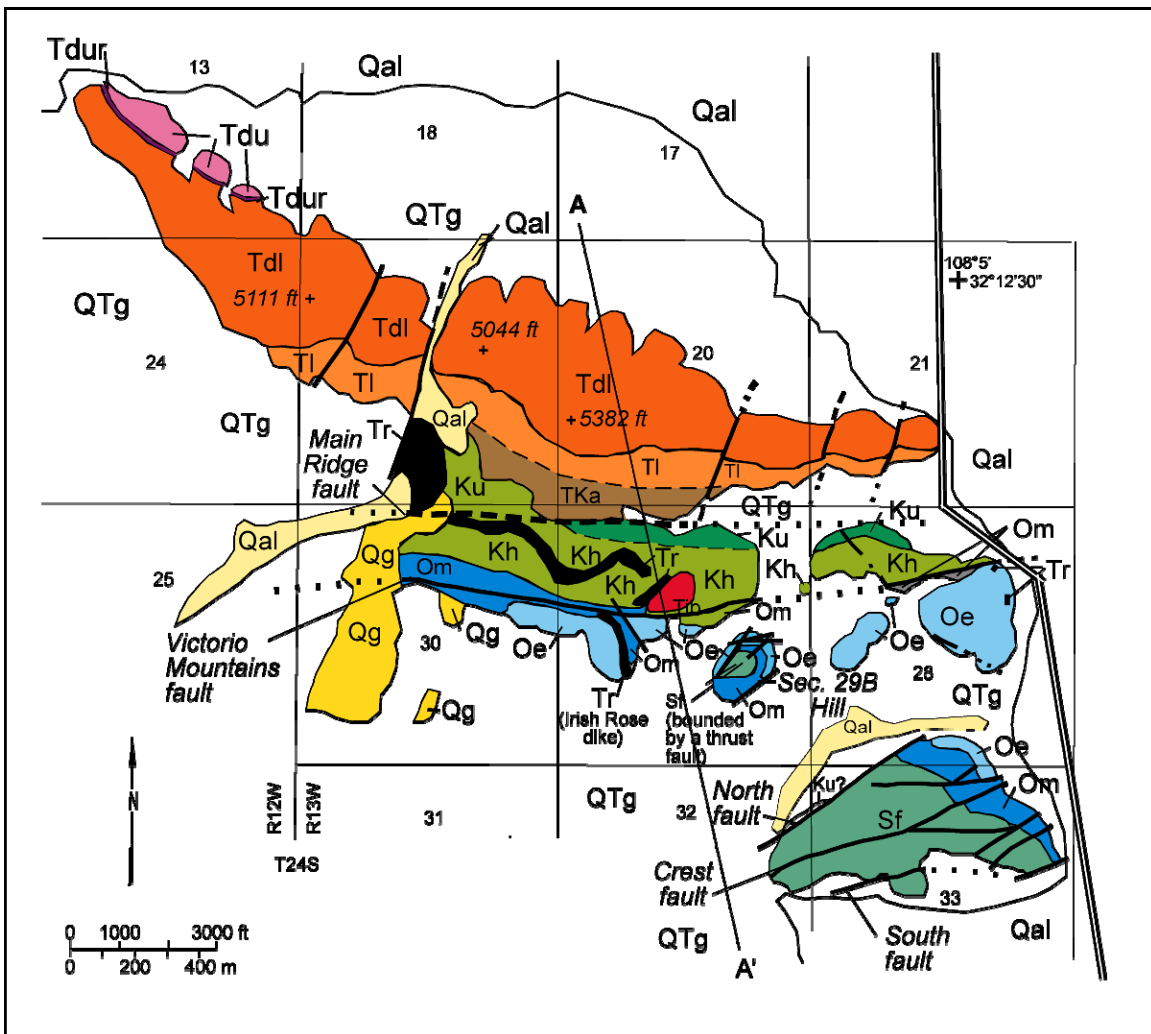
FIGURE 17. Simplified geologic map of the Victorio Mountains (modified from Kottlowski, 1960; Thorman and Drewes, 1980; unpublished mapping by Gulf Resources, Inc.; unpublished mapping by V. T. McLemore). Line A-A' is shown in Figure 18. Symbols explained in Figure 18.
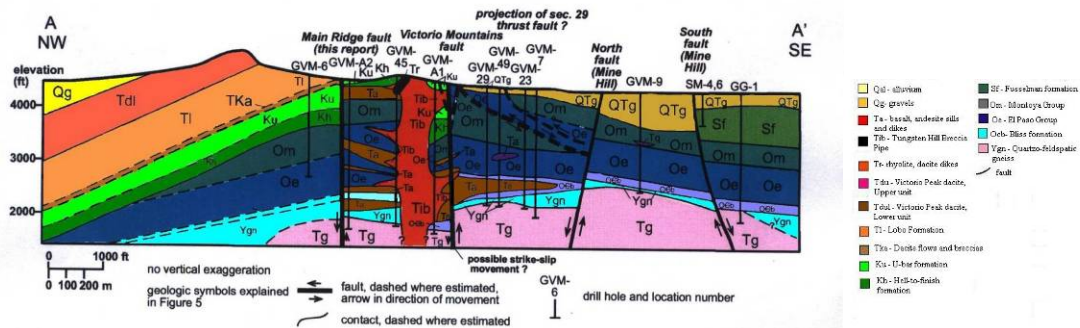
FIGURE 18. Simplified cross section of the Victorio Mountains (modified from company drill data and unpublished mapping by K. Donahue and V.T. McLemore). Some of the drill holes are projected onto the cross section. Symbols explained in Figure 17.

The Main Ridge of the Victorio Mountains is made up of Tertiary volcanic and volcaniclastic rocks, called the Victorio Peak dacite, which unconformably overlies the Lobo Formation. The Victorio Peak dacite consists of agglomerates, flow breccias, tuffs, and dacite lavas, including a 41.7±2 Ma dacite breccia (zircon, fission track; Thorman and Drewes, 1980). A 3-6-ft thick white to light gray, rhyolitic ash-flow tuff crops out in the upper part of the Victorio Peak dacite, north of the microwave towers. Ash-flow tuffs also make up South Hills, south of the mapped area shown in Figure 17. If the fission track age is correct, than the Victorio Peak dacite is correlative with the Rubio Peak Formation.

The Victorio Granite is 34.9±0.05 Ma (McLemore et al., 2000; Donahue, 2002) and it is found only in the subsurface. Based on petrographic observation, it is medium–coarse grained and consists of K-feldspar, plagioclase, quartz, biotite, ±muscovite, with trace pyrite, scheelite, apatite, garnet, fluorite, and zircon. The southern portion of the granite is a two-mica muscovite-biotite granite, whereas the northern portion is a biotite granite. The Victorio Granite mostly intrudes Proterozoic rocks, but also cuts the Bliss Formation in two drill holes (Fig. 18). Furthermore, there are several rhyolite dikes that branch upward from the main granitic body. The Victorio Granite is mostly unaltered with only small amounts of weak argillic to weak phyllic alteration. Molybdenite and scheelite also have been found in the Victorio Granite.

Sills and steeply-dipping dikes of basalt, andesite, dacite, and rhyolite porphyry intruded the Paleozoic and Cretaceous sedimentary rocks, especially in the Middle Hills area (Fig. 17, 18). The altered Irish Rose rhyolite porphyry dike at the Irish Rose mine in the Middle Hills is nearly flat lying, but cuts bedding in the limestone and dolostone. An altered rhyolite dike intruded a fault at the Rambler and Excess mines (NMLU0498, NMLU0448) at Mine Hill (Griswold, 1961). Altered andesite and rhyolite dikes also intruded the limestones and dolostones on East Hills.

A breccia pipe crosscuts the limestone in the Middle Hills (Fig. 17, 18). It consists of angular and brecciated fragments of quartz, quartz sandstone, conglomerate, limestone, granite, marble, andesite, rhyolite, quartzo-feldspathic gneiss, and is cemented mostly by quartz, rock flour, and hematite. Based on the presence of what are interpreted to be granite fragments in the breccia pipe, the breccia pipe is thought be related to a late stage of Victorio Granite crystallization. Quartz veins, some of which contain trace amounts of

pyrite and possibly molybdenite, locally cut the breccia pipe. A rhyolite dike intruded the breccia pipe and was dated as 24.8 Ma (fission track, zircon, Thorman and Drewes, 1980). These field relationships indicate that rhyolite intrusion occurred before and after formation of the breccia pipe and that the breccia pipe is younger than the marble alteration.

Based on field mapping and examination of drill core, three types of deposits have been found in the Victorio Mountains: 1) carbonate-hosted Pb-Zn replacement, 2) W-Mo-Be skarn/vein, and 3) porphyry Mo deposits. The porphyry Mo deposits are not exposed at the surface and found only in drill core in the Victorio Granite.

At the surface, the W-Mo-Be skarn/vein deposits occur as small veins and replacement lenses within the Ordovician limestones and dolostones in the vicinity of rhyolite intrusions. Samples assayed by Warner et al. (1959) ranged from 0.002 to 0.3% Be and 0.01 to 0.04% W. In drill core, nearly all of the Ordovician and Cambrian sedimentary rocks are mineralized to some extent. Based on optical examination, ore minerals include helvite, wolframite, scheelite, molybdenite, galena, sphalerite, and beryl in a gangue of quartz, calcite, and local talc, grossularite, tremolite, pyroxene, idocrase, and phlogopite (Holser, 1953; Warner et al., 1959; Richter and Lawrence, 1983; Northrop, 1996; McLemore et al., 2000). 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).

A wide range of sulfides and other metallic minerals are observed in the skarn samples (Table 8; McLemore et al., 2000), and these were examined using the microprobe. Sulfides and associated metallic phases include euhedral rods or masses of molybdenite, sphalerite, fine galena, a blocky iron sulphide, probably pyrite, Fe oxides, blocky masses of scheelite ($CaWO_4$), powellite ($CaMoO_4$), and a more-or-less complete solid solution between scheelite and powellite. The Fe oxides are typically finely dispersed throughout the sample. These metal-bearing minerals are more abundant in the samples that show distinct vein morphology as compared to the skarn replacement samples. In some samples, distinct bands of concentrated metal-bearing phases are present along vein margins, suggesting intervals of favorable conditions for ore formation during the growth of the veins. However, in other samples, the metal-bearing minerals are dispersed throughout the sample. Other phases include garnet, pyroxene, actinolite, serpentine, phlogopite, calcite, quartz, talc, and fluorite.

TABLE 8. Selected minerals found in the Victorio mining district (from Holser, 1953; Griswold, 1961; DeMark, 1992; Northrop, 1996; Beyer, 1997; McLemore et al., 2000; Gulf Minerals company reports). Minerals in bold are newly reported by McLemore et al. (2000). Type of deposit in parenthesis: 1—carbonate-hosted Pb-Zn replacement deposits, 2—W-Mo-Be skarn/vein deposits, and 3—porphyry Mo deposits.

Mineral	Chemical formula	Mineral	Chemical formula
SILICATES		**SULFIDES, SULFATES, METALS**	
Chondrodite (2)	$(Mg, Fe)_5(SiO_4)_2(F, OH)_2$	**Pyrrhotite** (1, 2, 3)	Fe_xS
Humite (2)	$(Mg, Fe)_7(SiO_4)_3(F, OH)_2$	**Marcasite** (1, 2)	FeS_2
Clinohumite	$(Mg, Fe)_9(SiO_4)_4(F, OH)_2$	Pyrite (1, 2, 3)	FeS_2
Helvite (2)	$Mn_4Be_3(SiO_4)_3S$	**Chalcopyrite** (1, 2)	$CuFeS_2$
Danalite (2)	$Fe_4Be_3(SiO_4)_3S$	Bornite (1)	Cu_5FeS_4
Willemite (1)	Zn_2SiO_4	Tetrahedrite (2?)	$(Cu,Fe)_{12}Sb_4S_{13}$
Zircon (3)	$ZrSiO_4$	Sphalerite (1, 2)	$(Zn, Fe)S$
Garnet (2, 3)	Range of compositions	**Wurtzite** (1)	$(Zn,Fe)S$
Allanite (3)	$(Y, Ce, Ca)_2(Al, Fe)_3(SiO_4)_3(OH)$	Molybdenite (2, 3)	MoS_2
Beryl (2, 3)	$Be_3Al_2Si_6O_{18}$	Gold (1)	Au

Mineral	Chemical formula	Mineral	Chemical formula
Diopside (2)	CaMgSi$_2$O$_6$	Argentite (1)	Ag$_2$S
Augite (2)	(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)$_2$O$_6$	Chlorargyrite (1)	AgCl
Tremolite (2)	Ca$_2$(Mg,Fe)$_5$Si$_8$O$_{22}$(OH)$_2$	Galena (1, 2)	PbS
Phlogopite (2)	KMg$_3$Si$_3$AlO$_{10}$(F, OH)$_2$	Anglesite (1)	PbSO$_4$
Serpentine (2)	(Mg, Fe, Ni)$_3$Si$_2$O$_5$(OH)	Friedrichite (1)	Pb$_5$Cu$_5$Bi$_7$S$_{18}$
Talc (2)	Mg$_3$Si$_4$O$_{10}$(OH)$_2$	**Galenobismutite** (2, 3)	PbSABi$_2$S$_3$
Hemimorphite (1)	Zn$_4$Si$_2$O$_7$(OH)$_2$AH$_2$O	**Bismuthinite** (2, 3)	Bi$_2$S$_3$
Quartz (1, 2, 3)	SiO$_2$		
Scapolite (2)	(Na,Ca)$_4$Al$_{3-6}$Si$_{6-9}$O$_{24}$ (Cl,CO$_3$,SO$_4$)	**OXIDES**	
		Adamite (1)	Mg$_5$B$_{12}$O$_{20}$A15H$_2$O
CARBONATES		Psilomelane (1, 2)	Mn oxide
Calcite (1, 2, 3)	CaCO$_3$	Magnetite (2, 3)	Fe$_3$O$_4$
Rhodochrosite (3)	MnCO$_3$	**Cassiterite** (2?)	SnO$_2$
Reevesite (1)	Ni$_6$Fe$_2$(CO$_3$)(OH)$_{16}$·4H$_2$O	Wulfenite (1, 2)	PbMoO$_4$
Smithsonite (1)	ZnCO$_3$	Vanadinite (1, 2)	Pb$_5$(VO$_4$)$_3$Cl
Cerussite (1)	PbCO$_3$	Mimetite (1)	Pb$_5$(AsO$_4$)$_3$Cl
Beyerite (2)	(Ca, Pb)Bi$_2$(CO$_3$)$_2$O$_2$	Descloizite (1)	PbZn(VO$_4$)(OH)
Bismutite (2)	Bi$_2$(CO$_3$)O$_2$		
Aurichalcite (1)	(Zn, Cu)$_5$(CO$_3$)$_2$(OH)$_6$	**OTHER**	
Kettnerite (1)	CaBi(CO$_3$)OF	Fluorite (2, 3)	CaF$_2$
		Kolfanite (1)	Ca$_2$Fe$_3$O$_2$(AsO$_4$)$_3$A2H$_2$O
TUNGSTATES		Bromargyrite (1)	AgBr
Scheelite (2)	CaWO$_4$	Carminite (1)	PbFe$_2$(AsO$_4$)$_2$(OH)$_2$
Powellite (2)	CaMoO$_4$	Beudantite (1)	PbFe$_3$(As,O$_4$)(SO$_4$)(OH)$_6$
Hübnerite (2)	MnWO$_4$	Pyromorphite (1)	Pb$_5$(PO$_4$)$_3$Cl
Wolframite (1, 2)	(Fe, Mn)WO$_4$		
Stolzite (2)	PbWO$_4$		

Detailed fluid inclusion studies by Donahue (2002) indicate the porphyry deposit has homogenization temperature range of 208-315°C and salinities between 2-11.9 eq. wt.% NaCl (Table 9). The skarn deposits have a range of homogenization temperatures of 180-350ºC and salinities 2-22.5 eq. wt.% NaCl. The carbonate-hosted deposits have homogenization temperatures of 105-289ºC and salinities <2-5 eq. wt.% NaCl. Campbell and Robinson-Cook (1987) found that fluid inclusions in wolframite from the Victorio mining district had temperatures of homogenization of 280–380ºC and salinities of 5.4-8.9 eq. wt. % NaCl. Quartz fluid inclusions had temperatures of homogenization of 141-320ºC and salinities of 1.3–10 eq. Wt. % NaCl. Fluid inclusion gas analysis results shows the possible origins of the fluids, the majority of the Victorio samples fall on the boundary and just outside the magmatic water box (Fig. 19). The field relationships, fluid inclusion, stable isotopes, and paragenesis indicate a continuum between the porphyry molybdenum, skarn, and carbonate-hosted replacement deposits.

TABLE 9. Summary of all fluid inclusion results. Figure below illustrates the classification used to identify the fluid inclusion type (From Donahue, 2002).

Deposit	Type	Size Range micron (ų)	Th range degrees	Th ave degrees	Salinity range eq. wt% NaCl	Salinity ave eq. wt% NaCl
Carbonate-hosted replacement	Ia, IIa, IIb, IIc	<2-15	109 - 350	213	0.8 - 19.3	8.8
Mine Hill siliceous veins	Ia, IIa, IIb, IIc	<2-10	109 - 350	217	0.8 - 4.1	2.1
E109 non-oxidized	Ia	<2-5	151 - 257	209	10.2 - 19.3	12.9
Skarn	Ia, Ib, IIa, IIb, III	<2-40	171 - 360	242	0.02 - 25.6	6.6
Barren qtz veins	Ia, Ib, IIa, IIb	<2-40	199 - 340	278	3.1 – 10.9	5.9
Porphyry	Ia, Ib, IIa, IIb	<2-10	179 - 325	255	2.0 - 11.2	6.1
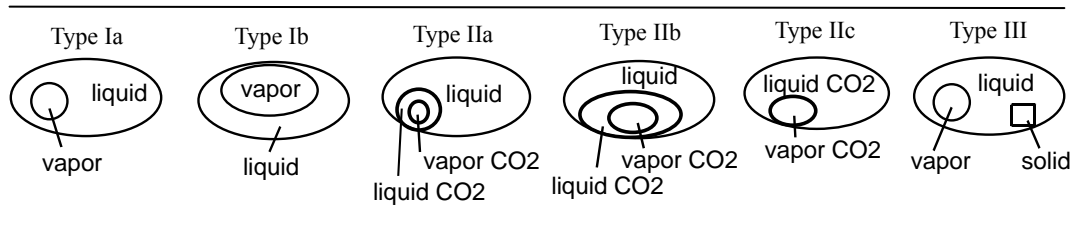
A paragenesis is in Figure 20 and mineral zonation is in Figure 21. Four stages of mineralization occurred: early contact-metasomatic alteration with the intrusion of the granite, deposition of scheelite-molybdenum-quartz, ±other minerals, retrograde mineralization and deposition of quartz, calcite, sulfides, and other minerals, and the last stage, the deposition of carbonate-hosted replacement deposits with sulfides and minor gold and silver (McLemore et al., 2000; Donahue, 2002).

The distribution and composition of W-Be-Mo skarn/vein deposits appear to be stratigraphically controlled. In the Bliss Formation, the three major lithologies have distinct differences in Mo-W ratios, vein thickness, and vein density. Lenses of dense mineralization occur in some Bliss lithologies, whereas others are nearly barren. The calcium-poor orthoquartzite contains very little scheelite, which occurs as thin veinlets. The silty glauconitic facies is richer in calcium and has intermediate tungsten values. The molybdenite in this facies is vein-controlled while the scheelite is predominantly disseminated. The silty limestone facies contains enough calcium to precipitate significant disseminated scheelite. The veins in this facies are thicker and more common. Molybdenum mineralization is primarily vein-controlled with minor dissemination. There also is a strong positive correlation between disseminated and vein-controlled W-Mo mineralization and disseminated fluorite mineralization (Heidrick, 1983).

Gulf Minerals Resources, Inc. drilled 71 holes in 1977-1983 and delineated a porphyry Mo and Mo-Be-W skarn deposit, northwest of Mine Hill, south of the Middle Hills at depths ranging from 800 to 1400 ft. Ore minerals include molybdenite, powellite, scheelite, beryl, helvite, bismuthinite, and wolframite (Table 8). At a cut off grade of 0.02% WO$_3$, resources were estimated as 57,703,000 short tons of 0.129% Mo and 0.142% WO$_3$. Open pit resources were estimated as 11,900,000 short tons of 0.076%

WO$_3$ and 0.023% Be (Bell, 1983). Galway Resources currently controls the property and the reported resources are in Table 10 (Raffield et al., 2008; Knudsen, 2008). The project is on hold until there is an improvement in the price of Mo and W. Currently, there are no plans to recover the Be because of recovery and metallurgical difficulties.

◇ GVM 21 1493.5 porphyry
⊗ GVM 8 1889 skarn
☐ GVM 41 1925.5 skarn
△ GVM 59 1702 skarn
∘ VIC 12-99 skarn
○ BRECCIA breccia pipe
+ E109 1942 carb-host replc
✛ RAMBLER carb-host replc
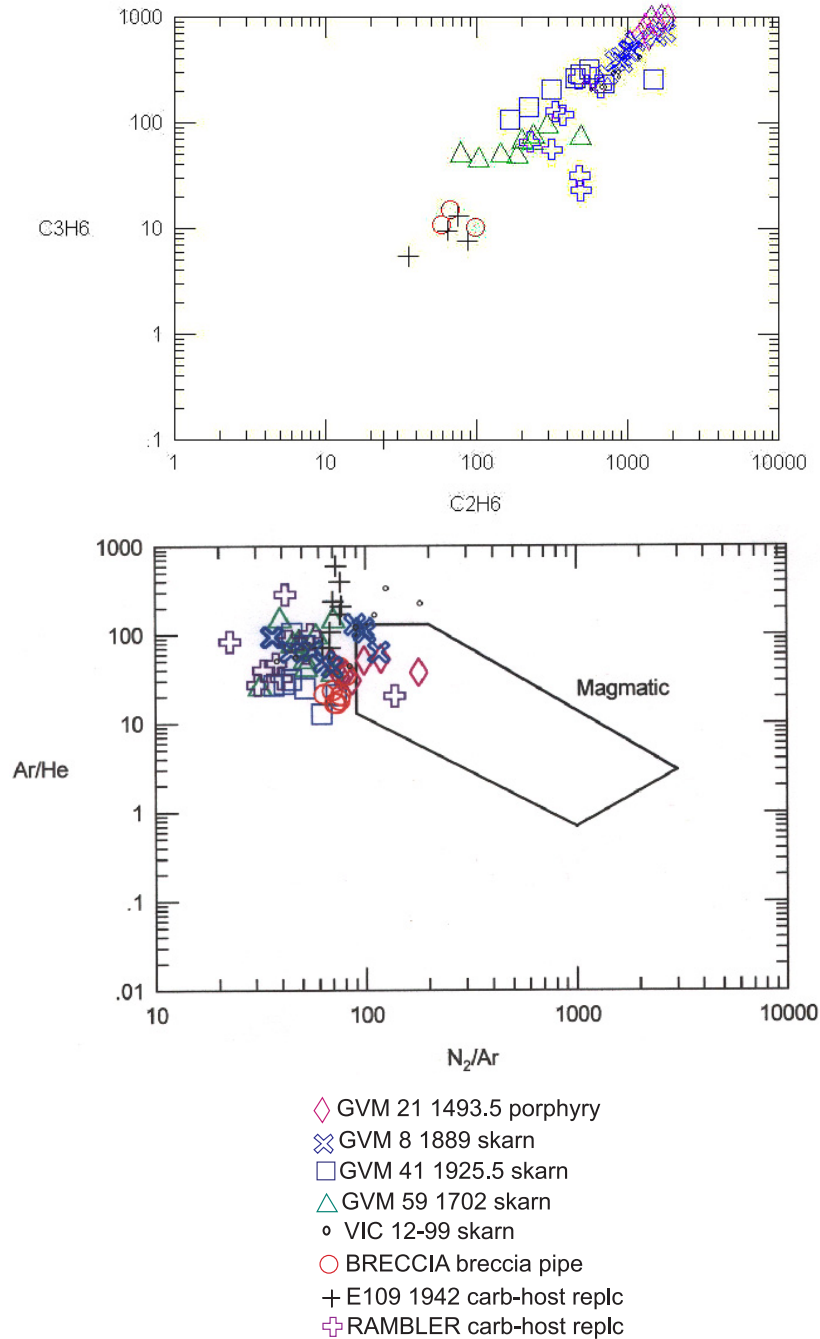
FIGURE 19. Fluid inclusion gas analysis results showing the possible origins of the fluids, the majority of the Victorio samples fall on the boundary and just outside the

magmatic water box. The fluid origin fields defined in Norman and Moore (1997). Magmatic water box defined from Blamey and Norman (2002).
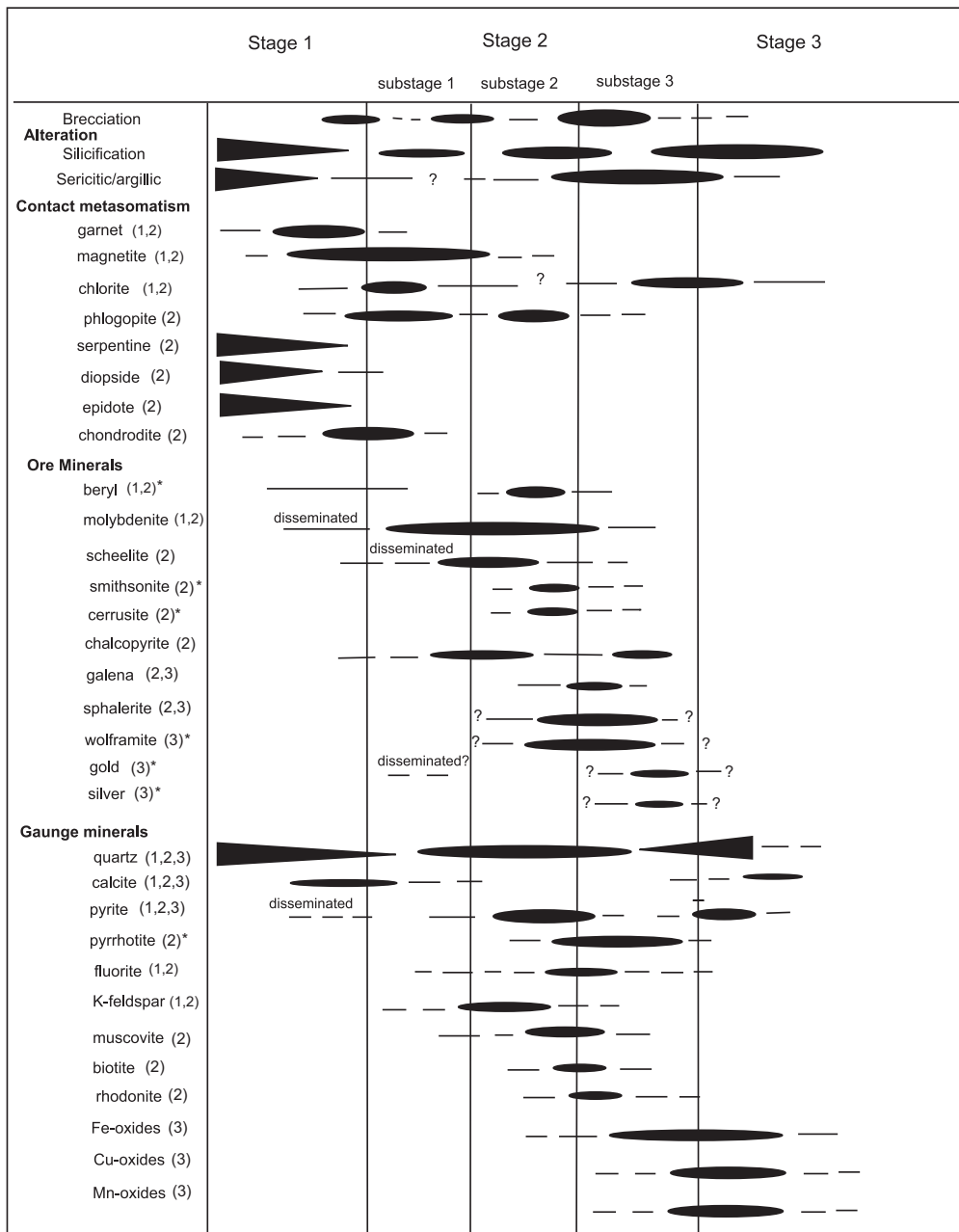
FIGURE 20. Relative paragenetic sequence for the Victorio mining district showing the mineral relationships and alteration events (from Donahue, 2002). The paragenetic sequence is for all three types of deposits. 1 = porphyry Mo , 2 = skarn, 3 = carbonate-hosted replacement deposit, * = mineral not seen in drill core relative paragenesis taken from literature (Heidrick, 1983). Core samples in (Donahue, 2002) were used to determine the paragenesis.
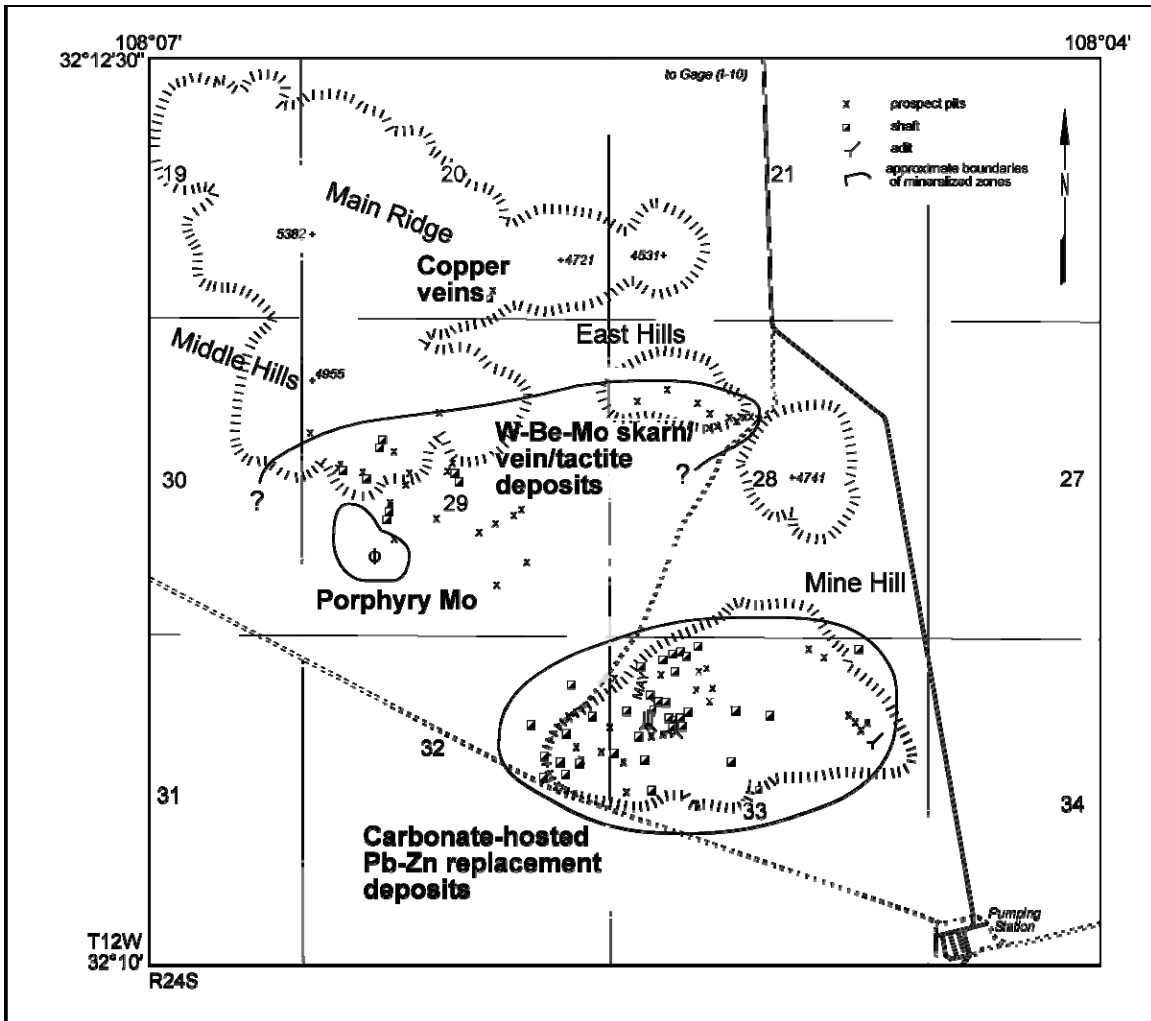
FIGURE 21. Mineral zonation in the Victorio Mountains mining district.

TABLE 10. Current mineral resources of the Victorio deposit (NI43-101 compliant from Knudsen, 2008).

Resource category	$Cuttoff (value/ton)	Total short tons	Grade Mo%	Grade WO3%
Measured	$25	37.7	0.1	0.08
Indicated		39.5	0.08	0.09
Inferred		77.2	0.07	0.09
Measured	$35	20.3	0.12	0.11
Indicated		19.1	0.1	0.12
Inferred		34.7	0.1	0.11

Iron Mountain, Cuchillo Negro district (DIS192), Sierra County

Iron Mountain is the northern part of the Cuchillo Negro district, in the Sierra Cuchillo mountain range, south of the Apache Warm Springs deposit in the Ojo Caliente No. 2 district (Fig. 10). Sierra Cuchillo is a monoclinal block with a gentle dip slope of 25° to the east and a mountain scarp to the west. It is structurally complex and is cut by numerous steeply dipping faults. Most of the range consists of Cambrian-Ordovician through Cretaceous sedimentary rocks and Tertiary volcanic rocks that are intruded by

Tertiary monzonite, quartz monzonite, latite, felsite, and rhyolite stocks, dikes, and sills (Fig. 10; Jahns et al., 1978, 2006). Beryllium, tungsten, and iron have been produced from limestone adjacent to Tertiary rhyolite at the Iron Mountain deposits (Lovering and Heyl, 1989).

Two periods of granitic-rhyolitic rocks have intruded the Paleozoic sedimentary section in the Sierra Cuchillo and San Mateo Mountains, which are separated by andesite to latite flows and breccias; the older event is >38-36 Ma and the younger is 27-29 Ma (Fig. 10; McLemore, 2010a). Similar age relationships are found in the Black Range (Harrison, 1992). The oldest intrusion is the Sierra Cuchillo porphyritic granodiorite to quartz monzonite laccolith in the southern portion of the Sierra Cuchillo (Fig. 10), and is 38.2±0.9 Ma (U-Pb on zircon, Michelfelder, 2009). The Reilly Peak rhyolite is 36.0±1.4 Ma (K-Ar, Davis, 1986a, b) and could be related to the Sierra Cuchillo laccolith because of similar major- and trace-element composition (Fig. 10, Davis, 1986a, b; Michelfelder, 2009; McLemore, 2010a) and the imprecise K-Ar age date. The Reilly Peak rhyolite was originally called monzonite porphyry by Jahns (1944a, b) and is intruded by younger rhyolite dikes and stocks. However, the monzonite plugs intruding the latite of Montoya Butte (36 Ma, McLemore, 2010a) and andesite of Monticello Box also are similar in geochemical composition to the Sierra Cuchillo laccolith and Reilly Peak rhyolite, which suggests continuous intrusive activity could span for ~2 Ma. More age determinations are required. These older intrusions could be related to the Emory caldera (34.9 Ma) in the Black Range to the southwest because of similar age and chemical composition to the Kneeling Nun Tuff that erupted from that caldera.

The Sierra Cuchillo consists of three types of intrusions; monzonite porphyry (Sierra Cuchillo and Reilly Peak laccoliths; Jahns, 1978; McMillan, 1979; Davis, 1986a, b; Michelfelder and McMillan, 2009), rhyolite porphyry, and rhyolite aplite (Jahns, 1978; Robertson, 1986). The Sierra Cuchillo and Reilly Peak laccoliths are fine-grained monzonite to granite to rhyolite and have been dated as 36-38 Ma (Davis, 1986a, b; Michelfelder and McMillan, 2009). The rhyolite porphyry intruded sedimentary rocks in the western Sierra Cuchillo and has been dated as 22.6 Ma (Davis, 1986a, b). It is pink to gray and contains 40-50% phenocrysts (orthoclase, quartz) in a groundmass of orthoclase, quartz, oligoclase, and trace biotite, apatite, magnetite, zircon, and fluorite. The rhyolite aplite is pink with local miarolitic to pegmatitic textures and consists of orthoclase, quartz, oligoclase, and trace biotite, apatite, fluorite and topaz. This rhyolite was dated as 29.2±1.1 Ma (Chapin et al., 1978), but is younger than the rhyolite porphyry as determined by field relationships (Jahns, 1944a, b; Robertson, 1986). More age determinations are required on the younger rhyolites.

The youngest granitic-rhyolitic rocks are found throughout the Sierra Cuchillo and San Mateo Mountains as dikes, stocks, and lavas. In the Sierra Cuchillo, porphyritic rhyolite and rhyolite aplite intruded the Paleozoic rocks and older granitic-rhyolitic rocks; the rhyolite aplite intrudes the porphyritic rhyolite (Fig. 10; Jahns, 1944; Robertson, 1986). K-Ar dating of these rhyolites is imprecise and ranges from 29.2±1.1 Ma at Iron Mountain to 22.6±0.8 Ma at Reilly Peak (Fig. 10; McLemore, 2010a). The Iron Mountain rhyolite porphyry is pinkish gray and contains 40-50% phenocrysts of orthoclase and quartz in a fine-grained groundmass of orthoclase, quartz, and oligoclase with minor biotite, apatite, magnetite, zircon, and fluorite. The Iron Mountain rhyolitic aplite is light pink, equigranular, and consists of orthoclase phenocrysts in a fine-grained matrix of

quartz, orthoclase, and oligoclase with minor biotite, apatite, fluorite, and topaz. The Reilly Peak rhyolite is white to gray, fine-grained, and consists of albite, quartz, and minor biotite, titanite, epidote, muscovite, hematite, amphibole, apatite, and magnetite (Davis, 1986a, b). The Reilly Peak rhyolite is 36.0±1,4 Ma (K/Ar, Davis, 1986a, b). The porphyritic rhyolite at Reilly Peak is 22.6±0.8 Ma (K/Ar, Davis, 1986a, b) and the Iron Mountain rhyolitic aplite is 29.2±1.1 Ma (K/Ar; Chapin et al., 1978; Robertson, 1986). Better age determinations exist for the rhyolite of Willow Spring in the eastern Sierra Cuchillo and in the San Mateo Mountains. The rhyolite of Willow Springs (or Willow Springs dome) is 28.2±0.5 Ma (U-Pb on zircon, Michelfelder, 2009) to 27.8±1.0 Ma (fission track, Heyl et al., 1983).

Three types of skarns are found at Iron Mountain; coarse massive andradite (Sn), banded garnet-magnetite (W, F), and ribbon rock or banded skarn (Fig. 22; F, Be). Adularia from scheelite skarn was 27.3±0.6 Ma (Davis, 1986a). Most of the beryllium is found in the ribbon rock, which consists of magnetite, hematite, fluorite, helvite, and trace garnet, diopside, idocrase, and chlorite. The beryllium is difficult to recover (Kennedy and O'Meara, 1948). The NURE stream-sediment sample with the highest Be concentration (38 ppm) is from near the Iron Mountain beryllium deposit in the Cuchillo Negro district.

FIGURE 22. Ribbon rock is a specific banded alteration with beryllium, mostly as helvite.

Round Top, Sierra Blanca, Texas

Sierra Blanca, Texas is south of the Cornudas Mountains in southern New Mexico, and is part of the Trans-Pecos alkaline magmatic province (Fig. 23, 24). Sierra Blanca consists of five rhyolite domes or laccoliths (Round Top, Little Round Top, Little Blanca, Sierra Blanca and Triple Hill). The rhyolites are mildly peraluminous, 36.2 Ma (Henry et al., 1986), and enriched in Li, Be, F, Zn, Rb, Y, Zr, Nb, Sn, REE, and Th (Rubin et al., 1987, 1989). Fluorspar replacement bodies, enriched in Be, Zr, REE, and other elements are found at the contacts of the laccoliths and Cretaceous limestones (Shannon, 1986; Shannon and Goodell, 1986; Rubin et al., 1988).

In 1984-1985, Cabot Corporation drilled and found Be-F veins and replacements of limestone adjacent to the rhyolite dome at Round Top Mountain (Fig. 25). An 1115-ft decline was constructed by Cyprus Sierra Blanca, Inc., successor to Cabot Corporation, and the West End Structure was reported to contain 300,000 short tons of 1.9% BeO at a cutoff grade of 0.5%, or 11 million pounds of BeO. The entire project area was reported to contain 25 million pounds of BeO (Standard Silver Corporation, 2008). In 1993, Cyprus merged with Amax becoming Cyprus-Amax, which subsequently merged with Phelps Dodge in 1999. Grades exceeding 1% U are found in the deposits. Currently Standard Silver Corporation owns the mineral deposit.

The Round Top Mountain rhyolite intruded Cretaceous limestone and was subsequently hydrothermally altered (Fig. 25; fluoritization, kaolinization). The rhyolite is gray, fine grained with visible local flow banding contains a variety of minerals (Table 11). Nearby Sierra Blanca rhyolite is 36.2±0.6 Ma (K/Ar, biotite, Henry et al., 1986) and Round Top Mountain rhyolite is likely similar in age. The rhyolite domes at Sierra Blanca are enriched in Li, Be, F, Zn, Rb, Y, Zr, Nb, Sn, REE, and Th and depleted in Mg, Ca, and Ti relative to typical calc-alkaline rhyolites (Fig. 25; Rubin et al., 1987). Chemically, the rhyolite is alkaline, peralkaline to slightly peraluminous and similar to topaz-bearing rhyolites (Fig. 26). Chondrite-enriched REE patterns exhibit depleted light REE and negative Eu anomaly (Fig. 26). Beryllium occurs mostly in contact metasomatic veins and replacements in limestones as behoite ($Be(OH)_2$), with lesser amounts of berborite (Be_2 $(BO_3)(OH,F) \cdot H_2O$), bertrandite, chrysoberyl, and phenakite and also contains fluorite and garnet (McAnulty, 1980; Rubin et al., 1987, 1989, 1990; Price et al., 1990).
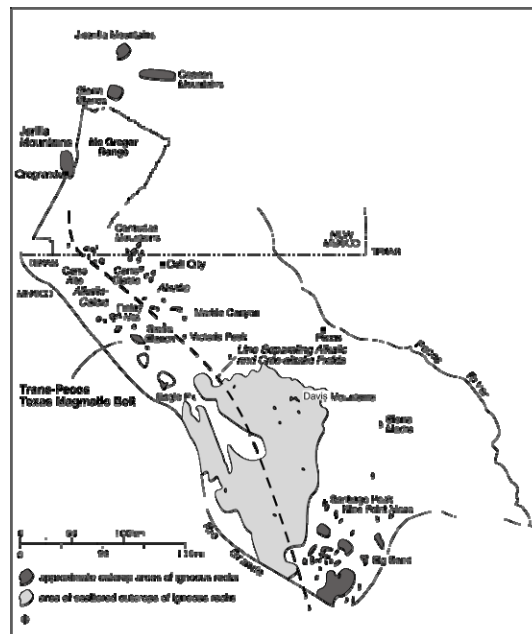
FIGURE 23. Trans-Pecos magmatic province, New Mexico and Texas (modified from Barker, 1987; Price et al., 1987).

FIGURE 24. Sierra Blanca, looking north.

TABLE 11. Selected minerals reported from the Sierra Blanca, Texas (Rubin et al., 1987, 1990; Price et al., 1990).

Mineral	Occurrence	Formula
Albitic plagioclase	Rock forming mineral	
K-feldspar	Rock forming mineral	
quartz	Rock forming mineral	SiO_2
biotite	Rock forming mineral	
Li-mica	Rock forming mineral	
Magnetite	Rock forming mineral, contact metasomatic deposit	
fluorite	Rock forming mineral, contact metasomatic deposit	
cassiterite	contact metasomatic deposit	SnO_2
changbaiite	contact metasomatic deposit	$PbNb_2O_6$
cryolite	contact metasomatic deposit	Na_3AlF_6
ferrocolumbite	contact metasomatic deposit	$FeNb_2O_6$
thorite	contact metasomatic deposit	$ThSiO_4$
yttrocerite	contact metasomatic deposit	$(Y,REE)F_3$
zircon	Rock forming mineral, contact metasomatic deposit	$ZrSiO_4$
fluellite	Vapor phase mica	$AlF_3 \cdot 4H_2O$
thomsenolite	Vapor phase	$NaCaAlF_6 \cdot H_2O$
zunyite	Vapor phase mica	$Al_{13}Si_5O_{20}(OH,F)_{18}Cl$
garnet	Contact metasomatic deposit	
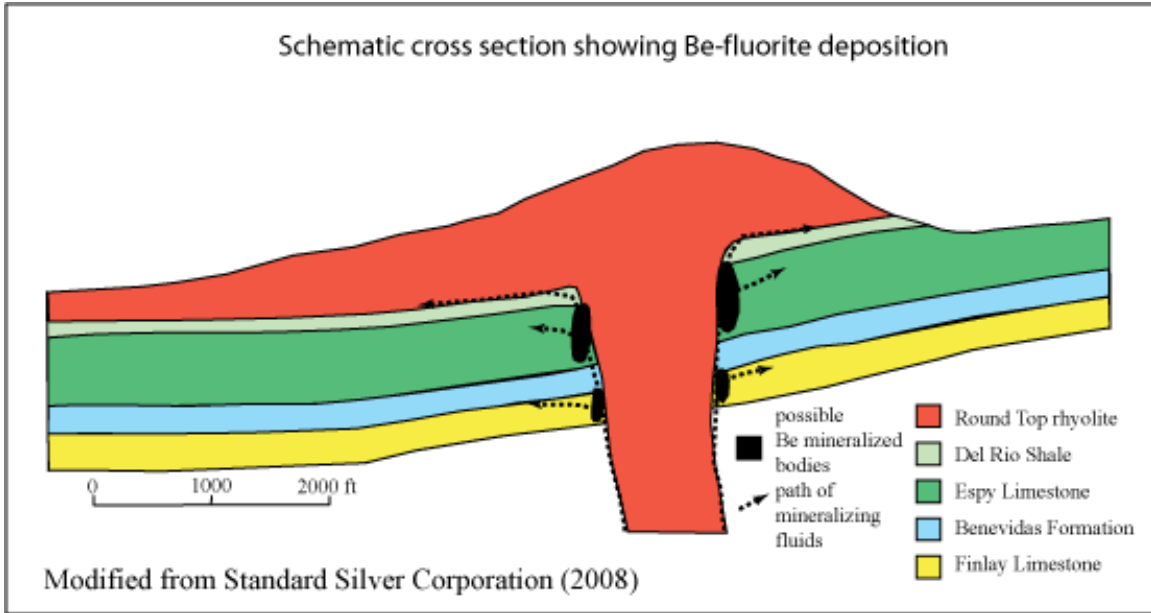
FIGURE 25. Schematic cross section showing Be-fluorite deposition at Round Top Mountain, Sierra Blanca, Texas (modified from Standard Silver Corporation, 2008).
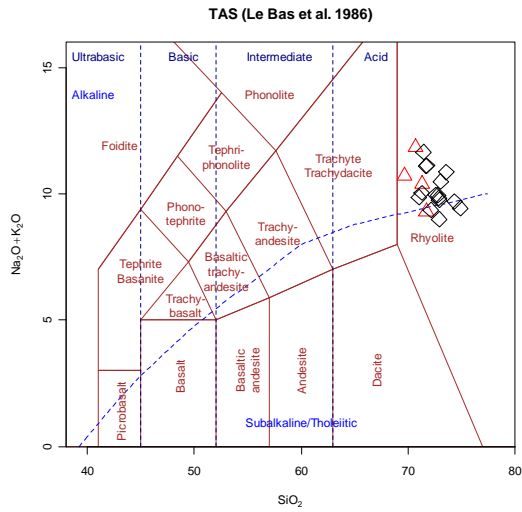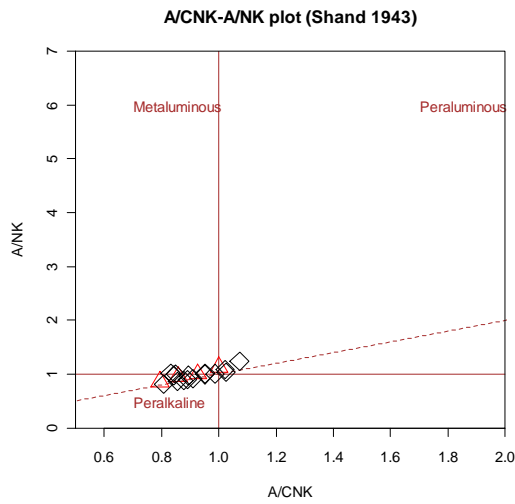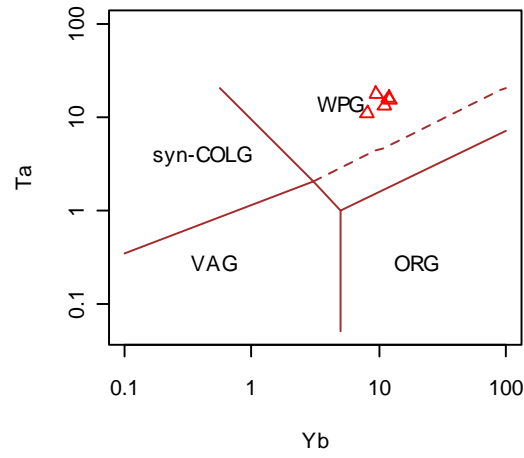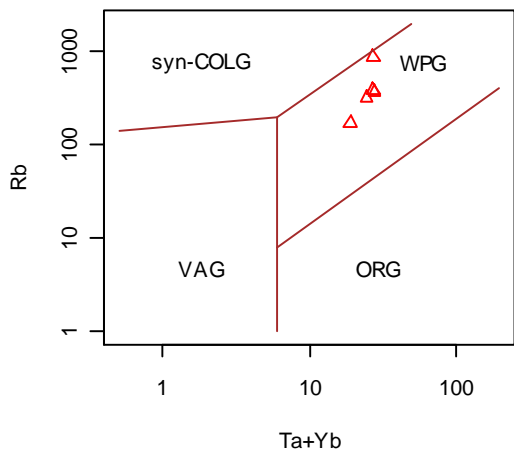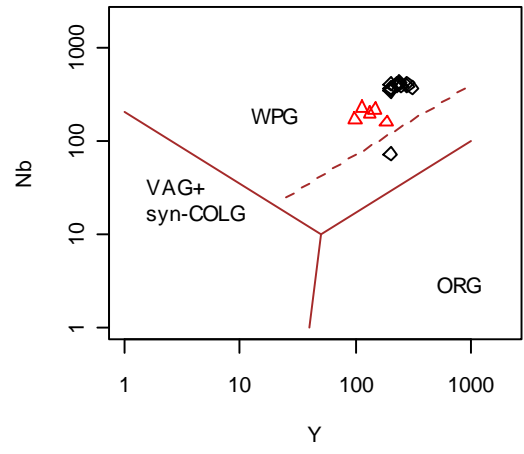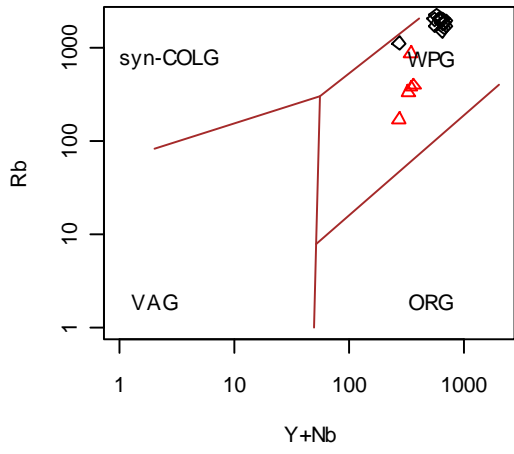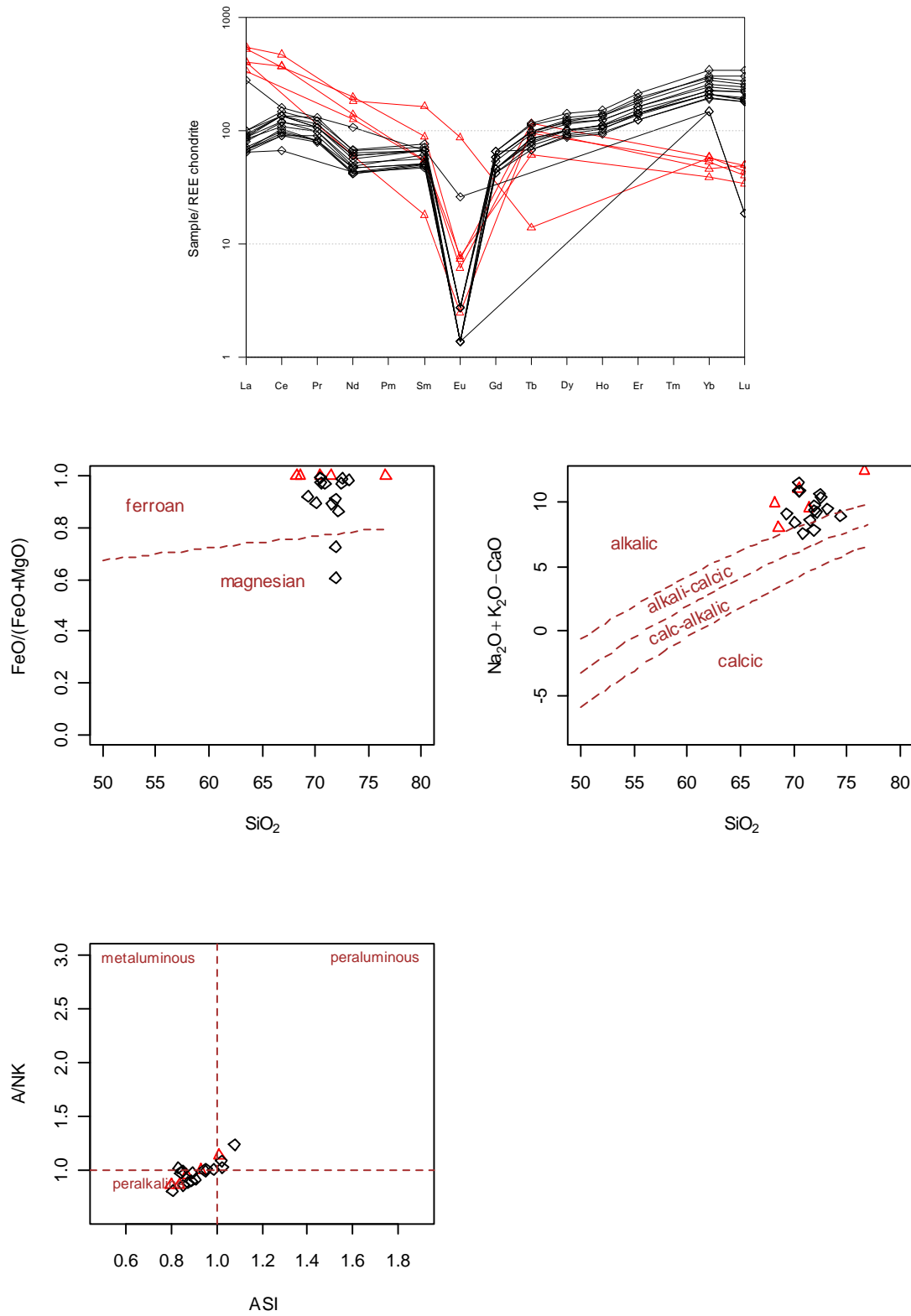
FIGURE 26. Chemical plots of the Sierra Blanca (black diamonds) and Aguachile (red triangles) rhyolites.

Aguachile, Coahuila, Mexico

The Aguachile Be-F-U deposit, east of Big Bend National Park, Texas, is one of the eastern-most of the fluorite deposits in Mexico (Levinson, 1962; McAnulty, 1963; Simpkins, 1983) and also is part of the Trans-Pecos alkaline magmatic province (Fig. 2, 23). Aguachile Mountain is a collapse caldera and is surrounded by rhyolite domes that intruded Cretaceous limestones and a plug of microsyenite intruded the rhyolite. Rhyolite and basanite ring dikes surround the dome and plug. Be-U-F veins, breccias, and replacements are found in limestone adjacent to the rhyolite dikes and contain fluorite, calcite, quartz, hematite, limonite, and minor amounts of aragonite, powellite, adularia, kaolinite, gypsum, sericite, and bertrandite (Levinson, 1962; McAnulty, 1963). The major ore body at Aguachile contains 0.1-0.3% BeO and beryllium is found only in the immediate Aguachile area. Three periods of fluoritization are recognized (Fig. 27; McAnulty, 1963). Chemically the rhyolite is alkaline, peralkaline to slightly peraluminous and similar to topaz-bearing rhyolites (Fig. 26). Chondrite-enriched REE patterns exhibit enriched light REE and negative Eu anomaly (Fig. 26). 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). The paragenesis is summarized in Figure 27.
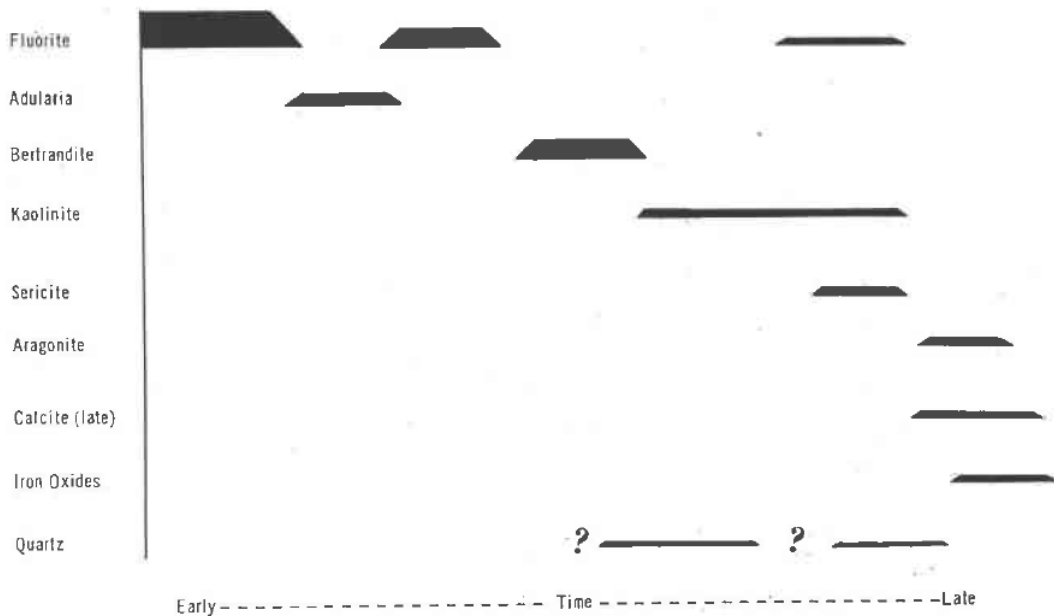
FIGURE 27. Paragenesis of the Aguachile deposit (Levinson, 1962; McAnulty, 1963).

Carpenter district (DIS049), Grant and Sierra Counties

The Carpenter (or Swartz, Schwartz) mining district occurs on the western slope of the Mimbres Mountains (Fig. 2) and in the 1880s, base-metals deposits were discovered at the Royal John property. The first recorded mining venture in the area was in 1906-07 at the Royal John by ASARCO and then by Albert Owen of the Black Range Mining Company. At least five mines in the district have produced Zn, Pb, and Cu with minor amounts of Ag and Au. The Royal John mine is the district's largest producer having reported sporadic production from 1916 until at least 1969. Total production from

the district from 1891 to 1969 was approximately 12.5 million pounds Zn, 6 million pounds Pb, 310,000 lbs Cu, 60,000-180,000 oz Ag, and 300 oz Au (McLemore et al., 1996c).

The area lies within a horst of Paleozoic sedimentary rock between the north-trending Mimbres fault on the west and the Owens fault on the east. West of the Grandview mine, mid-Tertiary andesite and rhyolite flows cover the sedimentary units. The mineral deposits consist chiefly of small and low-grade skarn and replacement deposits in the Montoya Dolomite, and are related to rhyolitic plutons of Oligocene age (34.8H.2 Ma, Hedlund, 1977). Most of the veins are fault controlled, and the skarns containing bedded-replacement deposits are well developed in the upper silicified cherty beds of the El Paso limestone (Hedlund, 1985). At the Royal John mine, replacement bodies are within a horst bounded by the Owens and Grandview faults, which strike N10-25ºW. Galena and sphalerite are the principal ore minerals and are associated with quartz, calcite, chalcopyrite, and pyrite. Calc-silicate minerals, such as abundant garnet, epidote, chlorite and magnetite, occur locally in the altered limestone. Helvite was found in Cu-Pb-Zn skarns with fluorite, scheelite, and chalcedony at the Grandview mine and samples from the mine contained as much as 0.02% BeO (Weissenborn, 1948; Warner et al., 1959). A sample of the mill concentrate contained 0.01% BeO (Warner et al., 1959). A NURE stream-sediment sample near the area contained 5 ppm Be (Appendix 2).

Alkaline igneous rocks in New Mexico containing beryllium deposits

Some alkaline igneous rocks, typically syenite or alkali-granite, 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, 1943). 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 beryllium 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 in New Mexico contain anomalous concentrations of beryllium; a syenite sample from the Caballo Mountains contained 600 ppm Be (Appendix 3). Samples from the Cornudas Mountains assayed as much as 0.2% BeO (Warner et al., 1959). Additional investigations are required to properly assess the beryllium resource potential of these rocks. The Trans-Pecos alkaline magmatic province form part of the southern portion of the North American Cordilleran alkaline igneous belt and includes beryllium deposits at Sierra Blanca, Cornudas and Hueco Mountains, and Agua Chile, Mexico. The North American Cordilleran alkaline igneous belt is a diffuse region of Cenozoic igneous rocks that extends along the eastern margin of the North American Cordillera from Alaska and British Columbia southward into Trans-Pecos Texas and eastern Mexico (Fig. 23; Barker, 1977, 1979, 1987; Mutschler et al., 1985, 1991; Woolley, 1987, McLemore et al., 1996a, b). Laughlin Peak and Gallinas Mountains are part of this belt (Fig. 1, 2).

Caballo Mountains (DIS190), Sierra County

The Caballo Mountains is an east-dipping fault block along the eastern Rio Grande Rift (Fig. 2) and consists of rocks ranging in age from Proterozoic to Recent. The

predominant Proterozoic rocks are the Caballo granite and Longbottom granodiorite that are separated by a section of supracrustal amphibolite and felsic gneiss (Condie and Budding, 1979; Bauer and Lozinsky, 1986; McLemore, 1986). Cambrian-Ordovician brick-red syenite dikes and pipes have intruded the Proterozoic rocks locally and contain local high concentrations of REE, Th, U, and Be (Melancon, 1952; Boyd and Wolfe, 1953; Staatz et al., 1965; McLemore, 1986; unpublished data). Paleozoic and Mesozoic sedimentary rocks and Tertiary volcanic and sedimentary rocks unconformably overlie the Proterozoic rocks (Kelley and Silver, 1952; Mason, 1976; Seager and Mack, 1991, 2003). Structural relationships are complex, as Proterozoic, Paleozoic, Laramide, and mid-Tertiary tectonic events have deformed the rocks.

Numerous radioactive, brick-red, flat-lying tabular bodies and near-vertical pipes of syenite intrude the Proterozoic granite in the central Caballo Mountains near Caballo Gap and in the Red Hills area in the southern Caballo Mountains (Staatz et al., 1965; Condie and Budding, 1979; McLemore, 1986). Small, discontinuous pockets of U, Th, and REE minerals are found locally in the syenite and consist of spinel, rutile, anatase, thorite, thorogummite, and uraninite. One syenite sample contained 600 ppm Be. The tabular bodies and pipes consist of microcline with subordinate quartz, muscovite, hematite/goethite, chlorite, and trace of plagioclase with accessory apatite, zircon, calcite, fluorite, limonite, magnetite, and barite. Lithologies range from syenite to quartz syenite to alkali granite. Metasomatism of the adjacent granite is common.

Cornudas Mountains (DIS142), Otero County

The Cornudas Mountains are in southern Otero County, New Mexico and northern Huspeth County, Texas and are part of the Trans-Pecos alkaline belt (Fig. 23). The Cornudas Mountains have been examined for potential deposits of U, Be, REE, Nb, Au, and Ag (McLemore and Guilinger, 1993; Schreiner, 1994; Nutt et al., 1997); but there has been no production except for test shipments of nepheline syenite for use as sand-blasting material in 1995.

In the 1950s, prospectors located several areas of anomalously high radioactivity in the Cornudas Mountains and attributed it to the presence of U. Shallow prospect pits were dug on many of the claims in the area; but, assay results were very low and the claims were later dropped with no production (Table 12, Fig. 23). In 1956, the U.S. Atomic Energy Commission examined the area to evaluate the potential for U (Collins, 1958). No further work was recommended. Beryllium was first reported from the Cornudas Mountains during the 1940s (Warner et al., 1959). In 1984, Leonard Minerals Co. in conjunction with U.S. Borax Corp. conducted an exploration program for REE, Nb, and Zr. Mapping, sampling, and drilling in the Chess Draw area failed to discover any significant mineralized zones (NMBGMR files).

The Cornudas Mountains consist of 10 larger sills, plugs, and laccoliths (Fig. 28, Table 12) and smaller dikes and plugs that intrude relatively flat-lying limestones and other sedimentary rocks of the Hueco Limestone and Bone Spring Limestone (Permian). Other dikes, sills, and plugs are buried by sedimentary cover as indicated by subsurface drilling (King and Harder, 1985), geophysical surveys, and structural anomalies (i.e. folds, synclines, faults) in the overlying sedimentary rocks. Wind Mountain is one of the largest intrusions with an approximate diameter of 2.5 km and is mineralogically, texturally, and chemically zoned (McLemore et al., 1996a, b).

TABLE 12. Description of igneous intrusive bodies within the Cornudas Mountains. Bodies shown in Figure 9.

Name	Form	Predominant lithology	Age Ma	References
Alamo Mountain	phonolite, foliated porphyritic nepheline syenite	discordant sheet or sill	36.8 ± 0.6 (K/Ar on biotite)	Barker et al. (1977), Clabaugh (1941), Henry et al. (1986)
Flat Top Mountain	phonolite, augite syenite dike	sill	—	Barker et al. (1977); Clabaugh (1941)
Cornudas Mountain	quartz-bearing syenite, syenite, trachyte	plug or laccolith	34.6 ± 1.5 (K/Ar on biotite)	Barker et al. (1977), Zapp (1941), Henry et al. (1986)
Wind Mountain	nepheline syenite, phonolite, porphyritic nepheline syenite	laccolith	—	Barker et al. (1977), Warner et al. (1959), McLemore and Guilinger (1993)
San Antonio Mountain	nepheline syenite	laccolith	—	Timm (1941), Barker et al. (1977)
Deer Mountain (Little Wind Mountain)	nepheline syenite	plug or laccolith	33.0 ± 1.4 (K/Ar on biotite)	Barker et al. (1977), Clabaugh (1941, 1950), Henry et al. (1986)
Chatfield Mountain	phonolite	sill	—	Timm (1941), Barker et al. (1977)
Black Mountain	porphyritic nepheline syenite	sill	—	Barker et al. (1977)
Washburn Mountain	porphyritic nepheline syenite	sill	—	Timm (1941), Barker et al. (1977)
Unnamed hill	nepheline-bearing augite syenite	plug	36.8 ± 0.6 (K/Ar on biotite)	Barker et al. (1977), Clabaugh (1941), Henry et al. (1986)

The Wind Mountain laccolith consists of six mineralogical and textural zones (McLemore et al., 1996a, b; McLemore and Guilinger, 1996). The laccolith is typically gray to cream colored and weathers to darker colors. Accessory minerals form dark-colored aggregates dispersed throughout the rock. The margin of the laccolith is foliated. The foliation dips steeply away from the center of the intrusive body. Chemical variations among the individual map units within the laccolith cannot be readily discerned by utilizing major element analyses (McLemore et al., 1996a, b). However, significant chemical differences in Ba and Sr between the nepheline syenite and syenite units are observed. The syenites contain more Ba and Sr than the nepheline syenites (McLemore et al., 1996a, b). These chemical analyses of the Wind Mountain laccolith suggests that the zonation appears to be controlled by crystal fractionation, volatile separation, and cooling history, not different pulses of magma (McLemore et al., 1996b). Feldspar crystallization under initially subsolvus conditions can account for most of the variations in the zones (McLemore et al., 1996a, b). The feldspar-rich solid forms at or migrates towards the top of the magma chamber and forms a capping syenite. Differential cooling of the magma resulted in the textural variations at Wind Mountain. The outer zone ($TNSP_2$) is most suitable for use in manufacturing amber-colored beverage containers, flatware, and ceramics.

Past exploration for U and Th has been unsuccessful. Uranium and thorium occur disseminated within the dikes and intrusions and are not economic. Assays ranged from 0 to 0.8% U_3O_8 (Collins, 1958) and 13-351 ppm Th (Schreiner, 1994). Past exploration for beryllium in the Cornudas Mountains was inconclusive. A few samples assayed as much as 0.2% BeO (Warner et al., 1959). Beryllium occurs in feldspar, nepheline, aegirine, and eudialite within dikes, sills, and laccoliths in the Cornudas Mountains; no beryllium minerals have been identified. In the Chess Draw area (NMOt0009), northwest of Wind Mountain, only one sample contained 150 ppm Be, whereas the remaining samples from that area contained less than 100 ppm Be (U.S. Borax, written communication, January

1986; McLemore and Guilinger, 1993; Schreiner, 1994; Goodell et al., 2002). Exploration should concentrate along the intrusive contacts between the Tertiary intrusions and Permian limestones for the potential discovery of a replacement beryllium deposit similar to that found at Sierra Blanca, Texas.

The abundant rare mineralogies at Wind Mountain (Table 13) suggest the area has potential for undiscovered deposits of REE, Nb, Be, and Zr (Nutt et al., 1997; Goodell et al., 2002). The igneous rocks probably have no potential because of the low concentrations (Schreiner, 1994; Nutt et al., 1997); however, areas surrounding the intrusions could have potential for Be, REE, Nb, and other elements. U.S. Borax sampled and drilled in the Chess Draw area, but their assays were low (up to 0.06% total REE oxides, 10-1,400 ppm Nb, 10-3,000 ppm Zr, 230-13,000 ppm F). Analyses reported by Schreiner (1994) are also low and subeconomic, as much as 3,790 ppm total REE, 2,332 ppm Nb, 92 ppm Be, and 3,137 ppm F. Additional geophysical and geochemical studies followed by drilling are required to properly assess the resource potential in the area surrounding the intrusions.
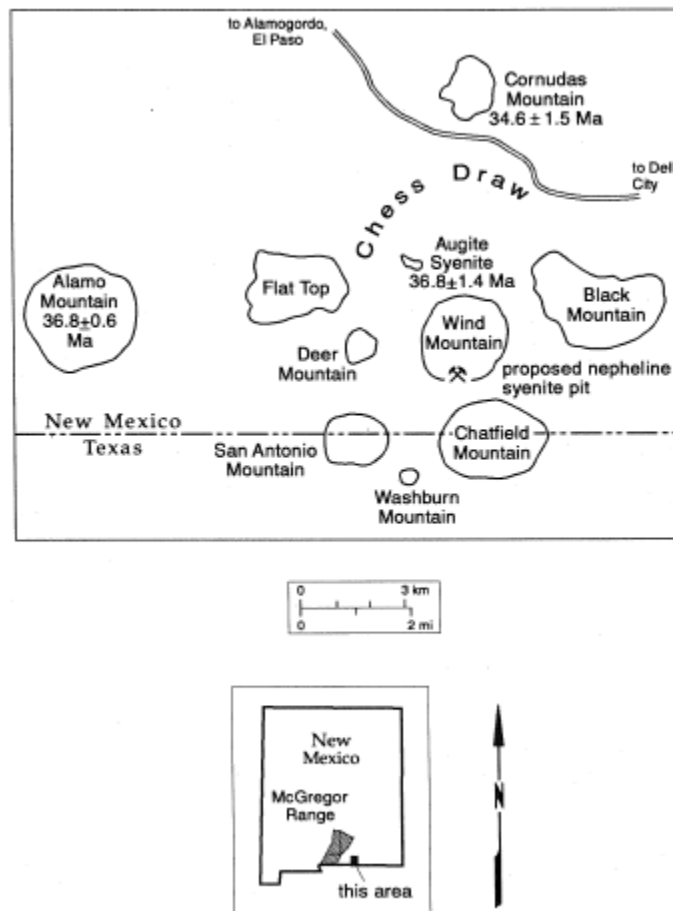
FIGURE 28. Location map of Cornudas Mountains.
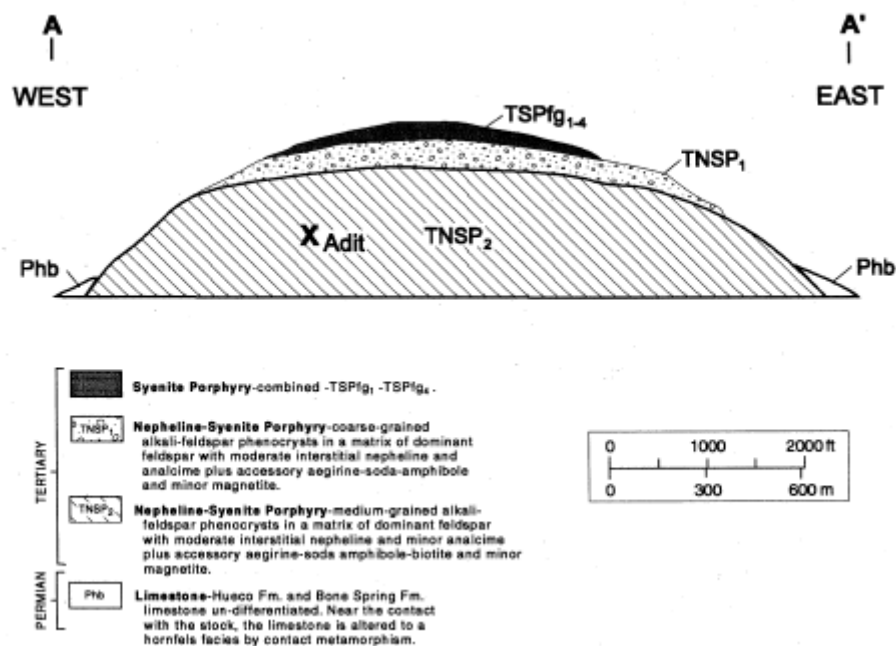
FIGURE 29. Schematic cross-section of Wind Mountain.

TABLE 13. Selected minerals and their occurrence reported from the Cornudas Mountains. Chemical formulae of rare species: [1]$Na_4(Ca, Ce)_2(Fe^{2+}, Mn^{2+}) YZrSi_8O_{22}(OH,Cl)_2$; [2]$Na_2ZrSi_3O_9 .2H_2O$; [3]$NaKZrSi_3O_9 \cdot 2H_2O$; [4]$Na_2ZrSi_2O_7$

Mineral	Occurrence	Reference
anaclime	replaces nepheline, lines vugs, vesicles and miarolitic cavities	Barker and Hodges (1977), Boggs (1985)
natrolite	replaces nepheline and feldspars	Barker and Hodges (1977)
olivine	mineral aggregates of ferromagnesian minerals and magnetite	Barker and Hodges (1977)
aenigmatite	in nepheline syenite	Barker and Hodges (1977)
eudialyte[1]	in dikes, sills, and laccoliths and in miarolitic cavities	Barker and Hodges (1977), Clabaugh (1950), Boggs (1985, 1987)
catapleiite[2]	miarolitic cavities	Boggs (1985)
georgechaoite[3]	miarolitic cavities	Boggs (1985), Boggs and Ghose (1985)
aegirine (acmite)	miarolitic cavities	Boggs (1985, 1987)
monazite	miarolitic cavities	Boggs (1985)
thomosonite	miarolitic cavities	Zapp (1941), Boggs (1985)
chabazite	miarolitic cavities	Boggs (1985)
parakeldyshite[4]	nepheline syenite, Wind Mountain	McLemore et al. (1996a)
pyrite	mineral aggregates of ferromagnesian minerals	McLemore et al. (1996a)
fluorite	breccia	Barker et al. (1977)

Hueco Mountains district (DIS255), Otero County

The Hueco Mountains are on the Fort Bliss McGregor Range in southern Otero County and also are part of the Trans-Pecos alkaline belt (Fig. 23). The igneous rocks are 34.5-34.7 Ma (McLemore, 2002) and are similar in age and chemical composition to those in the Cornudas Mountains. The main intrusive rock in the northern Hueco Mountains is the Red Hills syenite (McLemore, 2002). It is gray and black, and weathers to a dark reddish brown. The syenite is medium grained and consists of plagioclase

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phenocrysts (as much as 2 cm long) in a fine-grained groundmass of biotite, plagioclase, K-feldspar, pyroxene, and magnetite. Nepheline or quartz is present in small amounts locally. Syenite to trachyte dikes intruded the stock locally. These dikes are very fine-grained, are gray to brown, weather reddish brown, and consist of plagioclase, K-feldspar, iron oxides, and quartz. Syenite to trachyte dikes also are found as ring dikes partially surrounding the Red Hills syenite. Locally these dikes are highly altered with liesegang banding, indicating low-temperature fluid migration. Syenite sills cut the adjacent limestone. Thin skarns are exposed at or near the contact locally. Geochemical compositions of the igneous rocks suggest that the magma probably originated within the lithospheric mantle and acquired a significant enrichment in lithophile-group elements during its movement through the crust (McLemore, 2002). These data are consistent with either a continental rift or a subduction-related back-arc extension setting.

There is no reported precious- or base-metal production from the northern Hueco Mountains; however, one prospect pit was found during reconnaissance in 1997. The Red Hills prospect pit (NMOt0019) is in the Hueco Mountains and is 10 ft long, 0-10 ft deep, and 6 ft wide (McLemore, 2002). The pit exposes a hornfels and magnetite-hematite replacement body within a limestone xenolith of Pennsylvanian Panther Seep Formation in the Tertiary syenite. The hornfels is green to green-gray and consists of iron oxides, calcite, quartz, epidote, chlorite, and a trace of pyrite. The magnetite-hematite replacement body is brown to black and consists of magnetite, hematite, iron oxides, quartz, calcite, and a trace of pyrite. Samples of white to gray, silicified limestone from the waste dump contained calcite, quartz, iron oxides, and a trace of pyrite and malachite.

Silicified and recrystallized limestone beds of the Pennsylvanian Panther Seep Formation are found locally within several hundred to 1000 ft of the intrusive contact with the nepheline syenite. The altered zones are typically less than 1 ft thick and consist of quartz, calcite, iron oxides, and locally trace amounts of pyrite.

A large undeveloped jasperoid body is exposed along a hillside northeast of the Red Hills syenite in section 6 and 7, T26S, R9E. The jasperoid is approximately 100 ft long and up to 40 ft wide. It consists of jasper, iron oxides, quartz, and unmineralized limestone. The unmineralized limestone is cut by iron-oxide and jasper veins. Two samples of the jasperoid contained 85 and 92.3% SiO_2 and 30 and 27 ppm Be (McLemore, 2002). The resource potential for beryllium was estimated as low to moderate (New Mexico Bureau of Mines and Mineral Resources et al., 1998). The area is withdrawn from mineral entry.

Laughlin Peak district (DIS020), Colfax County

The Laughlin Peak district consists of Oligocene alkaline (trachyte, trachyandesite, phonotephrite, phonolite, lamprophyre, and carbonatite) rocks that have intruded Triassic through Cretaceous sedimentary rocks. Mineralized breccia pipes are common. Carbonatite dikes intrude phonotephrite and are 0.3-0.6 m wide, 1-2 m long, radioactive, dark brown to gray, fine- to medium-grained, and consists of calcite (70-95%), magnetite (5-10%), biotite and phlogopite (5-15%), apatite (5-10%), hematite (5-15%), and trace amounts of fluorite, sphene, K-feldspar, dolomite, and amphibole. Calcite crystals are 0.1-0.3 mm in diameter and rimmed by hematite and biotite. Embayed and corroded magnetite crystals, 0.8-0.9 mm in diameter, are rare. Thin carbonate veins fill fractures adjacent to the carbonatites. Selected samples from the

district contained as much as 0.007% BeO (Warner et al., 1959). Total REE content ranges from 100 to 30,000 ppm in the Laughlin Peak district (Staatz, 1985). Samples of the veins and breccias contained less than 17 ppm Be (Schreiner, 1991).

Gallinas Mountains district (DIS092), Lincoln County

The Gallinas Mountains are in northern Lincoln County where a series of alkaline igneous intrusions, including porphyritic latite, trachyte, syenite, andesite, and rhyolite laccoliths, dikes and plugs, have intruded Permian sedimentary rocks belonging to the Abo, Yeso, and Glorieta Formations (Perhac, 1970; McLemore, 2010c). Trachyte has been dated as 29.2 Ma by K-Ar dating methods on feldspar (Perhac, 1970). Alteration includes brecciation, silicification, chloritization, and fenitization (Griswold, 1959; Woodward and Fulp, 1991; Schreiner, 1993; McLemore, 2010c). Carbonatites are inferred at depth by the presence of fenitization, carbonatization of the breccias, presence of REE and similarity of the intrusive rocks and mineralization to areas with carbonatites.

The Gallinas Mountains were first examined about 1881 when the Red Cloud (NMLI0040), Buckhorn (NMLI0302), and Summit (NMLI0048) mining claims were established. In 1942-1943, iron ore was produced from the American (NMLI0003) and Gallinas (NMLI0299) mines (Kelly, 1949; McLemore, 2010c). In 1951-1954, fluorite was produced from the Red Cloud and Conqueror No. 10 (NMLI0318) mines. Bastnaesite was discovered in the district about 1943 (Glass and Smalley, 1943; Soule, 1946) and approximately 142,000 lbs of bastnaesite was produced from the Red Cloud mine in the 1950s. Phelps Dodge drilled a 532-ft deep hole at the Rio Tinto (NMLI0042) mine in 1980 and Molycorp, Inc. conducted a more extensive exploration program in 1980-1981, including two drill holes (Schreiner, 1999). Other companies examined the area in 1989-1991, including Canyon Resources, Hecla Mining Co., American Copper and Nickel, Inc. and Romana Resources. Woodward and Fulp (1991) reported gold assays as high as 183 ppb in brecciated trachyte sills that intrude Yeso sandstone. Samples from the district ranged from 2 to 80 ppm Be (Warner et al. 1959).

The igneous rocks in the Gallinas Mountains are metaluminous to peraluminous, alkaline volcanic rocks, and have chemical compositions similar to A-type granitoids (McLemore, 2010c). The geochemical data suggest a crustal source for the igneous rocks. Four types of deposits are found in the Gallinas Mountains: epithermal REE-F veins, Cu-REE-F veins, REE-F breccia pipes and iron skarn deposits; all are associated with Tertiary alkaline to alkalic-calcic igneous rocks. District zonation is defined by Cu-REE-F (±Pb, Zn, Ag) veins that form center of the district, surrounded by REE-F veins (Fig. 30). The magmatic-hydrothermal breccia pipe deposits form a belt partially surrounding the veins. Iron skarns formed at the top and edge of the trachyte/syenite body and are likely the earliest stage of mineralization. The iron skarns are probably related to the REE-F veins and breccias because they typically contain bastnaesite and fluorite and are similar in trace element geochemistry. The paragenesis is defined by four stages of brecciation and faulting with three stages of fluorite deposition. REE minerals were deposited during the 1st and 2nd stage of fluorite deposition. A genetic model is summarized by intrusion/extrusion of crustal-derived igneous source rock in an extensional terrain possibly related to an alkaline-carbonatite complex with mineralization related to mixing of magmatic-hydrothermal and formation fluids.

FIGURE 30. Mineral zoning in the Gallinas Mountains, Lincoln County, New Mexico, based upon predominant mineralogy and chemistry of the known deposits (McLemore, 2010c).

Granite/rhyolites (topaz rhyolites) and tin skarns in New Mexico

Topaz rhyolites are compositionally distinct, less common high-silica rhyolites that are metaluminous to slightly peraluminous, high-silica rhyolites that are enriched in F, Be, Li, Rb, Cs, Ga, Y, Nb, U, Th, 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 (Burt and Sheridan, 1981; Christiansen et al., 1983). 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. The Taylor Creek rhyolite is a topaz-bearing rhyolite. The rhyolites at Spor Mountain also 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). The rhyolite of Alamosa Canyon, rhyolite of Alum Springs, and 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), but topaz has not been found in the other rhyolites in the Sierra Cuchillo or San Mateo Mountains. Topaz rhyolites appear to be evolved from partial melts of Proterozoic lower crust in an extensional tectonic setting, which is consistent with the formation of the younger 27-29 Ma rhyolites in the Sierra Cuchillo and San Mateo Mountains. The older Reilly Peak rhyolite, Sierra Cuchillo laccolith, and monzonite plugs in the Montoya Butte quadrangle are more similar to other calc-alkaline rhyolites, not topaz rhyolites, and could represent a transition between older arc-related Laramide volcanism and younger extensional Rio Grande volcanism (McMillan et al., 2000).

Beryllium minerals are found in tin skarn deposits associated with granites and rhyolites, but rarely in economic concentrations (Cox and Singer, 1986). 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.

Taylor Creek district (DIS204), Catron, Sierra, and Socorro Counties

At Taylor Creek, 20 vents were active with pyroclastic flows, falls, and surges. The first stage of eruption was followed by extrusion of rhyolite flows forming domes (Duffield et al., 1990; Duffield and Dalrymple, 1990). The tin was in the rhyolite magma and as the lava cools and devitrifies, the tin differentiates into the outer rind of the lava. Four types of tin deposits are found in the altered Oligocene-Miocene rhyolite domes and tuffs in the Taylor Creek district, NM (Correa, 1980; Eggleston, 1983; 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. Subsequent low-temperature convection mobilizes them along faults and within permeable tuffs and rhyolites (Burt and Sheridan, 1981; Duffield et al., 1990). A similar origin is proposed for the Be-U-F deposits at Spor Mountain, except that the rhyolites were erupted through

carbonate sedimentary rocks, which aided in concentration of the beryllium. Beryllium is reported in trace amounts in the tin-bearing deposits and rhyolites. Topaz rhyolites are known to be enriched in REE, Be, U, and other elements. A sample from one of the tin prospects in the Taylor Creek area contained 0.002% BeO (Warner et al., 1959). The topaz rhyolites associated with the Taylor Creek tin deposits contain as much as 20 ppm Be (Webster and Duffield, 1994).

East Grants Ridge district (DIS013), Cibola County

East Grants Ridge forms part of the western Mount Taylor volcanic field. Volcanism at the Mount Taylor composite volcano began with eruption of basanite lavas (3.6 Ma) and fine-grained trachyte (3.3 Ma) followed by multiple eruptions of alkali rhyolite to trachyandesite lavas, domes and pyroclastic deposits (3.1–2.8 Ma; Goff et al., 2010). The 3.34 Ma alkali rhyolite dome forming East Grants Ridge is classified as a topaz-bearing rhyolite (Christiansen et al., 1986; Barker et al., 1989; Laughlin et al., 1994; Keating and Valentine, 1998). The topaz rhyolite at East Grants Ridge contains trace amounts of beryl in miarolytic cavities in the rhyolite and contains as much as 19 ppm Be (Johnston, 1953; Burt et al., 1982; Northrop, 1996).

Capitan district (DIS091), Lincoln County

The largest exposed Tertiary intrusion (outcrop area of approximately 280 sq km) in New Mexico is the Capitan granitic pluton, which lies along the east-west trending Capitan lineament (Allen and McLemore, 1991; McLemore and Zimmer, 2009). The best estimate of the age of the pluton is 28.8 Ma, based on $^{40}Ar/^{39}Ar$ dating of adularia that is associated with emplacement of the pluton (Dunbar et al., 1996; McLemore and Zimmer, 2009). The east-west trend of the Capitan pluton reflects the influence the Capitan lineament had on controlling its emplacement. The Capitan pluton is associated with REE-Th-U(±Au) vein, Fe skarn and vein, and manganese vein and replacement deposits.

The Capitan pluton is a calc-alkaline granite that consists of three textural zones: uppermost granophyric (~200 m thick), intermediate aplitic (~200 m), and lower porphyritic (>1000 m) zones. The textural zones are chemically distinct suggesting that the zones are related to magmatic and chemical processes, not simple cooling (Allen and McLemore, 1991). Chemically the Capitan pluton is subalkaline, metaluminous to peraluminous, plots in the WPG (within-plate granites of Pearce et al., 1984), and enriched in light REE (Fig.). The linear variation in Na_2O+K_2O/SiO_2, SiO_2 vs. TiO_2, and SiO_2 vs. Zr/TiO_2, and various major elements confirm that the textural zones are comagmatic.

Fine-grained texture, porous zones (i.e. open space fissures and miarolitic cavities) in the granohyritic and aplitic zones, and porphyritic texture in the center all suggest a rapid, shallow crystallization of the magma (Allen and McLemore, 1991; Dunbar et al. 1996). Rare exposures along the northern and southern longitudinal contacts of the pluton with the older Paleozoic sedimentary rocks are slightly dipping away from the pluton. The western and eastern contacts between the pluton and sedimentary rocks dip steeply away from the pluton to vertical. Flat lying roof pendants of Paleozoic limestone and sills on the western end suggest the pluton is a laccolith or batholith (Allen

and McLemore, 1991). The sedimentary roof pendants of are found west of Capitan Pass. Stoping and assimulation of the sedimentary rocks by the pluton is lacking.

Older, large rock glaciers are common in the porphyritic zone but younger, less developed rock glaciers are found in the aplite and granophyric zones (Blagbrough, 1999). Extensive alluvial fans surround the eastern porphyritic zone that consists of granite, limestone, sandstone, and magnetite-rich clasts, indicating a pre-erosion cap of Paleozoic sedimentary rocks with local iron deposits (Kelly, 1971). Anomalous concentrations of Mn and Fe are found in the alluvial fans adjacent to the intrusive contact by a stream sediment survey by Ellinger (1988; Ellinger and Cepeda, 1991) and the NURE data.

The REE-Th-U-Au veins are exclusively in the granophyric and aplitic zones along the western end of the pluton. Iron skarn and vein deposits are found along the western and northeastern portions of the pluton. Manganese deposits are found along the northeastern portion of the pluton. The REE-Th-U-Au veins contain quartz, fluorite, adularia, hematite, calcite, fluorite, titanite, allanite, thorite, chlorite, and clay minerals (McLemore and Phillips, 1991). They probably formed from magmatic fluids as indicated by highly saline (as much as 80% eq. NaCl) fluid inclusions with homogenization temperatures of 500-600°C (Willis et al., 1989; Phillips, 1990; Phillips et al., 1991; Banks et al., 1994; Campbell et al., 1994, 1995). The fluid inclusions contain Na, K, Ca, Cl, S, Fe, Mn, Zn, and light REE as determined from crush-leached samples of quartz and fluorite (Banks et al., 1994; Campbell et al., 1995). Similar fluid inclusions are found throughout the granitic rocks of the Capitan pluton (Ratajeski and Campbell, 1994). Porous zones characterized by open spaces, bubble-like features, miarolytic cavities, and fissures along fractures within the granite, locally associated with REE-Th-U-Au veins, are found only in the granophyric zone and are interpreted as pathways that allowed fluids to move through the magma into the outer zones of the pluton, forming the REE-Th-U(±Au) veins. A sample from a vein contained 0.005% BeO (Warner et al., 1959). Alteration of adjacent rocks to the veins includes minor silification, hematization, and sericitization.

Salinas Peak (DIS203) district, Sierra County

The Salinas Peak district includes a broad region in the northern San Andres Mountains on the White Sands Missile Range and includes the Capital and Salinas Peaks areas, Sheep Mountain, and Sly, Lee, Good Fortune, Rhodes, White Rock, and Sweetwater Canyons. The first prospecting was in 1655, but recorded production wasn't until 1935-1948. During 1935-1948, 530 short tons of ore containing 100 lbs Cu, 1 oz Au, 308 oz Ag, 72,700 lbs Pb, and 10,000 lbs Zn was produced All of the known deposits within this district are Rio Grande Rift barite-fluorite-galena deposits.

Rocks range in age from Proterozoic to Tertiary. However, the most prominent feature of the Salinas Peak district is the rhyolite sill that comprises Salinas Peak. The sill overlies the Pennsylvanian Lead Camp Limestone on the eastern flank and on the western flank the sill overlies and is interbedded with the Panther Seep Formation (Smith, 1981). Most of the barite-fluorite-galena deposits are found along the intrusive contact with the sill and limestone of the Lead Camp and Pather Seep formations. The deposits at the Bella Vista are at the unconformity between the limestone and the Proterozoic granite.

Several adits have developed small mineralized pods containing barite, fluorite, galena, azurite, malachite, and anglesite in a gangue of quartz, calcite, and iron oxides at the Salinas Peak mines. Many of the mineralized pods follow a series of en echelon faults that strike N85ºE–N80ºW and dip 55-45ºN. Some mineralized pods are along bedding planes. A selected sample assayed 0.3 ppm Ag, 0.41% Pb, 7.83% CaF_2, and 77.04% $BaSO_4$ (L.S. Clemmer and B. Sibbet, unpublished report, 1974.

Several Be anomalies in the NURE stream sediment samples are from streams draining the Salinas Peak district (Appendix 2). Beryllium is not known to occur in the Salinas peak district, although the presence of rhyolite sills and fluorite veins is favorable for volcanogenic Be deposits. Even though this area is on the White Sands Missile Range and withdrawn from mineral entry, it still should be examined.

Veins in New Mexico
Cap Rock Mountain district (DIS048), Grant and Counties

The Cap Rock Mountain mining district is north-northwest of Lordsburg in the Cap Rock Mountains along the boundary between Grant and Hidalgo Counties (Fig. 2) and was discovered in 1917. Epithermal manganese and fluorite veins in the district produced a few hundred short tons of manganese ore during World War I and were reopened during the World War II, producing additional limited production. In the 1950s, the mines produced intermittently from shallow pits and shafts. Hand-sorted ore and concentrates were sold to buyers in Deming or Socorro. Total production from the district is 1,148 long tons of 21-36% Mn and 3,339 long tons of concentrate ore grading 33-35% Mn (Farnham, 1961; Dorr, 1965).

The oldest rocks in the area are Oligocene basaltic breccias and porphyritic basalt and andesite flows of the Cliff volcanic center. Miocene volcanic-conglomerate of the Gila Formation overlie the volcanic rocks and consists of a lower member of consolidated coarse conglomerate (the host rock at the Cliff Roy, NMGR0161, and Ward, NMGR0163, mines) and a poorly consolidated upper member of thin sandstones interbedded with basalt and andesite flows; the basalt may be as young as Quaternary (Pradhan and Singh, 1960). These sandstones constitute the hanging wall of the vein at the Consolation mine, with basaltic andesite forming the footwall. Quaternary terrace gravels predominate to the northwest and southeast of the district, and minor Miocene and Oligocene rhyolite intrusives are found approximately a mile southwest (Drewes et al., 1985). At the Consolation vein, the basaltic andesite forming the footwall has been dated as 20.9±0.5 Ma (Elston, 1973, 1983).

Major structures in the Cap Rock Mountain district trend N45°W, and many of the well-defined faults and fracture zones with ore-bearing veins are parallel to this, most notably at the Consolation mine. Other veins trend N27°W, N30°W, and N35°W, with steep dips. The magnitude of displacements along the faults and the direction of motion are mostly unknown.

The epithermal manganese and fluorite deposits occur along steeply dipping fault and fracture zones, chiefly in the volcanic Gila Conglomerate (Farnham, 1961). However, Pradhan and Singh (1960) stated that the veins did not show any particular preference for any type of host rock. At the largest deposit, the Cliff Roy, the veins are 2-8 ft wide, strikes N9°W, steeply dipping, and the ore grades upward into banded travertine. The ore minerals, chiefly psilomelane with minor pyrolusite, occur in

disconnected, lenticular shoots ranging from a few tens of feet to 100 ft in length. In the ore shoots, the manganese minerals occur as irregular strands, bunches, and coatings surrounding the volcanic breccias fragments. Chalcedony, manganiferous calcite, and minor gypsum are gangue minerals. Much of the psilomelane contains small inclusions of milky chalcedony. A sample assayed 45% Mn, 3% SiO_2, and 0.15% P (Wells, 1918). A sample from veins in rhyolite contained 0.05% Be (Meeves, 1966).

The Consolation mine (NMGR0162) yielded approximately 10,000 long tons of 8-10% Mn during the 1950s (Gillerman, 1964; Ryan, 1985; Richter and Lawrence, 1983). The deposit occurs in basaltic andesite along a fault trending N45°W for 120 ft and is 8-14 ft wide. Argillic alteration and iron staining occur at the Consolation mine as well as at the Black Bob, where a argillized brecciated basalt is the host rock (Gillerman, 1964; Pradhan and Singh, 1960).

The other deposits are similar in form and composition to the Cliff Roy, but are smaller in size. Locally, fluorite is common. Geochemical anomalies in stream-sediment samples include Ag, Co, Cu, Mn, and Y and spotty La, Sn, Th, and Ti.

Porphyry molybdenum (±tungsten) deposits in New Mexico

Porphyry molybdenum (±tungsten) deposits are large, low-grade deposits that contain disseminated and stockwork veinlets of Mo sulfides and are associated with porphyritic intrusions (Ludington and Plumlee, 2009). Four styles of porphyry molybdenum deposits are found and mineralized breccia deposits are common (Fig. 31). Porphyry molybdenum deposits occur in three areas in New Mexico (Fig. 2; Questa, NMTA0017, Rialto stock, NMLI0121, in Nogal district, Victorio Mountains); the largest Mo deposits are at Questa in Taos County (Rowe, 2005; McLemore, 2009). 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 (Fig. 31). 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, except perhaps for the Victorio district.
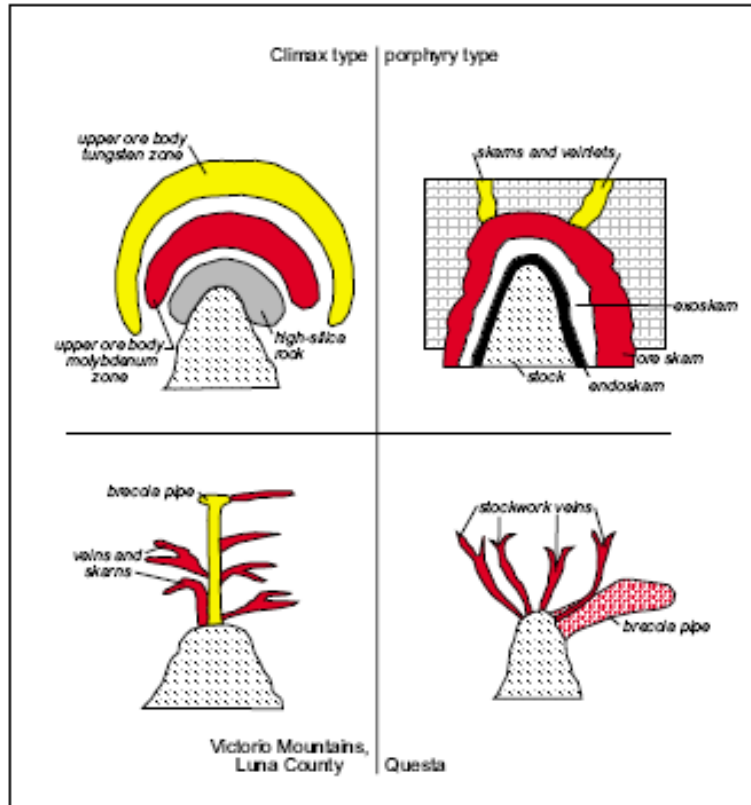
FIGURE 31. Schematic sketch of porphyry molybdenum deposits that are dependent upon the amount of fluid in the source magma, overpressures, host rock permeability, and other physical and chemical characteristics (modified in part from Guilbert and Park, 1986; Ross et al., 2002).

Coal deposits in New Mexico

Beryllium is found in low to moderate concentrations in some coal deposits (Stadnichenko et al., 1961). In New Mexico, beryllium in coal deposits ranges from trace to 520 ppm and averages 23.1 ppm (Fig. 32; Hoffman, 1991).
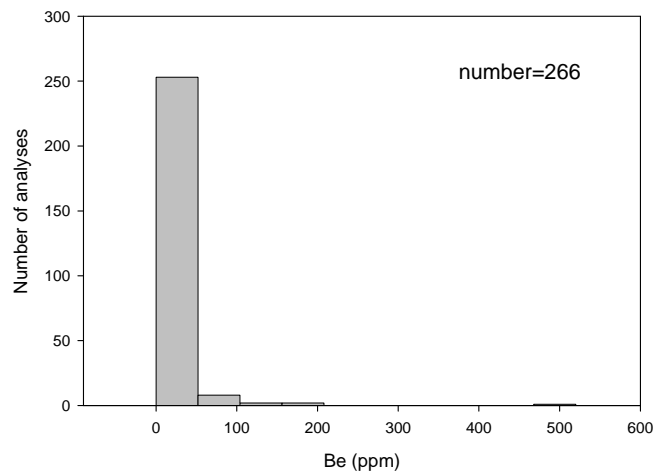
FIGURE 32. Beryllium analyses in coal samples (Hoffman, 1991).

PETROCHEMISTRY OF IGNEOUS ROCKS ASSOCIATED WITH BERYLLIUM DEPOSITS

Rhyolites from Iron Mountain, Apache Warm Springs, Spor Mountain, and granites from Victorio Mountains associated with known beryllium mineralization are predominantly peraluminous (i.e. $Al_3O_5/(CaO+K_2O+Na_2O) > l.0$) to metaluminous (i.e. $Al_3O_5/(CaO+K_2O+Na_2O) < l.0$), 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. (1984) 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 et al., 2000; 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.
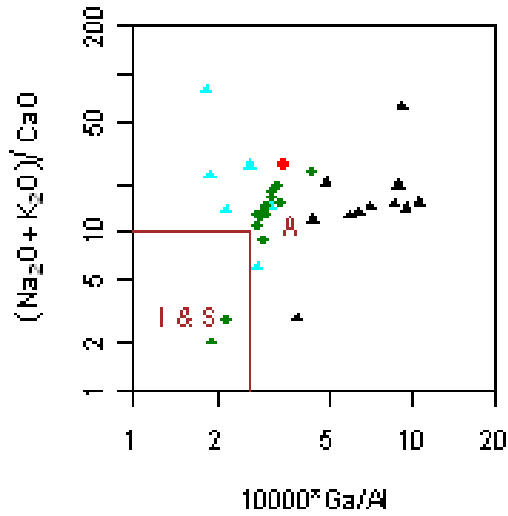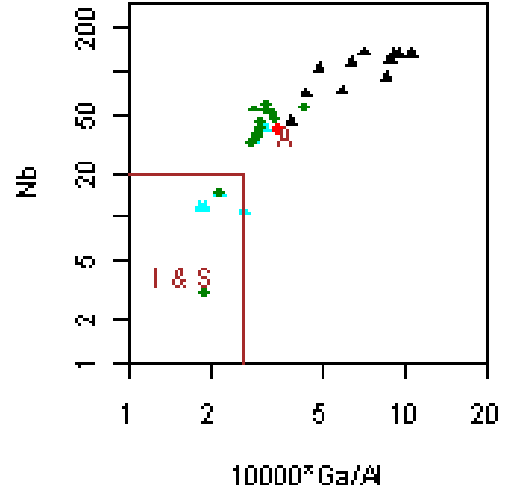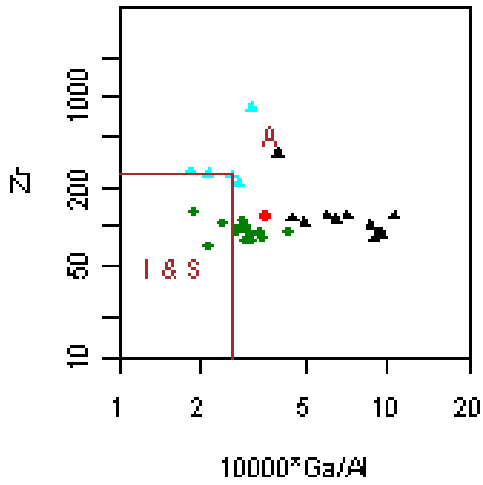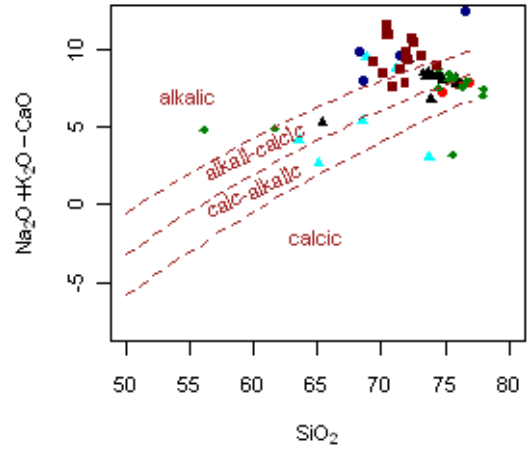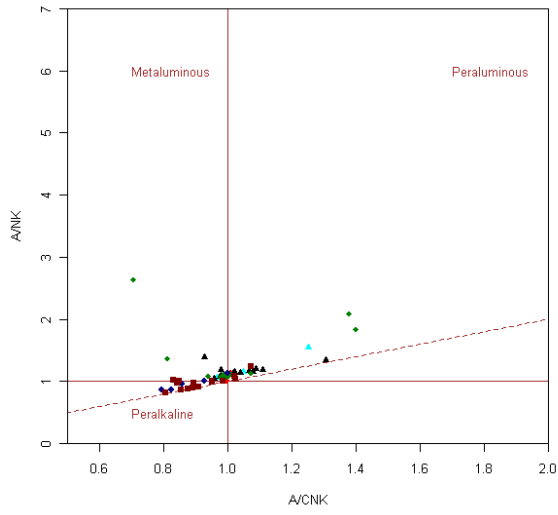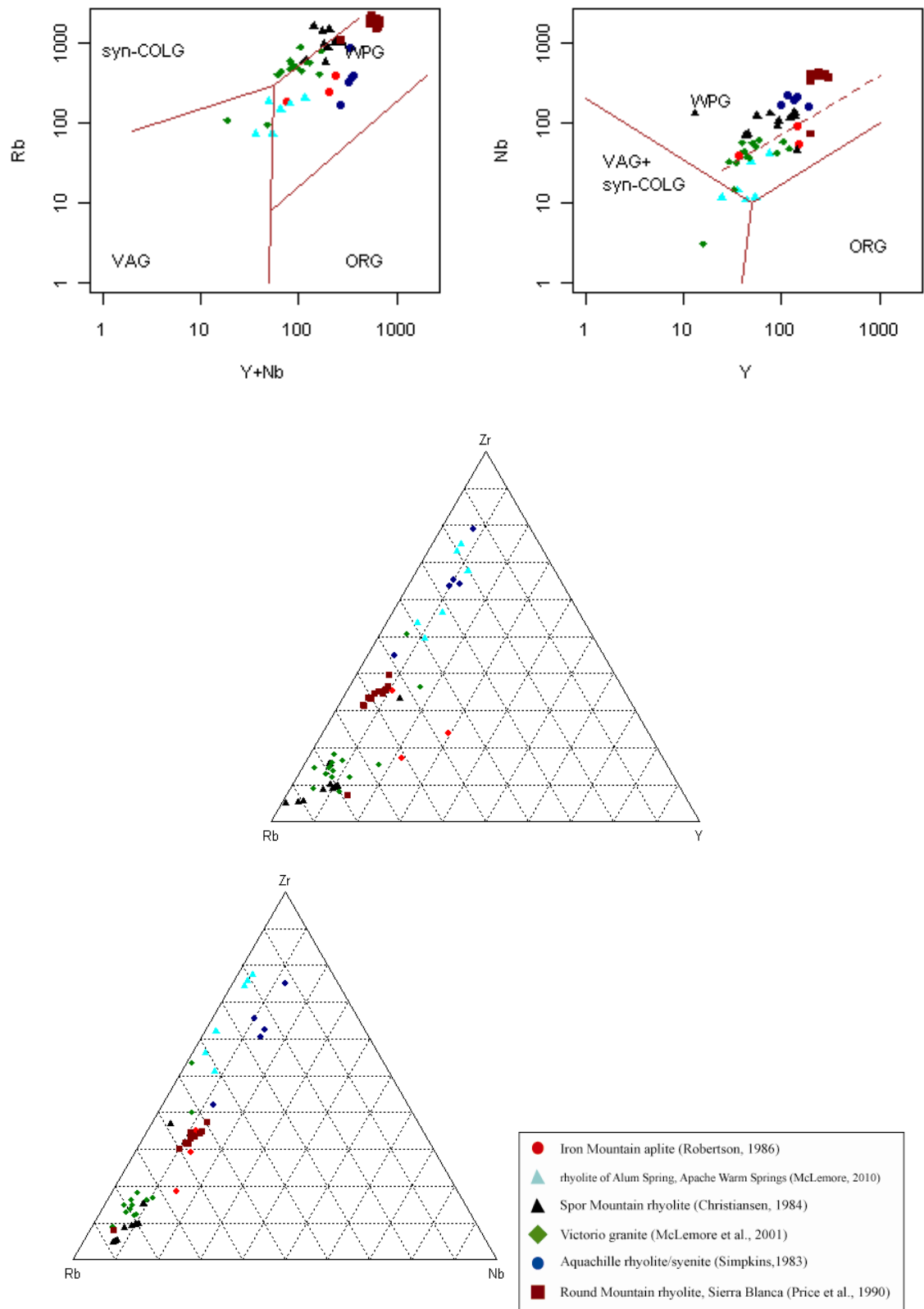
FIGURE 33. A/CNK $(Al_2O_3/(CaO+Na_2O+K_2O))$ verses ANK $(Al_2O_3+Na_2O+K_2O)$ (Shand, 1943). A (A-type), I (I-type), and S (S-type) granite fields from Whalen et al.

(1987). Pearce et al. (1984) tectonic diagrams, showing the samples are similar to within plate to syn-collusion 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 on selected deposits are summarized in Table 14 and provide an estimate of the temperature and chemical conditions of the mineralizing fluids. These studies indicate that magmatic deposits are higher in temperature and salinity then distal hydrothermal deposits.

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 Rowe (2005) of the Questa porphyry molybdenum breccia indicated that the breccia deposits were formed by boiling, cooling, and meteoric mixing with magmatic fluids. The breccia cooled and crystallized from the inside out (Rowe, 2005). The fluid inclusion analyses ranged in temperatures (68-520°C) and salinities (0-64 eq. wt.% NaCl+KCl+CaCl2).

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.

TABLE 14. Summary of fluid inclusion data of selected beryllium deposits.

Area	Temperature °C	Salinity eq. wt.% NaCl	Reference
Victorio Mountains—porhyry Mo deposit	208-315	2-11.9	Donahue (2002)
Victorio Mountains—skarn deposits	180-350	2-22.5	Donahue (2002)
Victorio Mountains—carbonate-hosted replacement	105-289	<2-5	Donahue (2002)
Questa porphyry Mo breccia deposit	68-520	0-64	Rowe (2005)

Area	Temperature °C	Salinity eq. wt.% NaCl	Reference
Iron Mountain skarn deposits	300-385	36-45	Nkambule (1988)
Iron Mountain fluorite deposits	275-290	4-12	Nkambule (1988)
Long Lost Brother fluorite vein, Burro Mountains	160-175	0.8-1.7	Hill (1994)
Capitan Mountains Th-U-REE veins	110-600	10-80	Phillips (1990)
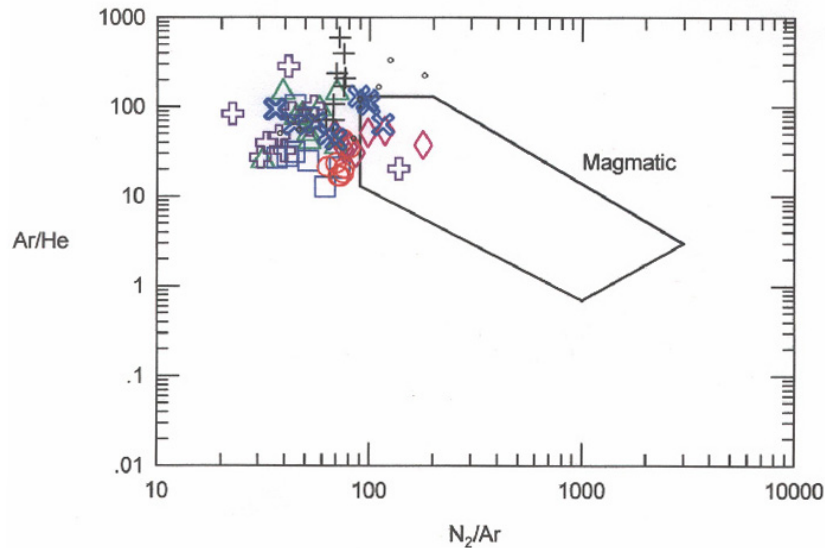
FIGURE 34. Fluid inclusion gas results at indicate the majority of the gas compositions are meteoric and fall outside the magmatic water box as defined by Norman et al. (2002).
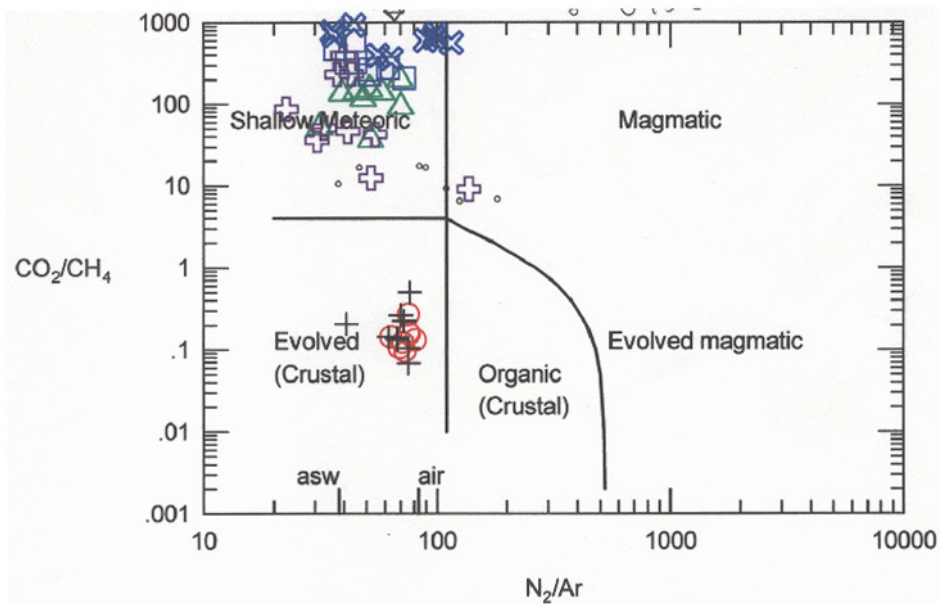
FIGURE 35. Fluid inclusion gas analyses results indicate the skarn and carbonate-hosted replacement deposits gas compositions fall within the shallow meteoric and magmatic

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).
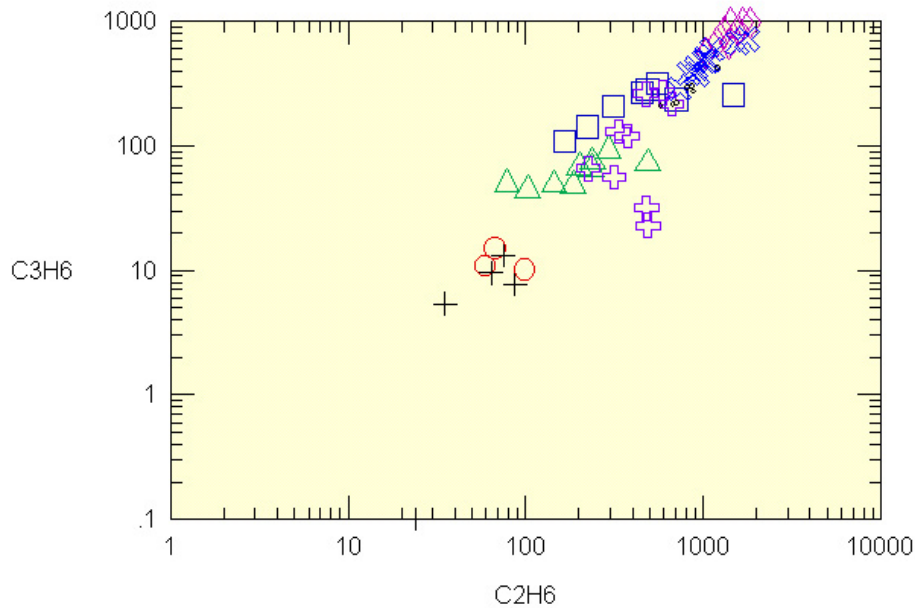
FIGURE 36. The fluid inclusion gas analysis showed high concentrations of complex hydrocarbons. The hydrocarbons are most likely coming from the carbonate host rocks. The decrease in concentration from the porphyry to the carbonate-hosted replacement deposits could be due to a decrease in the water/rock ratio or dilution by another fluid.

FORMATION OF BERYLLIUM DEPOSITS

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, 2010a), and is similar to the Spor Mountain deposit. Deposits at Iron Mountain and Reilly Peak in the northern Cuchillo Negro district (south of the Ojo Caliente No. 2 district), contain Be-W-Sn-Fe skarn deposits that are related to chemically-similar rhyolites as the Apache Warm Springs deposit (McLemore, 2010a). 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, 1986a, b). 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 Proterozoic lower crust in an extensional tectonic setting, which is consistent with the formation of these rocks.

At the Victorio district, the evidence suggests 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 beryllium resources and are associated with rhyolites. Only the Spor Mountain deposit is currently being mined and has enough reserves to meet the current demand.
    o Spor Mountain, UT volcanogenic beryllium 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.
    o Apache Warm Springs volcanogenic beryllium deposit in the Sierra Cuchillo contains resources in rhyolite amounting to 39,063 metric tons Be grading less than 0.26% Be (BE Resources, Inc.).
    o Iron Mountain (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.
    o W-Mo-Be 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.
    o At Round Top Mountain (Sierra Blanca, TX), the West End skarn contains 272,200 metric tons of 1.9% BeO.

      o   Aguachile, Mexico contact-metasomatic deposit contains 17,000,000 metric tons of 0.1% Be.

2. The average of stream-sediment samples from the NURE data in New Mexico is 1.63 ppm Be with 129 geochemical anomalies that were between 5-38 ppm Be. Most of the anomalies are related to rhyolitic complexes, including ignimbrites (i.e. ash flow tuffs); 51 anomalies (5-11 ppm) are related to the outcrop of the Bandelier Tuff in the Jemez Mountains. The NURE stream-sediment sample with the highest Be concentration (38 ppm) is from near the Iron Mountain beryllium deposit in the Cuchillo Negro district.

3. 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.

4. 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 beryllium, 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.

5. 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 and dolomite, appears to be important.

POTENTIAL FOR BERYLLIUM DEPOSITS IN NEW MEXICO

It is unlikely that any of the beryllium deposits in New Mexico will be mined in the near future because the known deposits are small and low grade and the Spor Mountain deposit contains sufficient beryllium reserves to meet the expected demand in the next few years (Jaskula, 2009). However, there are concerns about long-term supply of beryllium (Department of Defense, 2005; Committee on Critical Mineral Impacts of the U.S. Economy, 2008) and additional deposits could be needed. Metallugical problems in recovering beryllium from the carbonate-hosted replacement and skarn deposits need to be resolved for those deposits to become of interest. High-silica rhyolites and granites throughout New Mexico, especially in the Mogollon-Datil volcanic field are known to be enriched in beryllium. Topaz rhyolites are fluorine-rich alkaline rhyolite lavas and shallow intrusions that are characterized by topaz, Mn-Fe garnet, bixbyite, psueodobrookite, specularite, quartz, beryl, and other minerals (Burt et al., 1982). Areas with rhyolitic volcanic and alkaline rocks throughout New Mexico, especially where NURE data indicates potential anomalies, should be examined for beryllium potential. The volcanic rocks in the Jemez Mountains contain less than 9 ppm Be (Shawe and Bernold, 1966), but 51 NURE anomalies (5-11 ppm) are related to the outcrop of the Bandelier Tuff in the Jemez Mountains (Appendix 2).

ACKNOWLEDGEMENTS

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APPENDIX 1. SUMMARY OF BERYLLIUM DEPOSITS AND OCCURRENCES IN NEW MEXICO

TABLE A1. Districts and areas with beryllium occurrences. The mining district identification numbers are from the New Mexico Mines Database (McLemore et al., 2005a, b). Names of districts are after File and Northrop (1966) and McLemore (2001), wherever practical, but some districts have been added.

District Id	District Name	Type of deposit	Age	Reference
none	Black Range (Rabb Park)	pegmatite	Tertiary	Warner et al. (1959), Northrop (1996)
DIS046	Burro Mountains	pegmatite	Proterozoic	Warner et al. (1959)
DIS190	Caballo Mountains	alkaline (vein)	Cambrian-Ordovician	Meeves (1966), McLemore (1986)
DIS048	Cap Rock Mountain	Carbonate-hosted replacement/skarn	Tertiary	
DIS091	Capitan	granite (vein)	Tertiary	Warner et al. (1959)
DIS049	Carpenter	Carbonate-hosted replacement/skarn	Tertiary	Warner et al. (1959)
DIS128	Cornudas Mountains	Syenite, breccias, veins	Tertiary	Warner et al. (1959), Schreiner (1994)
DIS002	Coyote Canyon	pegmatite	Proterozoic	Kelly and Northrop (1975)
DIS192	Cuchillo Negro (Iron Mountains)	Carbonate-hosted replacement/skarn	Tertiary	Jahns (1944a, b), Warner et al. (1959), Davis (1986a, b)
DIS013	East Grants Ridge	rhyolite	Tertiary	Northrop (1996)
DIS161	El Porvenir	pegmatite	Proterozoic	Northrop (1996)
DIS162	Elk Mountain	pegmatite	Proterozoic	Holmquist (1946)
DIS092	Gallinas Mountains	alkaline (veins)	Tertiary	Warner et al. (1959)
DIS058	Gold Hill	pegmatite	Proterozoic	Meeves et al. (1966)
DIS255	Hueco Mountains	Syenite, jasperiods, veins	Tertiary	New Mexico Bureau of Mimes and Mineral Resources et al. (1998)
DIS092	Hillsboro	Carbonate-hosted replacement/skarn	Laramide	
DIS232	La Cueva	pegmatite	Proterozoic	McLemore (1990)
DIS020	Laughlin Peak	alkaline (vein)	Tertiary	Warner et al. (1959), Staatz (1985)
DIS220	Luis Lopez	vein	Tertiary	Meeves (1966)
DIS082	Lordsburg	Carbonate-hosted replacement/skarn	Laramide	Warner et al. (1959)
DIS126	Mora	pegmatite	Proterozoic	Redmon (1961)
DIS185	Nambe	pegmatite	Proterozoic	Redmon (1961)
DIS186	New Placers	Carbonate-hosted replacement/skarn	Tertiary	Warner et al. (1959), Meeves (1966)
DIS147	Ojo Caliente No. 1	pegmatite	Proterozoic	Redmon (1961)

District Id	District Name	Type of deposit	Age	Reference
DIS230	Ojo Caliente No. 2	rhyolite	Tertiary	McLemore (2010a)
DIS030	Organ	Carbonate-hosted replacement/skarn	Tertiary	Warner et al. (1959)
DIS148	Petaca	pegmatite	Proterozoic	Jahns (1946)
DIS236	Picuris	pegmatite	Proterozoic	Meeves et al. (1966), Jahns and Ewing (1979)
DIS237	Questa	porphyry	Tertiary	McLemore (2009)
DIS238	Red River-Rio Hondo	vein	Tertiary	McLemore and Mullen (2004)
DIS164	Rociada	pegmatite	Proterozoic	Warner et al. (1959), Redmon (1961)
DIS203	Salinas Peak	rhyolite	Tertiary	NURE data
DIS204	Taylor Creek	rhyolite	Tertiary	Warner et al. (1959), Eggleston (1983), Eggleston and Norman (1983)
DIS166	Tecolote	pegmatite	Proterozoic	Redmon (1961)
DIS114	Victorio	Carbonate-hosted replacement/skarn	Tertiary	McLemore et al. (2000)
DIS068	White Signal	pegmatite	Proterozoic	Gillerman (1964)

APPENDIX 2. SUMMARY OF NURE STREAM SEDIMENT ANOMALIES, 5-38
PPM BE IN NEW MEXICO

TABLE A2-1. NURE stream sediment anomalies (data from Smith, 1997).

Record Number	Latitude	Longitude	Rock type	Be (ppm)	Comments
Bandelier Tuff					
5114271	35.86810	-106.69530	Igneous	11	Bandelier Tuff
5114463	35.78360	-106.43940	Igneous	10	Bandelier Tuff
5114261	35.90860	-106.77780	Igneous	9	Bandelier Tuff
5114272	35.86610	-106.69440	Igneous	9	Bandelier Tuff
5114310	35.99170	-106.64330	Igneous	9	Bandelier Tuff
5114462	35.78330	-106.43690	Igneous	9	Bandelier Tuff
5114301	35.93250	-106.70810	Igneous	8	Bandelier Tuff
5072540	36.08580	-106.44310	Igneous	7	Bandelier Tuff
5114126	35.95670	-106.24030	Igneous	7	Bandelier Tuff
5114262	35.90920	-106.77860	Igneous	7	Bandelier Tuff
5114263	35.98750	-106.67810	Igneous	7	Bandelier Tuff
5114265	35.97390	-106.64440	Igneous	7	Bandelier Tuff
5114273	35.86280	-106.71970	Igneous	7	Bandelier Tuff
5114280	35.87890	-106.79360	Igneous	7	Bandelier Tuff
5114311	35.93060	-106.69000	Igneous	7	Bandelier Tuff
5114314	35.94140	-106.64360	Igneous	7	Bandelier Tuff
5114434	35.70780	-106.62560	Igneous	7	Bandelier Tuff
5114452	35.71470	-106.63780	Igneous	7	Bandelier Tuff
5114460	35.71890	-106.41330	Igneous	7	Bandelier Tuff
5114124	35.94670	-106.22250	Igneous	6	Bandelier Tuff
5114166	35.86920	-106.21140	Igneous	6	Bandelier Tuff
5114258	35.86610	-106.75750	Igneous	6	Bandelier Tuff
5114259	35.92080	-106.70580	Igneous	6	Bandelier Tuff
5114264	35.98830	-106.68060	Igneous	6	Bandelier Tuff
5114274	35.85030	-106.77530	Igneous	6	Bandelier Tuff
5114299	35.87440	-106.74580	Igneous	6	Bandelier Tuff
5114427	35.78890	-106.64190	Igneous	6	Bandelier Tuff
5114461	35.72060	-106.41080	Igneous	6	Bandelier Tuff
5072538	36.10080	-106.44610	Igneous	5	Bandelier Tuff
5072539	36.08670	-106.44420	Igneous	5	Bandelier Tuff
5072541	36.10750	-106.42500	Igneous	5	Bandelier Tuff
5114118	35.91220	-106.26750	Igneous	5	Bandelier Tuff
5114120	35.93690	-106.30280	Igneous	5	Bandelier Tuff
5114122	35.89720	-106.19610	Sedimentary	5	Bandelier Tuff
5114123	35.89280	-106.19640	Sedimentary	5	Bandelier Tuff
5114125	35.95970	-106.23190	Igneous	5	Bandelier Tuff
5114127	35.96920	-106.26420	Igneous	5	Bandelier Tuff
5114165	35.85920	-106.22690	Igneous	5	Bandelier Tuff
5114185	35.81280	-106.23860	Igneous	5	Bandelier Tuff
5114218	35.94810	-106.74940	Igneous	5	Bandelier Tuff
5114257	35.88110	-106.72310	Igneous	5	Bandelier Tuff
5114266	35.93860	-106.67470	Igneous	5	Bandelier Tuff
5114270	35.84250	-106.66560	Igneous	5	Bandelier Tuff
5114309	35.98920	-106.64530	Igneous	5	Bandelier Tuff
5114317	35.85810	-106.75720	Igneous	5	Bandelier Tuff
5114426	35.80030	-106.64470	Igneous	5	Bandelier Tuff

Record Number	Latitude	Longitude	Rock type	Be (ppm)	Comments
5114440	35.87170	-106.64330	Igneous	5	Bandelier Tuff
5114441	35.96920	-106.59720	Igneous	5	Bandelier Tuff
5114443	35.96670	-106.54470	Igneous	5	Bandelier Tuff
5114450	35.87360	-106.51110	Igneous	5	Bandelier Tuff
5114464	35.73470	-106.41670	Igneous	5	Bandelier Tuff
Other rhyolites					
5220188	32.93190	-107.80860	Igneous	5	Black Range, north Carpenter
5217452	33.01360	-107.79500	Igneous	5	Black Range, west Kingston
5113840	35.18390	-107.80250	Igneous	11	East Grants Ridge
5113852	35.24310	-107.69190	Igneous	5	Mount Taylor
5217834	33.80250	-107.07780	Sedimentary	7	east of San Mateo Mountains
5120347	34.01890	-107.52780	Igneous	6	north San Mateo Mountains
5120346	34.02060	-107.52920	Igneous	5	north San Mateo Mountains
5217898	33.68280	-107.43670	Igneous	11	San Mateo Mountains
5217896	33.69940	-107.44170	Igneous	5	San Mateo Mountains
5217899	33.68330	-107.43440	Igneous	5	San Mateo Mountains
5215300	33.04310	-108.99000	Igneous	7	east of Steeple Rock
5215296	33.10140	-108.98110	Unknown	6	east of Steeple Rock
5217404	33.46670	-107.64360	Metamorphic	38	Iron Mountain
5219944	32.20530	-107.58750		9	Little Florida Mountains
5120584	34.48420	-107.04690	Sedimentary	5	north Ladron Mountains
5120588	34.51940	-107.15060	Sedimentary	7	north of Ladron Mountains
5216059	33.29390	-108.27060	Igneous	6	north Gila Cliff Dwellings
5215883	33.20390	-108.40640	Igneous	5	north Gila Cliff Dwellings
5216056	33.23330	-108.23440	Igneous	5	north Gila Cliff Dwellings
5215882	33.20310	-108.40420	Igneous	7	northwest of Alum Mountain, Gila
5215869	33.14560	-108.39470	Igneous	6	northwest of Alum Mountain, Gila
5215287	33.40330	-108.84830	Unknown	12	west Mogollon
5220775	32.32190	-106.57250	Sedimentary	6	Organ Mountains
5220741	32.21970	-106.60560	Sedimentary	5	Organ Mountains
5220746	32.18750	-106.65110	Sedimentary	5	Organ Mountains
5217072	31.39420	-108.93670	Sedimentary	5	Peloncillo Mountains
5077181	36.69640	-105.54970	Igneous	6	Questa
5077431	36.69330	-105.49830	Igneous	6	Questa
5331097	33.36750	-106.44190	Igneous	6	east Salinas Peak
5219132	33.31720	-106.52030		5	Salinas Peak
5219133	33.31610	-106.51970		5	Salinas Peak
5219134	33.30420	-106.50060	Igneous	5	Salinas Peak
5219138	33.31140	-106.50060	Igneous	5	Salinas Peak

Record Number	Latitude	Longitude	Rock type	Be (ppm)	Comments
5219266	33.37470	-106.42140	Igneous	5	Salinas Peak
5219267	33.37250	-106.42470	Igneous	5	Salinas Peak
5219589	33.44170	-106.41610	Igneous	5	Salinas Peak
5219679	33.39110	-106.40940	Igneous	5	Salinas Peak
5331111	33.39940	-106.41110	Igneous	5	Salinas Peak
5216990	31.35220	-108.70530	Sedimentary	6	south Animas Mountains
5217830	33.85420	-107.11940	Sedimentary	5	south Magdalena Mountains
5217833	33.81610	-107.07670	Sedimentary	5	south Magdalena Mountains
5217835	33.79750	-107.08780	Sedimentary	5	south Magdalena Mountains
5217837	33.79310	-107.06280	Sedimentary	5	south Magdalena Mountains
5078441	36.48030	-104.16390	Igneous	20	southeast Laughlin Peak area
5217324	33.58060	-107.94440	Igneous	7	Talyor Creek
5217334	33.54170	-107.84530	Igneous	7	Talyor Creek
5216159	33.47420	-108.02000	Metamorphic	6	Taylor Creek
5216161	33.46060	-108.03250	Igneous	6	Taylor Creek
5217335	33.53860	-107.84560	Igneous	6	Taylor Creek
5217319	33.59390	-107.87920	Igneous	5	Taylor Creek
5217322	33.57360	-107.84140	Igneous	5	Taylor Creek
5217325	33.55440	-107.92560	Igneous	5	Taylor Creek
5217327	33.53170	-107.89530	Igneous	5	Taylor Creek
5217329	33.52250	-107.93360	Igneous	5	Taylor Creek
5217331	33.50670	-107.98530	Igneous	5	Taylor Creek
5217333	33.54610	-107.84940	Igneous	5	Taylor Creek
5217336	33.54080	-107.88330	Igneous	5	Taylor Creek
5217337	33.50780	-107.85610	Igneous	5	Taylor Creek
5216436	32.18470	-108.10190	Sedimentary	9	Victorio Mountains
5216435	32.18500	-108.10610	Sedimentary	8	Victorio Mountains
5216437	32.18530	-108.09890	Sedimentary	8	Victorio Mountains
Misc					
5114641	35.32810	-106.57190	Sedimentary	7	Bernallilo
5114136	35.52140	-107.49750	Sedimentary	5	Cretaceous San Juan Basin
5120536	34.63530	-107.10250	Sedimentary	14	Mesa Aparejo
5220706	32.14670	-107.23560		5	Portillo volcanic field
5110356	34.37420	-104.15580	Sedimentary	5	south Fort Sumner
Precambrian					
5216206	32.67360	-108.44500	Igneous	5	Burro Mountains
5216239	32.43640	-108.46250	Sedimentary	5	Burro Mountains-east Gold Hill
5216240	32.43560	-108.43190	Sedimentary	5	Burro Mountains-east Gold Hill
5216241	32.42360	-108.43330	Sedimentary	5	Burro Mountains-east Gold Hill
5216330	32.40420	-108.43440	Sedimentary	5	Burro Mountains-east Gold Hill
5216224	32.44220	-108.55420	Metamorphic	5	Burro Mountains-Gold Hill
5216225	32.43810	-108.56530	Metamorphic	5	Burro Mountains-Gold Hill
5216643	32.43690	-108.56830	Sedimentary	5	Burro Mountains-Gold Hill
5216644	32.43780	-108.57080	Sedimentary	5	Burro Mountains-Gold Hill
5216646	32.42720	-108.57170	Sedimentary	5	Burro Mountains-Gold Hill

Record Number	Latitude	Longitude	Rock type	Be (ppm)	Comments
5078114	36.91360	-105.26140	Igneous	5	east of La Cueva district
5181984	33.22280	-105.41690	Sedimentary	6	Pajarito Mountain

APPENDIX 3. CHEMICAL ANALYSES OF BERYLLIUM IN ROCKS AND MINERALIZED SAMPLES FROM NEW MEXICO

TABLE A3. Selected chemical analyses of beryllium in rocks and mineralized samples from New Mexico.

Sample	Area	Be (ppm)	Reference
329-711	Taylor Creek, Catron	20	Warner et al. (1959)
329-376 thru 382	Cimarroncito, Colfax	<4	Warner et al. (1959)
329-262 thru 275	Elizabethtown-Baldy, Colfax	<4	Warner et al. (1959)
329-372 thru 373	Raton-Clayton volcanic rocks	<10-70	Warner et al. (1959)
329-790 thru 802	Organ, Dona Ana	<4	Warner et al. (1959)
329-318	Long Lost Brother, Burro Mountains	2	Warner et al. (1959)
329-315 thru 735	Carpenter, Grant	<10-200	Warner et al. (1959)
329-276 thru 807	Central, Grant	<4-20	Warner et al. (1959)
329-738 thru 740	Piños Altos district	<4-4	Warner et al. (1959)
329-752 thru 783	Apache No. 2, Hidalgo	<4	Warner et al. (1959)
329-740a thru 751	Eureka, Sylvanite	<4	Warner et al. (1959)
329-421 thru 426	Lordsburg	<4-30	Warner et al. (1959)
329-429, 433	San Simon	<4	Warner et al. (1959)
329-810	Capitan	50	Warner et al. (1959)
329-808	Gallinas	2-80	Warner et al. (1959)
329-760	Tres Hermanas	4	Warner et al. (1959)
329-390 thru 420	Victorio	<10-1000	Warner et al. (1959)
329-384	Azure-Rising Sun, Rociada	<4	Warner et al. (1959)
329-386	Pecos	<4	Warner et al. (1959)
JA49-4, 5	Cochiti	5-7	Warner et al. (1959)
329-323 thru 345	New Placers	<4-4	Warner et al. (1959)
329-349 thru 359	Old Placers	<4	Warner et al. (1959)
329-705, 706	Apache No. 2	<4-100	Warner et al. (1959)
329-700 thru 702	Cuchillo Negro	5-10	Warner et al. (1959)
329-214 thru 238	Red River	<3-20	Warner et al. (1959)
	Grandview, Grant	14	Meeves (1966)
	Cornudas	20-100	Meeves (1966)
	San Pedro, New Placers	200	Meeves (1966)
	White Top, Grant	20	Meeves et al. (1966)
BENT1		1	NMBGMR files
Bent1		2	NMBGMR files
Bent2a		11	NMBGMR files
Bent3		9	NMBGMR files
CAB20		10	NMBGMR files
8803	Caballo	13	NMBGMR files
8804	Caballo	31	NMBGMR files
9028	Caballo	600	NMBGMR files
9039	Caballo	25	NMBGMR files
9040	Caballo	20	NMBGMR files
CAB-110	Caballo	30	NMBGMR files
7369-Cornudas	Cornudas	24	NMBGMR files
CORN 10-102	Cornudas	29	NMBGMR files
CORN 18-111	Cornudas	28	NMBGMR files
CORN 33	Cornudas	21	NMBGMR files
CORN 34	Cornudas	33	NMBGMR files

Sample	Area	Be (ppm)	Reference
Wind Mt	Cornudas	11	NMBGMR files
33	Cornudas	35.5	NMBGMR files
34	Cornudas	36.2	NMBGMR files
MG11		40	NMBGMR files
ABC		35	NMBGMR files
TAY14	Taylor Creek	30	NMBGMR files
TAY13	Taylor Creek	22	NMBGMR files
BR-19		12	NMBGMR files
BR-28		10	NMBGMR files
HC-3		10	NMBGMR files
3M016R		75	NMBGMR files
3M032R		50	NMBGMR files
VTM97-188F		64	NMBGMR files