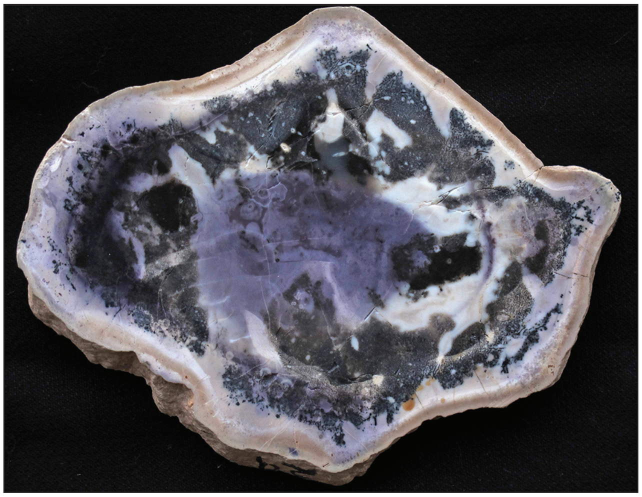
Beryllium

Chapter E of

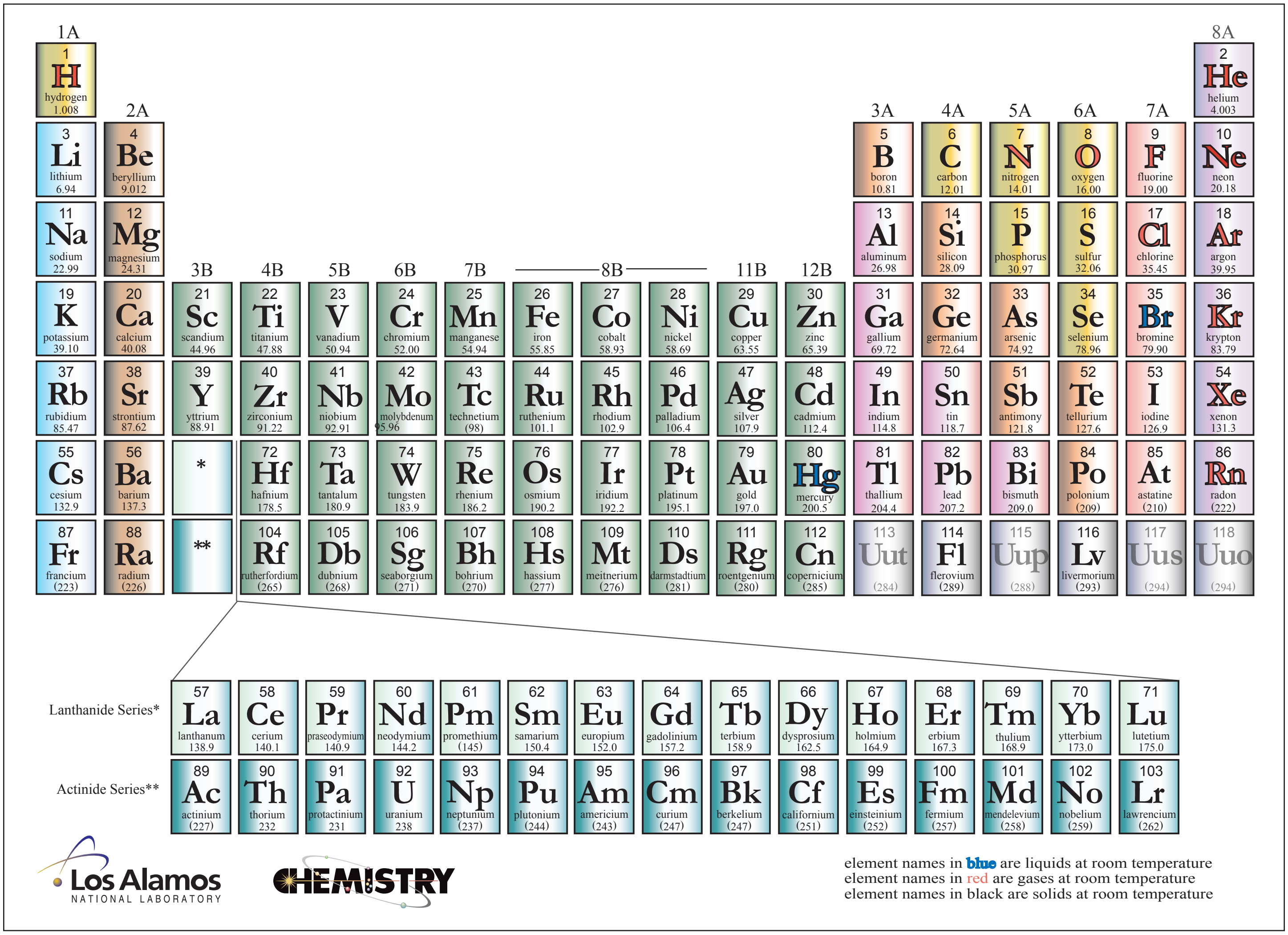
Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply



Professional Paper 1802–E

U.S. Department of the Interior
U.S. Geological Survey

Periodic Table of Elements



1A	2A	3B	4B	5B	6B	7B	8B			11B	12B	3A	4A	5A	6A	7A	8A
1 H hydrogen 1.008																	2 He helium 4.003
3 Li lithium 6.94	4 Be beryllium 9.012											5 B boron 10.81	6 C carbon 12.01	7 N nitrogen 14.01	8 O oxygen 16.00	9 F fluorine 19.00	10 Ne neon 20.18
11 Na sodium 22.99	12 Mg magnesium 24.31											13 Al aluminum 26.98	14 Si silicon 28.09	15 P phosphorus 30.97	16 S sulfur 32.06	17 Cl chlorine 35.45	18 Ar argon 39.95
19 K potassium 39.10	20 Ca calcium 40.08	21 Sc scandium 44.96	22 Ti titanium 47.88	23 V vanadium 50.94	24 Cr chromium 52.00	25 Mn manganese 54.94	26 Fe iron 55.85	27 Co cobalt 58.93	28 Ni nickel 58.69	29 Cu copper 63.55	30 Zn zinc 65.39	31 Ga gallium 69.72	32 Ge germanium 72.64	33 As arsenic 74.92	34 Se selenium 78.96	35 Br bromine 79.90	36 Kr krypton 83.79
37 Rb rubidium 85.47	38 Sr strontium 87.62	39 Y yttrium 88.91	40 Zr zirconium 91.22	41 Nb niobium 92.91	42 Mo molybdenum 95.96	43 Tc technetium (98)	44 Ru ruthenium 101.1	45 Rh rhodium 102.9	46 Pd palladium 106.4	47 Ag silver 107.9	48 Cd cadmium 112.4	49 In indium 114.8	50 Sn tin 118.7	51 Sb antimony 121.8	52 Te tellurium 127.6	53 I iodine 126.9	54 Xe xenon 131.3
55 Cs cesium 132.9	56 Ba barium 137.3	*	72 Hf hafnium 178.5	73 Ta tantalum 180.9	74 W tungsten 183.9	75 Re rhenium 186.2	76 Os osmium 190.2	77 Ir iridium 192.2	78 Pt platinum 195.1	79 Au gold 197.0	80 Hg mercury 200.5	81 Tl thallium 204.4	82 Pb lead 207.2	83 Bi bismuth 209.0	84 Po polonium (209)	85 At astatine (210)	86 Rn radon (222)
87 Fr francium (223)	88 Ra radium (226)	**	104 Rf rutherfordium (265)	105 Db dubnium (268)	106 Sg seaborgium (271)	107 Bh bohrium (270)	108 Hs hassium (277)	109 Mt meitnerium (276)	110 Ds darmstadtium (281)	111 Rg roentgenium (280)	112 Cn copernicium (285)	113 Uut (284)	114 Fl flerovium (289)	115 Uup (288)	116 Lv livermorium (293)	117 Uus (294)	118 Uuo (294)

Lanthanide Series*	57 La lanthanum 138.9	58 Ce cerium 140.1	59 Pr praseodymium 140.9	60 Nd neodymium 144.2	61 Pm promethium (145)	62 Sm samarium 150.4	63 Eu europium 152.0	64 Gd gadolinium 157.2	65 Tb terbium 158.9	66 Dy dysprosium 162.5	67 Ho holmium 164.9	68 Er erbium 167.3	69 Tm thulium 168.9	70 Yb ytterbium 173.0	71 Lu lutetium 175.0
Actinide Series**	89 Ac actinium (227)	90 Th thorium 232	91 Pa protactinium 231	92 U uranium 238	93 Np neptunium (237)	94 Pu plutonium (244)	95 Am americium (243)	96 Cm curium (247)	97 Bk berkelium (247)	98 Cf californium (251)	99 Es einsteinium (252)	100 Fm fermium (257)	101 Md mendelevium (258)	102 No nobelium (259)	103 Lr lawrencium (262)

Los Alamos
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CHEMISTRY

element names in blue are liquids at room temperature
element names in red are gases at room temperature
element names in black are solids at room temperature

Modified from Los Alamos National Laboratory Chemistry Division; available at http://periodic.lanl.gov/images/periodictable.pdf.

Cover. Upper left, nodule of fluorite, opal, and quartz that contains about 1 percent beryllium as bertrandite. Photograph from Foley and others (2012). Lower left, lithium-cesium-tantalum-type pegmatite that shows typical green coloration in an assemblage of quartz and mica. Photograph from USGS archive. Upper right, beryllium metal is used to make mirrors of powerful telescopes. Photograph courtesy of Ball Aerospace. Lower right, beryllium-copper alloys are used to make contacts and connectors, switches, relays, and shielding for everything from cell phones and computers to thermostats, high-definition televisions, and automobiles, as well as electrical connectors necessary for next-generation Thermal Ionization Mass Spectrometers, and electrical contacts in cell phones and computers. Photograph courtesy of Spectromat Massenspektrometer GmbH.

Beryllium

By Nora K. Foley, Brian W. Jaskula, Nadine M. Piatak, and Ruth F. Schulte

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Edited by Klaus J. Schulz, John H. DeYoung, Jr., Robert R. Seal II, and Dwight C. Bradley

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U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
William H. Werkheiser, Acting Director

U.S. Geological Survey, Reston, Virginia: 2017

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Conversion Factors

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
angstrom (Å) (0.1 nanometer)	0.003937	microinch
angstrom (Å) (0.1 nanometer)	0.000003937	mil
micrometer (µm) [or micron]	0.03937	mil
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.6214	mile (mi)
	Area	
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
square centimeter (cm^2)	0.1550	square inch (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
milliliter (mL)	0.03381	ounce, fluid (fl. oz)
liter (L)	33.81402	ounce, fluid (fl. oz)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
	Mass	
microgram (µg)	0.00000003527	ounce, avoirdupois (oz)
milligram (mg)	0.00003527	ounce, avoirdupois (oz)
gram (g)	0.03527	ounce, avoirdupois (oz)
gram (g)	0.03215075	ounce, troy
kilogram (kg)	32.15075	ounce, troy
kilogram (kg)	2.205	pound avoirdupois (lb)
ton, metric (t)	1.102	ton, short [2,000 lb]
ton, metric (t)	0.9842	ton, long [2,240 lb]
	Deposit grade	
gram per metric ton (g/t)	0.0291667	ounce per short ton (2,000 lb) (oz/T)
	Pressure	
megapascal (MPa)	10	bar
gigapascal (GPa)	10,000	bar
	Density	
gram per cubic centimeter (g/cm^3)	62.4220	pound per cubic foot (lb/ft^3)
milligram per cubic meter (mg/m^3)	0.00000006243	pound per cubic foot (lb/ft^3)
	Energy	
joule (J)	0.0000002	kilowatthour (kWh)
joule (J)	6.241×10^{18}	electronvolt (eV)
joule (J)	0.2388	calorie (cal)
kilojoule (kJ)	0.0002388	kilocalorie (kcal)

International System of Units to Inch/Pound—Continued

Multiply	By	To obtain
	Radioactivity	
becquerel (Bq)	0.00002703	microcurie (µCi)
kilobecquerel (kBq)	0.02703	microcurie (µCi)
	Electrical resistivity	
ohm meter (Ω-m)	39.37	ohm inch (Ω-in.)
ohm-centimeter (Ω-cm)	0.3937	ohm inch (Ω-in.)
	Thermal conductivity	
watt per centimeter per degree Celsius (watt/cm °C)	693.1798	International British thermal unit inch per hour per square foot per degree Fahrenheit (Btu in/h ft^2 °F)
watt per meter kelvin (W/m-K)	6.9318	International British thermal unit inch per hour per square foot per degree Fahrenheit (Btu in/h ft^2 °F)

Inch/Pound to International System of Units

	Length	
mil	25.4	micrometer (µm) [or micron]
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
ounce, fluid (fl. oz)	29.57	milliliter (mL)
ounce, fluid (fl. oz)	0.02957	liter (L)
	Mass	
ounce, avoirdupois (oz)	28,350,000	microgram
ounce, avoirdupois (oz)	28,350	milligram
ounce, avoirdupois (oz)	28.35	gram (g)
ounce, troy	31.10 348	gram (g)
ounce, troy	0.03110348	kilogram (kg)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	ton, metric (t)
ton, long (2,240 lb)	1.016	ton, metric (t)
	Deposit grade	
ounce per short ton (2,000 lb) (oz/T)	34.285714	gram per metric ton (g/t)
	Energy	
kilowatthour (kWh)	3,600,000	joule (J)
electronvolt (eV)	1.602×10^{-19}	joule (J)
	Radioactivity	
microcurie (µCi)	37,000	becquerel (Bq)
microcurie (µCi)	37	kilobecquerel (kBq)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Celsius (°C) may be converted to kelvin (K) as follows:

$$K = °C + 273.15$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

Datum

Unless otherwise stated, vertical and horizontal coordinate information is referenced to the World Geodetic System of 1984 (WGS 84). Altitude, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in soils and (or) sediment are given in milligrams per kilogram (mg/kg), parts per million (ppm), or parts per billion (ppb).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L), micrograms per liter (µg/L), nanogams per liter (ng/L), nanomoles per kilogram (nmol/kg), parts per million (ppm), parts per billion (ppb), or parts per trillion (ppt).

Concentrations of suspended particulates in water are given in micrograms per gram (µg/g), milligrams per kilogram (mg/kg), or femtograms per gram (fg/g).

Concentrations of chemicals in air are given in units of the mass of the chemical (milligrams, micrograms, nanograms, or picograms) per volume of air (cubic meter).

Activities for radioactive constituents in air are given in microcuries per milliliter (µCi/mL).

Deposit grades are commonly given in percent, grams per metric ton (g/t)—which is equivalent to parts per million (ppm)—or troy ounces per short ton (oz/T).

Geologic ages are expressed in mega-annum (Ma, million years before present, or 10^6 years ago) or giga-annum (Ga, billion years before present, or 10^9 years ago).

For ranges of years, “to” and (or) the en dash (“–”) mean “up to and including.”

Concentration unit	Equals
milligram per kilogram (mg/kg)	part per million
microgram per gram (µg/g)	part per million
microgram per kilogram (µg/kg)	part per billion (10^9)

Equivalencies

part per million (ppm): 1 ppm = 1,000 ppb = 1,000,000 ppt = 0.0001 percent

part per billion (ppb): 0.001 ppm = 1 ppb = 1,000 ppt = 0.0000001 percent

part per trillion (ppt): 0.000001 ppm = 0.001 ppb = 1 ppt = 0.0000000001 percent

Metric system prefixes

tera- (T-)	10^{12}	1 trillion
giga- (G-)	10^{9}	1 billion
mega- (M-)	10^{6}	1 million
kilo- (k-)	10^{3}	1 thousand
hecto- (h-)	10^{2}	1 hundred
deka- (da-)	10	1 ten
deci- (d-)	10^{-1}	1 tenth
centi- (c-)	10^{-2}	1 hundredth
milli- (m-)	10^{-3}	1 thousandth
micro- (µ-)	10^{-6}	1 millionth
nano- (n-)	10^{-9}	1 billionth
pico- (p-)	10^{-12}	1 trillionth
femto- (f-)	10^{-15}	1 quadrillionth
atto- (a-)	10^{-18}	1 quintillionth

Abbreviations and Symbols

°C	degree Celsius
μg/m^3	microgram per cubic meter
Å	angstrom
BCMA	beryllium-copper master alloy
cm	centimeter
DOD	U.S. Department of Defense
EPA	U.S. Environmental Protection Agency
IED	improvised explosive device
km	kilometer
LCT	lithium-cesium-tantalum
LED	light-emitting diode
LOEL	lowest observable effect limit
m	meter
Ma	mega-annum
mg/m^3	milligram per cubic meter
MRI	magnetic resonance imaging
ng/m^3	nanogram per cubic meter
NI	National Instrument
NYF	niobium-yttrium-fluorine
ppb	part per billion
ppm	part per million
ppt	part per trillion
REE	rare-earth element

Beryllium

By Nora K. Foley, Brian W. Jaskula, Nadine M. Piatak, and Ruth F. Schulte

Abstract

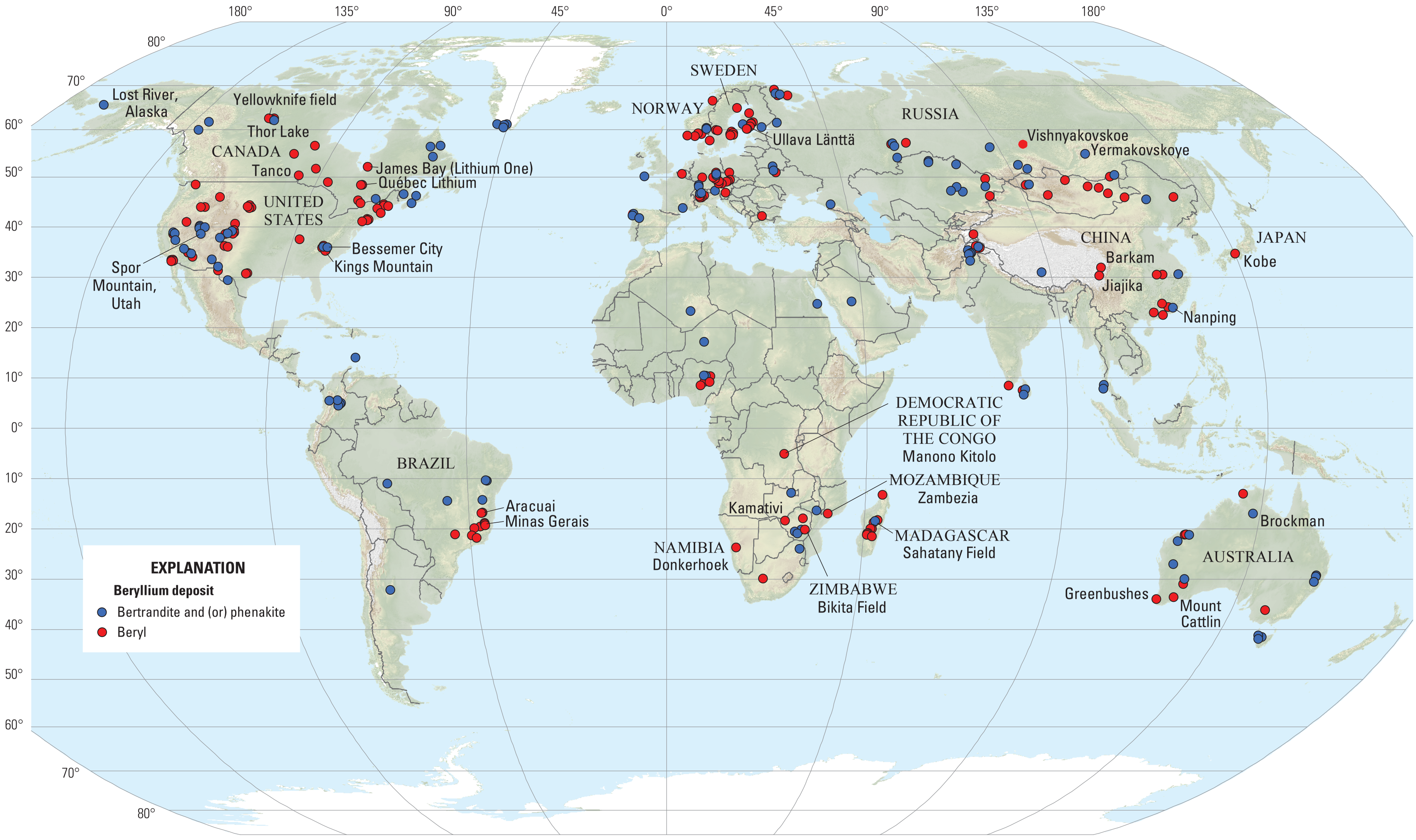
Beryllium is a mineral commodity that is used in a variety of industries to make products that are essential for the smooth functioning of a modern society. Two minerals, bertrandite (which is supplied domestically) and beryl (which is currently supplied solely by imports), are necessary to ensure a stable supply of high-purity beryllium metal, alloys, and metal-matrix composites and beryllium oxide ceramics. Although bertrandite is the source mineral for more than 90 percent of the beryllium produced globally, industrial beryl is critical for the production of the very high purity beryllium metal needed for some strategic applications. The current sole domestic source of beryllium is bertrandite ore from the Spor Mountain deposit in Utah; beryl is imported mainly from Brazil, China, Madagascar, Mozambique, and Portugal. High-purity beryllium metal is classified as a strategic and critical material by the Strategic Materials Protection Board of the U.S. Department of Defense because it is used in products that are vital to national security. Beryllium is maintained in the U.S. stockpile of strategic materials in the form of hot-pressed beryllium metal powder.

Because of its unique chemical properties, beryllium is indispensable for many important industrial products used in the aerospace, computer, defense, medical, nuclear, and telecommunications industries. For example, high-performance alloys of beryllium are used in many specialized, high-technology electronics applications, as they are energy efficient and can be used to fabricate miniaturized components. Beryllium-copper alloys are used as contacts and connectors, switches, relays, and shielding for everything from cell phones to thermostats, and beryllium-nickel alloys excel in producing wear-resistant and shape-retaining high-temperature springs. Beryllium metal composites, which combine the fabrication ability of aluminum with the thermal conductivity and highly elastic modulus of beryllium, are ideal for producing aircraft and satellite structural components that have a high stiffness-to-weight ratio and low surface vibration. Beryllium oxide ceramics are used in a wide range of applications, including missile guidance systems, radar applications, and cell phone transmitters, and they are critical to medical technologies, such as magnetic resonance imaging (MRI) machines, medical lasers, and portable defibrillators.

The United States is expected to remain self-sufficient with respect to most of its beryllium requirements, based on information available at the time this chapter was prepared (2013). The United States is one of only three countries that currently process beryllium ores and concentrate them into beryllium products, and these three countries supply most of the rest of the world with these products. Exploration for new deposits in the United States is limited because domestic beryllium production is dominated by a single producer that effectively controls the domestic beryllium market, which is relatively small and specialized, and the market cannot readily accommodate new competition on the raw material supply side.

Introduction

This chapter provides an overview of the main types of mineral resources from which beryllium is extracted and refined. Beryllium is a mineral commodity that is used in a variety of industries to make products that are important for modern society. It updates the work of Griffitts (1973) on the history and then-current status of domestic resources of beryllium. Advances in understanding the geochemistry of beryllium (table E1), the mineralogy (table E2), and the genesis of current and potential sources of beryllium (tables E3 and E4), the global distribution of beryllium resources (fig. E1), and the consequences of mining these resources all contribute to a better sense of the factors that can influence beryllium supply and demand in a global market. Two distinct classes of deposits currently account for most beryllium ores; they are (a) volcanic and carbonate-hosted deposits that contain the mineral bertrandite, and (b) pegmatite deposits that have an abundance of the mineral beryl (fig. E2). The primary global provider of bertrandite is a single world-class deposit of the volcanogenic beryllium type located in the United States near Spor Mountain, Utah. Beryllium is also derived from beryl found in rare-metal pegmatite deposits



Base from U.S. Geological Survey Global 30 arc-second elevation data (1996) and from Natural Earth (2014); Robinson projection; World Geodetic System 1984 datum

Figure E1. World map showing locations of selected deposits of beryllium by the two major beryllium-bearing mineral types: bertrandite and (or) phenakite, and beryl. Bertrandite and phenakite are beryllium-bearing silicate minerals; beryl is a beryllium-bearing aluminum silicate mineral. Spor Mountain, Utah, is the only deposit of bertrandite in the United States that is currently being mined. Dots with labels indicate pegmatite districts and deposits that reportedly have been or are currently being mined for beryl (Foley and others, 2012; Kesler and others, 2012; Bradley and McCauley, 2013).

Figure E2. Photographs showing the minerals bertrandite, which can contain up to 42 percent beryllium oxide, and industrial beryl, which can contain up to about 5 percent beryllium. Photograph *A* is a nodule of fluorite, opal, and quartz that contains about 1 percent beryllium as bertrandite (Foley and others, 2012). Photograph *B* is beryl from a pegmatite of the lithium-cesium-tantalum family and shows typical green coloration in an assemblage of quartz and mica (U.S. Geological Survey archive).

(mainly of the lithium-cesium-tantalum [LCT] family), which are widely distributed throughout the world. These pegmatite ores provide the beryllium industry with the beryllium metals and metal-oxides of various levels of purity that are essential in the production of many special alloys and ceramics. In addition, some isotopes of beryllium metal (including ^{10}Be and ^{7}Be) are used by research scientists to understand many geologic processes. Some important uses of beryllium isotopes are as a petrogenetic index to trace (a) the connection between sediment subduction and island arc volcanism to show whether sediments are younger than about 3 to 4 months in age, and (b) climatic changes as reflected in soils, snow, and ice.

Strategic and Critical Resource Issues

High-purity beryllium metal is classified as a strategic and critical material by the Strategic Materials Protection Board of the U.S. Department of Defense (DOD) because it is used in products that are vital to national security (U.S. Department of Defense, 2009). The DOD is required by the Board to continue to take special actions to maintain a long-term domestic supply because domestic beryllium production capabilities have diminished over time. As a result, a partnership between the DOD and Materion Corp. of Ohio was established to ensure a long-term stable domestic supply of primary beryllium metal, and the United States continues to maintain a stockpile of beryllium metal for use during a national emergency. As of December 31, 2011, the National Defense Stockpile goal for hot-pressed beryllium metal powder was 45 metric tons. In 2015, the goal, now updated to include vacuum-cast beryllium metal, was 47 metric tons. In 2015, the inventory held 78 metric tons, a surplus of 31 metric tons. Although bertrandite (fig. E2*A*) is the source mineral for more than 90 percent of beryllium produced globally, industrial beryl (fig. E2*B*), which has been supplied in recent years by imports, is critical in the production of ultra-high-purity beryllium metal. Ultra-high-purity beryllium is made exclusively from beryl, as beryl typically has fewer impurities (for example, fluorine and uranium) than bertrandite. Beryl-sourced ultra-high-purity beryllium is most effectively used in nuclear applications, where the absence of uranium in the beryl allows for safe and timely disposal of nuclear waste, and in foil for use as X-ray windows for medical applications. Thus, at the present time, both volcanogenic beryllium and LCT pegmatite resources are needed to ensure a stable supply of beryllium for strategic and critical applications.

Uses and Applications

Because of its chemical properties, beryllium metal is indispensable in many industrial applications. Products made from beryllium (fig. E3) are used in the aerospace, computer, defense, medical, nuclear, and telecommunications industries (Jaskula, 2013a).

Complex processing techniques and high costs (the price of beryllium generally ranges from $150 to $225 per pound) restrict the use of beryllium to applications where performance is critical and for which there are no practical alternatives. Although it is such a light metal, beryllium is strong and refractory; it is also highly resistant to corrosion because it readily develops an oxide film, and it has high thermal conductivity (table E1). Strategic military applications for high-purity beryllium metal include housings for optical targeting systems used for real-time imagery and surveillance in both manned helicopters and unmanned aerial systems and beryllium mirrors for ensuring vibration-free

A. **James Webb Space Telescope**

B. **Be-Cu alloy connectors**

C. **Al-In-Be-P LEDs**

Figure E3. Photographs illustrating some of the many uses of beryllium. *A*, Beryllium metal has been used to make mirrors of powerful telescopes. *B*, Beryllium-copper (Be-Cu) alloys are used to make contacts and connectors, switches, relays, and shielding for everything from cell phones and computers to thermostats, high-definition televisions, and automobiles, as well as electrical connectors necessary for next-generation Thermal Ionization Mass Spectrometers, and electrical contacts in cell phones and computers. *C*, Metal matrix composites of beryllium are used in high-performance electronics for aluminum-indium-beryllium-phosphorus light-emitting diode (LED) pins, which provide superior performance in high-voltage heat-producing circuits. (Photograph *A* is courtesy of Ball Aerospace; photographs *B* and *C* are courtesy of Spectromat Massenspektrometer GmbH.)

paths for targeting and firing controls in battle tanks and guided missile defense systems. Beryllium metal is also integral to the airborne equipment used to detect and destroy improvised explosive devices (IEDs) and tactical mines. Because beryllium metal is transparent to X-rays, it is also used to produce metallic glasses, thin foils, and mirrors. Beryllium glasses and foils are used in medical X-ray imaging and detector applications, for beryllium mirrors in satellites, for telescope optics, and in optical guidance systems. For example, mirror segments for the James Webb Space Telescope (fig. E3*A*) are made from beryllium.

When combined with copper, aluminum, and other metals, beryllium is used to produce light and very strong alloys needed for aerospace, automobile, and computer technologies; oil and gas drilling equipment; musical instruments; medical devices; and telecommunications equipment. Alloys are used in many specialized electronics applications, as they are energy efficient and can be used to fabricate miniaturized components. Beryllium-copper alloys (fig. E3*B*) are used to make contacts and connectors, switches, relays, and shielding to everything from cell phones and computers to thermostats, high-definition televisions, and automobiles. Beryllium-nickel alloys excel in producing wear-resistant and shape-retaining high-temperature springs, contacts, and connectors. Beryllium-aluminum alloys are prepared for applications where critical weight, stiffness, and thermal specifications must be met. Beryllium-metal composites (fig. E3*C*) combine the fabrication ability of aluminum with the thermal conductivity and highly elastic modulus of beryllium. These qualities are valuable for producing aircraft and satellite structural components that have a high stiffness-to-weight ratio and low surface vibration.

Beryllium oxide is an excellent refractory material that is produced from beryllium metal, and it has some interesting uses in ceramics. In high-performance electronics, heat dissipation and electrical insulation are of critical importance for the electrical circuits to function effectively. Beryllium oxide ceramics provide superior thermal management performance in heat-producing circuits, such as those carrying high currents, where there is little airflow, or where the circuits are exposed to high ambient temperatures. These types of ceramics are used in a wide range of applications, including missile guidance systems, radar applications, and cell phone transmitters. Beryllium oxide in ceramic form is used to make high-performance semiconductor parts for radio equipment because it has good thermal conductivity and is a good electrical insulator. Semiconductor devices that use beryllium oxide ceramics instead of aluminum oxide between the silicon chip and the metal mounting base tend to last longer because the beryllium oxide ceramics provide more heat resistance. Beryllium ceramics are also vital to critical medical technologies, such as magnetic resonance imaging (MRI) machines, medical lasers, and portable defibrillators, because they are used to build parts of high-performance microwave devices, vacuum tubes, magnetrons, and gas lasers that are used in such medical devices.

The uses of materials produced from beryllium in certain specialized applications are expected to expand rapidly with advances in technology. For example, work is underway to develop a viable manufacturing process for nuclear fuel that contains both beryllium and uranium oxides because, in spite of the high cost of beryllium relative to that of uranium (the price of U235 was about $43 per pound in 2013 compared with beryllium's cost of $150 to $225 per pound), beryllium fuels may be longer lasting, more efficient, and safer than conventional nuclear fuels (Kim and others, 2010). Because the cost of beryllium is high compared with the cost of many other materials, less expensive materials are substituted where possible. For example, in some less-demanding applications, copper alloyed with Ni-Si, Sn, Ti, or Sn-P may be substituted for high-cost beryllium-copper alloys, and aluminum nitride or boron nitride may be substituted for high-cost beryllium oxide with no loss in performance. The substitution of high-strength grades of aluminum metal, pyrolytic graphite (an ultra-thin graphite film with a thermal conductivity up to four times greater than that of copper), silicon carbide, steel, or titanium metal for beryllium metal or composites, however, can result in substantially reduced performance.

A snapshot of uses of beryllium in the United States for the main classes of products by market share for 2011 are shown in figure E4. Performance alloys include the beryllium-copper and beryllium-aluminum alloys that consume most of the beryllium produced globally. Beryllium and composites include high-purity metals and metal-matrix composites and ceramics. Sales of performance alloys (fig. E4*A*) are about 600 percent greater than sales of the beryllium metal, composites, and ceramics sectors combined (fig. E4*B*). For beryllium metal and composites, defense and science applications accounted for approximately one-half of company sales in 2011, which was an 8 percent decrease compared with that of 2010; the decrease was thought to be owing to Government funding delays. Sales increased, however, for industrial component and commercial aerospace applications of both alloys and composites owing to an increase in the production of X-ray window assemblies. Sales for energy applications of performance alloys increased slightly in 2011 compared with those of 2010 (Materion Corp., 2012a). Sales of ceramic products decreased slightly in 2011 after increasing by more than 50 percent in 2010 owing largely to increased shipments for applications within the telecommunications infrastructure market (Materion Corp., 2012a). Worldwide beryllium consumption is predicted to increase to 506 metric tons per year of contained beryllium by 2017 owing to sustained consumption from the computer and telecommunications infrastructure markets and the growing automotive electronics market (Global Industry Analysts, Inc., 2012). Developing markets in Asia and Latin America are also expected to increase consumption even though miniaturization in component manufacturing is requiring less beryllium than before for many uses.

Recycling efforts are important because of the huge energy savings that recycled beryllium brings to manufacturing. Manufacturing beryllium products from recycled sources requires only 20 percent of the energy required to manufacture beryllium products from ore. China, Kazakhstan, and the United States are the only countries that are currently capable of processing recycled scrap. Beryllium is recycled from new scrap generated during the manufacture of beryllium-containing components as well as from post-consumer scrap collected from end users worldwide. Owing to the long lifetime of many beryllium products, the technical difficulty of recycling beryllium (because of its use in complex alloys), and the low concentration of beryllium present in many consumer products, the percentage of scrap in the recycling flow was previously estimated to be between

Table E1. Selected properties of beryllium, which is a Group 2 alkaline earth metal.

[Source: Lide (2005, p. 14–39). Å, angstrom; Be, beryllium; BeH, beryllium hydride; °C, degree Celsius; eV, electronvolt; g/cm^3, gram per cubic centimeter; GPa, gigapascal; J/mol K, joule per mole kelvin; K, kelvin; kJ/mol, kilojoule per mole; Mpa, megapascal; nΩ-m, nano ohm-meter; ppm, part per meter; µm/m K, micrometer per meter kelvin; W/m K, watt per meter kelvin]

Property	Value
Atomic number	4
Atomic weight	9.012182
Isotopes	12 known radioisotopes; ^{9}Be is the only stable isotope; ^{10}Be has a half-life of 1.39 million years
Density at 293 K (g/cm^3)	1.8477
Melting point (°C)	1,287
Boiling point (°C)	2,469
Heat of fusion (kJ/mol)	12.2
Heat of vaporization (kJ/mol)	297
Molar heat capacity (J/mol K)	16.443
Hardness (Mohs scale)	5.5
Vickers hardness (Mpa)	1,670
Electrical resistivity at 20 °C (nΩ-m)	36
Thermal conductivity (W/m K)	200
Thermal expansion at 25 °C (µm/m K)	11.3
Young's modulus (GPa)	287
Crystal structure	Hexagonal
Magnetic ordering	Diamagnetic
Electron configuration	1s^{2}2s^2
Ionic radius (Å)	0.27
First ionization potential (eV)	9.32
Second ionization potential (eV)	18.21
Common valance states	+2, rarely +1 (BeH molecule)
Abundance, upper continental crust (ppm)	About 1.9 (Hu and Gao, 2008)

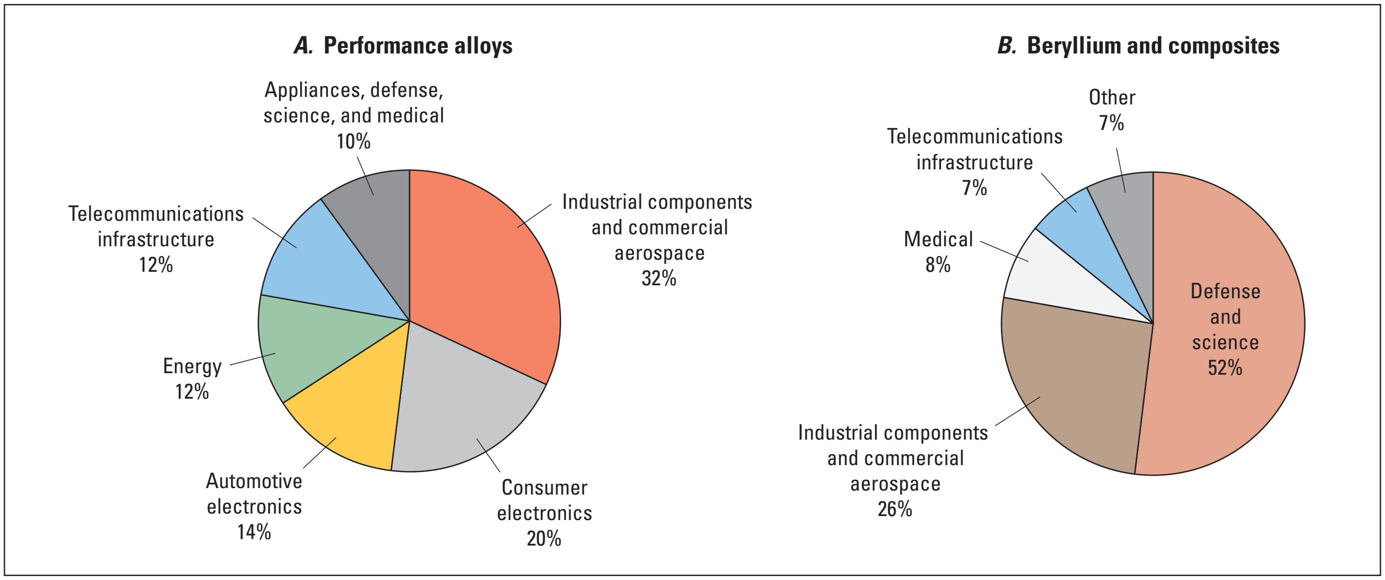


Figure E4. Pie charts showing reported end uses of beryllium consumed in the United States in 2011 for the two main classes of products—*A*, performance alloys, and *B*, beryllium and composites (metals and ceramics). Usage is shown as a percentage of market share (Materion Corp., 2012a).

10 and 25 percent, based on data collected for 2000 through 2005 (Graedel and others, 2011). Recent information from Materion, however, shows that an extensive worldwide recycling program for beryllium products is currently achieving a 40 percent recovery rate of beryllium from both of its new and postconsumer scrap sources (Jaskula, 2013a).

Geology

Geochemistry

Beryllium (table E1) is a member of Group 2 of the periodic table of elements; however, it has distinct differences in its crystal chemistry from other elements in the group, and these differences contribute to beryllium's fundamentally unique attributes. Beryllium has 12 known isotopes and only 1, ^{9}Be, is stable. Of the radiogenic isotopes of beryllium, the most stable are ^{10}Be, which has a half-life of 1.39 million years, and ^{7}Be, which has a half-life of about 53 days; most of the others decay in milliseconds. Beryllium is the lightest of the alkaline earth elements, and its low atomic number (4) results in high first and second ionization potentials (9.32 and 18.21 electronvolts, respectively). As a consequence, beryllium can readily strip (or ionize) electrons from other uncharged atoms, and, owing to its small size (ionic radius of about 0.27 angstroms (Shannon, 1976), Be^{2+} has a strong tendency to polarize the electron clouds of the ligands to which it binds, forming bonds of shared electrons in compounds (Wuensch, 1972). These are strong and short chemical bonds that generate compounds displaying great hardness and high melting temperatures. Beryllium generally behaves as a hard acid (Pearson, 1963), preferentially forming complexes with hard ligands, such as carbonate, fluoride, and hydroxide. Because of its extremely small size, beryllium is not easily displaced by other elements in crystals and tends to form distinct minerals. Studies of the speciation and solubility of beryllium minerals at temperatures to 300 degrees Celsius (°C) for Be^{2+} (its only known oxidation state in aqueous solution) suggest that beryllium is most likely to be transported in low-temperature hydrothermal fluid as a fluoride or fluoride-carbonate complex (Wood, 1992, and references therein). Over a wide range of temperatures and pH, the solubility of beryllium as a simple ion and its hydrolysis products are much less than 1 part per million (ppm) in solution. Thus, once formed, most beryllium minerals persist in surficial environments.

Beryllium is the 47th most abundant element found in Earth's crust (Emsley, 2001), and it is widely distributed in many rocks types (Hörmann, 1978). Beryllium behaves as a lithophile element in that it combines readily with oxygen to form light beryllium oxide compounds, which leads to its enrichment in Earth's crust rather than in the core. The concentration in primitive mantle is inferred to be about 60 parts per billion (ppb) beryllium (Taylor and McLennan, 1985, 1995), whereas estimates of the concentration of beryllium in the upper continental crust range from 1.9 to 3.1 ppm beryllium (table E1), which is an increase of more than fortyfold. This also accounts for the notable increases in beryllium concentrations in highly evolved volcanic and plutonic rocks, in granitic pegmatites, and in alkalic rocks compared with mantle compositions. In granite, the averages vary from 5 ppm beryllium (in biotite granite) to 10 ppm beryllium (in muscovite and two-mica granite) (Hörmann, 1978; Taylor and

McLennan, 1985, 1995). Nepheline syenite and fluorine-rich topaz-bearing rhyolites are even more enriched in beryllium than common felsic rocks. For example, alkalic rocks from Lovozero, Murmansk Oblast, Russia, contain beryllium in the range of about 3 to 24 ppm beryllium, and some fluorine-rich topaz-bearing volcanic rocks in the Western United States have average contents of 50 ppm beryllium (Hörmann, 1978). Extreme enrichments are encountered in some unique rocks; for example, the Ilímaussaq complex in southern Greenland has peralkaline nepheline syenites that contain from 7 to 44 ppm beryllium—including some unusual rocks that have between 330 and 1,970 ppm beryllium (Engell and others, 1971)—and the Cornudas Mountains deposit in New Mexico, which has nepheline syenites that contain up to 150 ppm beryllium (McLemore and Guilinger, 1993). Most beryllium-rich pegmatites have bulk beryllium contents of less than 250 to 420 ppm beryllium (London and Evensen, 2002), although some albitic pegmatites have bulk contents in the range of from 360 to 720 ppm beryllium, which can be highly concentrated in specific zones within zoned granitic pegmatites (Černý, 2002). Hydrothermal processes can further concentrate beryllium in both pegmatite and volcanogenic systems. For example, altered rock (griesen) around a granite pluton at the Boomer Mine in Colorado contains up to 2.3 percent beryllium, by weight, and volcanic tuff altered by heated circulating waters at Spor Mountain, Utah, may contain up to 3,600 ppm beryllium (Foley and others, 2012). Weathering of beryllium-enriched igneous rocks results in clay-bearing sedimentary rocks that serve as an important reservoir of beryllium in Earth's crust. Metamorphism of such rocks as crustal plates subducted at convergent boundaries plays a critical role in the recycling of beryllium. Anatectic processes in the subduction zone cause partial melting of the crust, which releases the lithophile component in the rocks and generates beryllium-enriched magmas that are the source for new granitic rocks, thus completing the beryllium geochemical cycle.

Mineralogy

More than 100 distinct minerals that contain beryllium as an essential component of the mineral structure are known to occur in nature; these include arsenate, borate, hydroxide, oxide, phosphate, and silicate types. The relative stabilities of the major beryllium minerals (table E2) and their occurrence in diverse geologic environments are well established (Beus, 1966; Barton and Young, 2002; Černý, 2002).

Beryl is the main beryllium ore mineral in plutonic systems and metamorphic environments, whereas bertrandite and phenakite are the predominant ore minerals in near-surface volcanogenic and carbonate-hosted deposits. A number of other beryllium-bearing minerals, such as chrysoberyl and helvite, have reportedly been mined in small amounts from some deposits.

Beryl (fig. E2) is the primary beryllium silicate mineral that forms in rocks at high temperatures, and it has relatively widespread natural abundance (Barton, 1986; Barton and Young, 2002, and references therein). Beryllium saturation, and thus beryl solubility, varies as a function of the activities of beryllium, aluminum, and silicon. Beryl saturation can occur in granitic melts containing about 50 ppm beryllium at temperatures of 400 °C (London, 2005). Beryl has the ability to incorporate high and variable amounts of cesium, sodium, and water in large channels in its crystal structure and may show isomorphic substitutions of lithium for beryllium and magnesium, and iron and scandium for aluminum. These factors result in beryl being stable over a large range of temperature and pressure conditions and account for its presence in diverse geologic environments. The lower stability limit of beryl occurrence varies from 200 to 350 °C, depending on the compositions of coexisting minerals.

Beryl is the predominant beryllium phase in zoned granitic rare-element pegmatite environments where it occurs with other rare minerals of commercial importance, such as cesium, lithium, and tantalum, as well as clays, feldspar, muscovite, and high-purity quartz (London and Kontak, 2012; Glover and others, 2012). In general, beryl is the only source of beryllium found in pegmatite deposits, although chrysoberyl is locally abundant in some pegmatites (table E2) (Linnen and others, 2012). Other occurrences of beryl include its presence in miarolitic cavities in volcanic rocks related to topaz-bearing igneous systems; for example, red beryl in the Wah Wah Mountains of Utah (Keith and others, 1994).

Bertrandite is the stable mineral in surface environments, as it forms at or below a temperature of 250 °C, and phenakite is stable at temperatures greater than 250 °C. Phenakite hydrates to bertrandite at lower temperatures (Barton, 1986). Bertrandite and phenakite are commonly found with beryl in carbonate-hosted skarn deposits and greisen associated with granite intrusions. Bertrandite is the predominant host for beryllium in volcanogenic deposits and occurs with phenakite in veins in carbonate replacement deposits. Precipitation in epithermal environments can result in cryptocrystalline and possibly colloidal bertrandite having variable amounts of molecular water that is readily lost on heating. The variety of bertrandite at Spor Mountain, Utah, reportedly has chemical and physical properties intermediate between colloidal bertrandite and bertrandite proper (Montoya and others, 1962).

The beryllium content in minerals in which it occurs as a substitute for another element, such as the important rock-forming minerals, is typically 10 ppm or less and rarely exceeds 100 ppm (London and Evensen, 2002). Several minerals have been reported to incorporate beryllium in higher amounts (that is, >0.1 weight percent beryllium oxide, or 350 ppm beryllium). These include clay minerals of the smectite group that reportedly can contain up to 2.8 weight percent beryllium oxide as either crystallographic substitution or ionic adsorption on clay surfaces (Montoya and others, 1962).

Table E2. Selected beryllium minerals.

[Sources: Barton and Young (2002), Grew (2002), Foley and others (2010), and Jaskula (2013b). BeO, beryllium oxide; —, limited or no commercial use]

Mineral name	Chemical formula	BeO (percent)	Use	Deposit model, occurrence type
Barylite	$BaBe_2Si_2O_7$	16	—	Alkalic pegmatite, skarn, greisen
Bazzite	$Be_3(Sc,Al)_2Si_6O_{18}$	13.29	—	Alkalic and granitic pegmatite, vein
Behoite	$Be(OH)_2$	58.13	—	Alkalic pegmatite, skarn, rhyolite
Bertrandite	$Be_4Si_2O_7(OH)_2$	42	Industrial	Greisen, skarn, vein, rhyolite
Beryl	$Be_3Al_2Si_6O_{18}$	13.96	Industrial, gem	Granitic pegmatite, greisen, skarn, vein, rhyolite
Beryl, variety emerald	$Be_3(Al,Cr,V)_2Si_6O_{18}$	13.96	Gem	Granitic pegmatite and metamorphosed equivalents, vein
Beryl, variety aquamarine	$Be_3(Fe,Al)_2Si_6O_{18}$	13.96	Gem	Granitic pegmatite and metamorphosed equivalents, vein
Beryllite	$Be_3SiO_4(OH)_2 \cdot (H_2O)$	43.84	Industrial?	Rocks of the Ilimaussaq intrusion
Chrysoberyl	$BeAl_2O_4$	19.7	Industrial, gem	Granitic pegmatite, skarn, vein
Danalite	$Fe_4Be_3Si_3O_{12}S$	13.43	—	Skarn, granitic pegmatite
Epididymite	$Na_2Be_2Si_6O_{15} \cdot H_2O$	10.2	—	Alkalic pegmatite, skarn
Euclase	$BeAlSiO_4(OH)$	17.24	Gem	Granitic pegmatite, greisen, skarn, vein
Gadolinite-(Y),-(Ce)	$Be_2Fe(Y,REE)_2Si_2O_{10}$	10.69	—	Alkaline pegmatite and granite, vein, greisen
Hambergite	$Be_2(OH,F)BO_3$	53.31	—	Alkaline and granitic pegmatite
Helvite	$Mn_4Be_3Si_3O_{12}S$	13.52	Industrial	Veins, skarn, greisen, alkaline and granitic pegmatite
Herderite	$CaBePO_4(F,OH)$	15.34	—	Greisen, granitic pegmatite
Hurlbutite	$CaBe_2(PO_4)_2$	20.17	—	Granitic pegmatite, vein
Leucophanite	$CaNaBeSi_2O_6F$	10.6	—	Alkaline pegmatite, skarn
Meliphanite	$Ca_4(Na,Ca)_4Be_4AlSi_7O_{24}(F,O)_4$	10.37	—	Alkaline pegmatite, skarn
Milarite	$K(H_2O,Na)_2(Ca,Y,REE)_2(Be,Al)_3Si_{12}O_{30}$	5.05	—	Alkaline and granitic pegmatite, skarn, vein
Phenakite	Be_2SiO_4	45.43	Industrial, gem	Alkaline and granitic pegmatite, skarn, greisen, vein
Tugtupite	$Na_4AlBeSi_4O_{12}Cl$	5.35	Gem, industrial?	Rocks of the Ilimaussaq intrusion

Deposit Types

Magmatic-Related Beryllium Deposits

Beryllium deposits are most commonly associated with geologic environments that show a clear link to magmatic processes (Barton and Young, 2002; Černý, 2002). Magmatic-related beryllium deposits can be characterized in terms of (a) the petrologic association of the igneous rocks, (b) the type of associated country rock, and (c) the nature of the depositional environment (table E3).

Magmatic-related beryllium deposits and occurrences are found in two general rock types—alkaline to peralkaline and metaluminous to peraluminous—which are distinguished on the basis of whole-rock chemistry. The deposit types can be divided into those associated with rare-metal enriched felsic intrusions and related volcanic sequences and pegmatite bodies, and those that form where rare-metal enriched magmas interact with adjacent country rocks. Thus, rare-metal plutons and related pegmatite deposits containing beryl; skarn and greisen deposits containing bertrandite, beryl, and phenakite; and volcanogenic and carbonate-hosted deposits of mainly bertrandite are the types associated with large-scale magmatic systems (for example, fig. E5). Of these, lithium-rich pegmatites that contain beryl in high-grade pockets (Bradley and McCauley, 2013) and large-tonnage, high-grade volcanogenic beryllium deposits (Foley and others, 2012) are economically important at present (table E3, shown in shading; modified from Barton and Young, 2002).

Rare-Metal Pegmatite Deposits—Beryllium Type

Many plutons of gabbro, granite, and syenite composition contain minor amounts of beryl; however, in general, only rare-metal granitic pegmatites contain beryl in sufficient quantities to mine. Although granitic pegmatites are widespread and relatively common, rare-metal pegmatites make up only about 0.1 percent of the total fraction (Laznicka, 2006). Rare-metal pegmatites (table E3; fig. E5) that contain relatively abundant beryl include those of the rare element class, lithium subclass, beryl type (LCT family) and those of the miarolitic class, REE subclass, topaz-beryl type (niobium-yttrium-fluorine [NYF] family), and of the miarolitic class, lithium subclass, beryl-topaz type (LCT family) (Černý and others, 2012, table 1). Of these, the most important sources of industrial beryl are granitic pegmatites of the rare-element LCT family. Miarolitic LCT-family and NYF-family pegmatites (fig. E6) are mainly sources of gemstone beryl. Industrial beryl is also produced from more complex types of pegmatite; for example, Anjanabonoina pegmatites in Antananarivo Province, Madagascar, which have a mixed NYF–LCT signature (Martin and De Vito, 2005). Many pegmatite districts that are of interest now for lithium and niobium originally attracted attention for other rare metals, especially beryllium, tantalum, and tin, and industrial minerals, such as feldspar, micas, and high-purity silica (Glover and others, 2012; Kesler and others, 2012).

Most granitic pegmatites of the LCT family show peraluminous compositions (table E3; fig. E5) that are characteristic of S (or sedimentary)-type granites, which form from anatexis, or melting, of metamorphosed pelitic rocks owing to the crustal thickening that is typically associated with subduction and continental collision (Černý and others, 2012). LCT pegmatites have been linked to subduction zones because of the high abundance of granitic pegmatites in orogenic belts (Martin and De Vito, 2005), although others affiliate them with a post-tectonic phase of evolution in continental-collision belts (Tkachev, 2011). Nonetheless, the geochemical character of LCT pegmatites depends on their derivation from previously unmelted, mica-rich metamorphic rocks because muscovite-paragonite-phengite and biotite group minerals carry the distinguishing rare elements (Černý and others, 2012). The presence of diverse fluxing components, such as boron, flourine, and phosphorus, in addition to water, in the metamorphosed juvenile sediments that make up the peraluminous sedimentary-type source materials are thought to have an essential role in the formation of LCT pegmatites because they mobilize the rare metals, including Be, Cs, Nb, Rb, Sn, and Ta, into the fluid phase (Linnen and others, 2012).

Rare-metal pegmatites typically occur as halos that encircle large leucocratic plutons or as swarms that extend into country rock adjacent to these intrusions. The best quality deposits are found in zoned pegmatites where beryl is mined from certain, typically highly fractionated, pegmatite zones; from massive vein and fracture fillings; and from replacement bodies in complexly heterogeneous pegmatites. Important pegmatite districts for beryl mining (fig. E1) occur in Brazil (in the Rio Doce Valley and adjacent areas in the State of Minas Gerais; the city of Campina Grande in the State of Rio Grande do Norte; Cristais-Berilandia in the State of Ceara; and Rio Jequitinhonha [Jequitinhonha River] in the State of Minas Gerais); Portugal (in the Covas do Barroso pegmatite district, Viseu); Mozambique (at Alto Ligonhain in the Province of Zambezia); Canada (at the Bernic Lake Mine—commonly known as the Tanco Mine—on the shore of Bernic Lake in the Province of Manitoba; and at the James Bay (Lithium One) Mine on the shore of James Bay in the Province of Quebec); Namibia (at Karibib); Zimbabwe (at the Bikita Field in the Province of Masvingo); and China (Kesler and others, 2012). Pegmatite districts located in weathered granites of southeastern China—for example, the city of Nanping in Fujian Province—may supply some of the reported Chinese production, although little information is available on resource types for beryllium from China. Subeconomic occurrences in the United States that were mined historically include pegmatite bodies of North Carolina (at the Kings Mountain crushed rock quarry near Bessemer City), South Dakota (at Tin Mountain Mine in the Black Hills; Sabey, 2006), and New Hampshire. For example, pegmatites at the Palermo Mine on Bald Mountain near North Groton, New Hampshire, and at Beryl Mountain near South Acworth, New Hampshire, produced much of the beryllium for the U.S. Manhattan Project.

Table E3. Global and domestic types of magmatic-related beryllium resources.

[Modified from Barton and Young (2002). Shading indicates information for deposits that are economically important at present. For each petrologic association listed, the following is included: 1, frequency of known occurrences (abundant, common, uncommon, rare) and end use for which the beryllium is most valuable (gems, industrial beryllium); 2, the main beryllium-bearing phase(s); and 3, one or more example localities. “Transbaikalia” is the conventional spelling of the “Zabaykal’ye” region. LCT, lithium-cesium-tantalum; NYF, niobium-yttrium-fluorine. Locality abbreviations: Colo., Colorado; Ill., Illinois; N.C., North Carolina; N.H., New Hampshire; N. Mex., New Mexico; Nev., Nevada; Tex., Texas; UK, United Kingdom; Va., Virginia; Mt., Mount; Mtn., mountain; —, not applicable]

Petrologic association			**Host rock (type of mineralization)**			
			Igneous (pegmatitic, late-stage plutonic, volcanic glasses)	**Aluminosilicate (greisen, veins)**	**Carbonate (skarn, replacement)**	**Mafic/ultramafic (blackwall, vein)**
Metaluminous to peraluminous	Granite	1	Common?/Industrial-beryllium resource?	Abundant/gems ± industrial-beryllium resource?	Abundant/industrial-beryllium resource	Common/gems, emerald
		2	Lithium micas, beryl	Beryl, phenakite	Phenakite, chrysoberyl, bertrandite, helvite	Beryl, chrysoberyl, phenakite
		3	Beauvoir, France; Sheeprock, Utah	Sherlova Gora, Russia; Mt. Antero, Colo.; Aqshatau, Kazakhstan; Erzgebirge, Germany; Cornwall, UK; Boomer Mine, Pikes Peak, Colo.	Lost River, Alaska; Mt. Wheeler, Nev.; Mt. Bischoff, Australia; McCullough Butte, Nev.	Reft River, Russia; Khaltro, Pakistan; Carnaiba, Brazil
	Granitic pegmatite (LCT-type)	1	Abundant/gems and major industrial-beryllium resource	—	—	—
		2	Beryl			
		3	Minas Gerais, Brazil; Bernic Lake, Canada; Transbaikalia, Russia; Greenbushes, Australia; Bikita, Zimbabwe; Donkethoek, Namibia; Sahatany Valley, Madagascar; King’s Mountain, N.C.			
	Granitic pegmatite (NYF-type)	1	Abundant/gems and major industrial-beryllium resource	—	—	—
		2	Beryl			
		3	Mt. Antero, Colo.; Ledu, Quebec; Transbaikalia, Russia; Klein Spitzkoppe, Namibia; Amherst Co., Va.; Sawtooth batholith, Idaho; Kitsamby, Madagascar			
	Rhyolite	1	Common/no economic value?	Rare/gems, red beryl	Uncommon/principal industrial-beryllium resource	—
		2	Beryllium in glass or micas	Beryl	Bertrandite	
		3	Macusani, Peru; Spor Mtn., Utah; topaz rhyolites, Western United States; Warm Springs, N. Mex.	Wah Wah Mtns., Utah; Black Range, N. Mex.; Spor Mtn., Utah	Spor Mtn., Utah; Aguachile, Mexico; Sierra Blanca, Tex.	

Table E3. Global and domestic types of magmatic-related beryllium resources.—Continued

[Modified from Barton and Young (2002). Shading indicates information for deposits that are economically important at present. For each petrologic association listed, the following is included: 1, frequency of known occurrences (abundant, common, uncommon, rare) and end use for which the beryllium is most valuable (gems, industrial beryllium); 2, the main beryllium-bearing phase(s); and 3, one or more example localities. "Transbaikalia" is the conventional spelling of the "Zabaykal'ye" region. LCT, lithium-cesium-tantalum; NYF, niobium-yttrium-fluorine. Locality abbreviations: Colo., Colorado; Ill., Illinois; N.C., North Carolina; N.H., New Hampshire; N. Mex., New Mexico; Nev., Nevada; Tex., Texas; UK, United Kingdom; Va., Virginia; Mt., Mount; Mtn., mountain; —, not applicable]

Petrologic association			Host rock (type of mineralization)			
			Igneous (pegmatitic, late-stage plutonic, volcanic glasses)	Aluminosilicate (greisen, veins)	Carbonate (skarn, replacement)	Mafic/ultramafic (blackwall, vein)
Alkaline to peralkaline	Granite	1	Rare?/no economic value?	Rare/industrial-beryllium resource	Rare/industrial-beryllium-resource	—
		2	Gadolinite group?	Phenakite, helvite, gadolinite	Phenakite, bertrandite, leucophanite	
		3	Khaldzan-Burgtey, Mongolia	Verknee Espee, Kazakhstan	Yermakovskoye, Russia; Iron Mtn., N. Mex.	
	Granitic pegmatite (NYF-type)	1	Uncommon/industrial-beryllium resource	—	—	—
		2	Gadolinite, phenakite			
		3	Strange Lake, Canada; Pikes Peak, Colo.; Sawtooth batholith, Idaho; South Baldface Mtn., N.H.			
	Granitic pegmatite (LCT-type)	1	Uncommon/industrial-beryllium resource	—	—	—
		2	Beryl			
		3	Ivisaartoq, Greenland			
	Rhyolite	1	Rare?/industrial-beryllium resource?	—	Rare/industrial-beryllium-resource	—
		2	Bertrandite, beryllium in glass, feldspar, micas, helvite		Bertrandite	
		3	Brockman, Australia; Shixi, China		Aguachile, Coahuila, Mexico	
	Syenitic pegmatite (both LCT and NYT-types?)	1	Common/no economic value?	—	—	—
		2	Epididymite, eudidymite, chkalovite			
		3	Lovozera, Russia; Ilímaussaq, Greenland; Oslo, Norway			
	Syenite	1	Uncommon/industrial-beryllium resource?	Rare/industrial-beryllium resource	Rare/industrial-beryllium resource	—
		2	Chkalovite, epididymite	Barylite, eudidymite	Bertrandite	
		3	Ilímaussaq, Greenland; Wind Mtn., N. Mex.	Seal Lake, Canada; Thor Lake, Canada	Hicks Dome, Ill.; Thor Lake, Canada (skarn)	

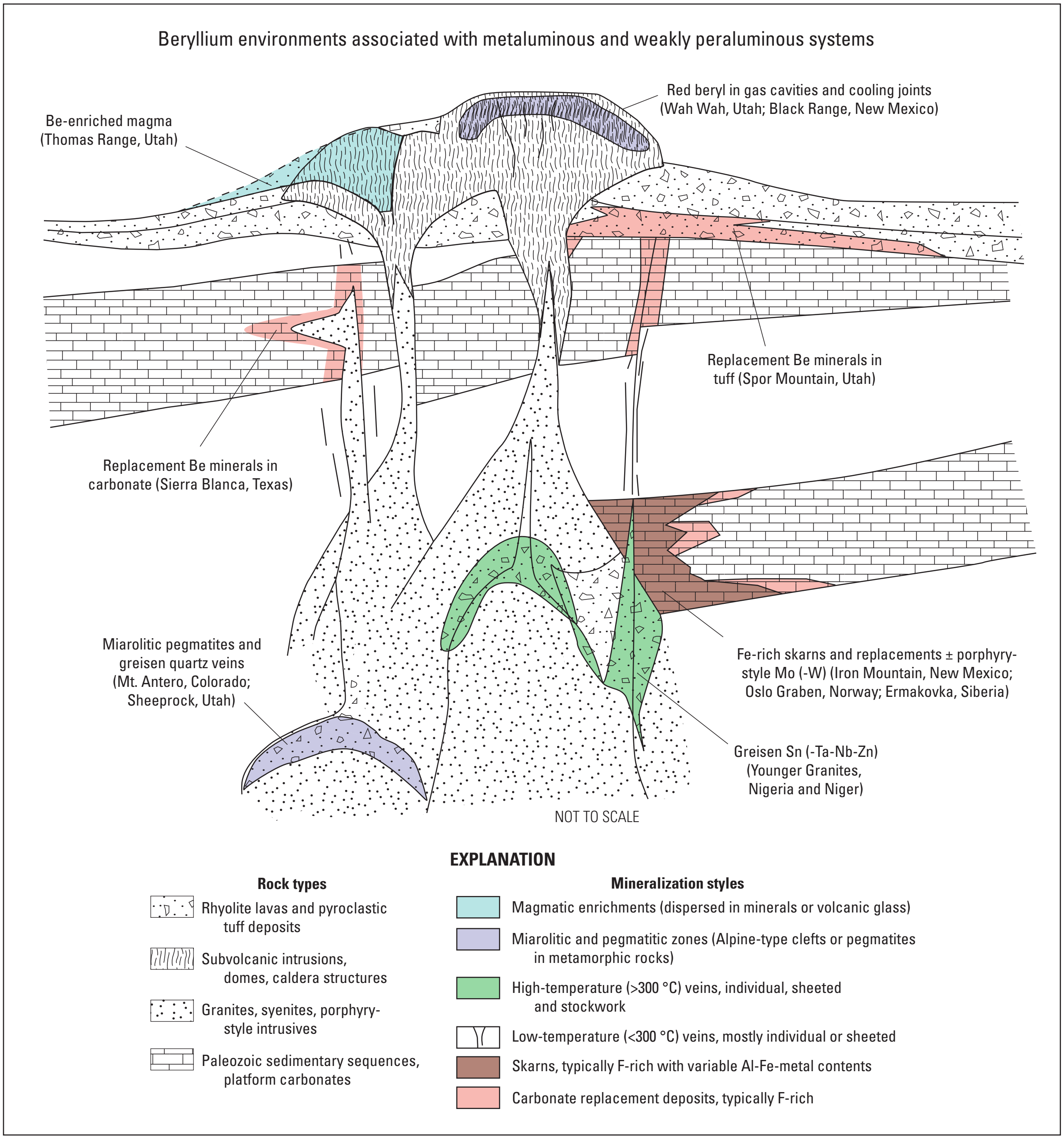


Figure E5. A generalized cross section showing the geologic setting of and some example deposits for the major types of beryllium resources associated with rare-metal magma systems. The cross section also shows the relation of volcanogenic beryllium deposits, such as the one at Spor Mountain, Utah, to other types of deposits that are associated with magmas of this general composition. Modified from Barton and Young (2002). °C, degree Celsius. Elements: Al, aluminum; Be, beryllium; F, fluorine; Fe, iron; Mo, molybdenum; Nb, niobium; Sn, tin; Ta, tantalum; W, tungsten; Zn, zinc

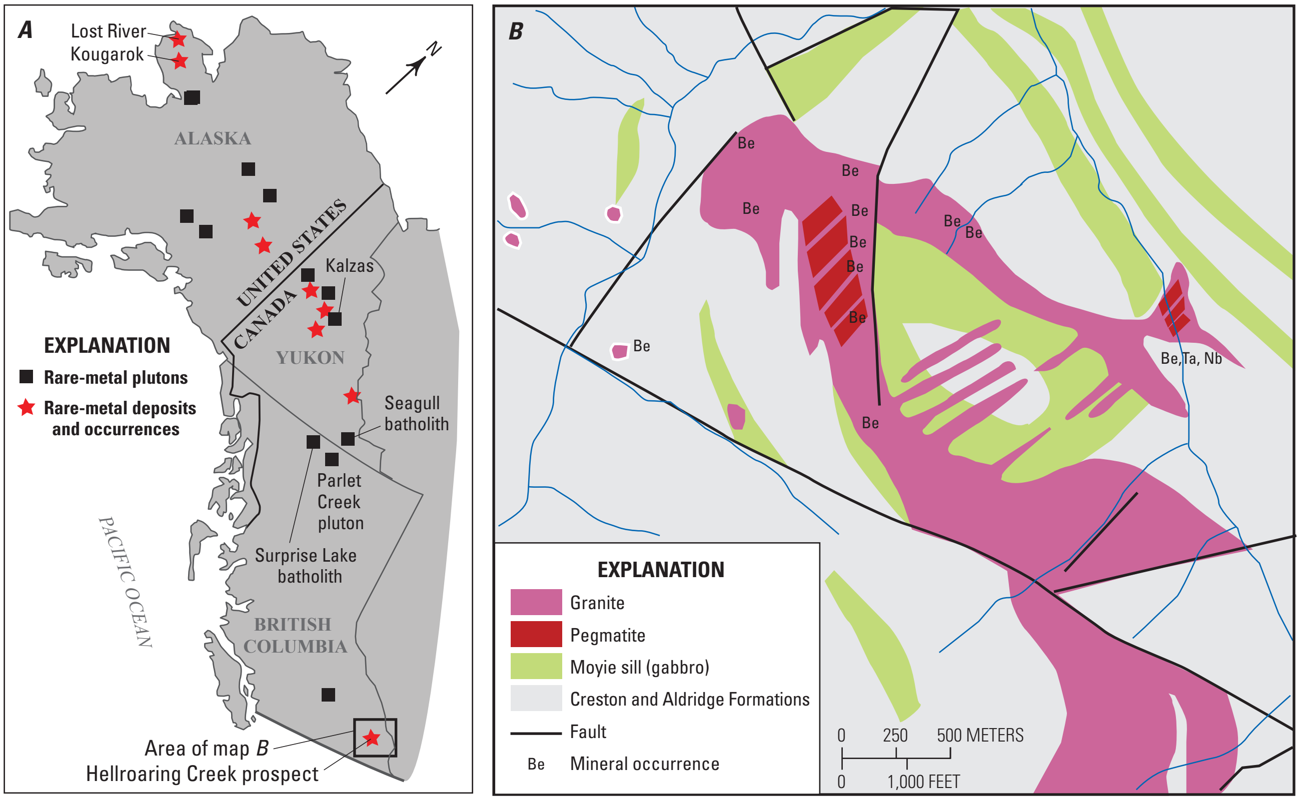


Figure E6. Location map and simplified geologic map of the Hellroaring Creek prospect, which is located west of Kimberley, British Columbia, Canada. Location map *A* shows the distribution of potential rare-metal-bearing granite and pegmatite deposits of the Canadian and Alaskan Cordillera and of rare-metal deposits associated with the plutons. Geologic map *B* shows the pegmatite and granite-related beryllium-bearing rare-metal mineralization at the Hellroaring Creek prospect. Maps modified from Soloviev (2011). Be, beryllium; Nb, niobium; Ta, tantalum

Most pegmatite deposits consist of a few thousand tons of rock, although the largest contain as much as 1 million metric tons. For example, the Tanco deposit in Manitoba, Canada, is a large, mineralogically complex, and strongly zoned LCT pegmatite that contains an estimated 900,000 metric tons of beryllium ore. The Tanco pegmatite is part of the rare-metal-bearing Bernic Lake pegmatite group (Černý, 2005) and is currently being mined for cesium, rubidium, and spodumene (a lithium-bearing mineral). Ores of the Tanco pegmatite contain greater than 350 ppm beryllium, which is an enrichment factor of 180 over bulk continental crust, in addition to 13,900 ppm lithium, 236,000 ppm cesium, 28,900 ppm rubidium, and greater than 1,200 ppm tantalum (Stilling and others, 2006). Beryl at Tanco and in many other large complex pegmatite deposits occurs both as fine-grained rinds and as crystal up to 20 centimeters (cm) in length in pockets in albitic aplite, which is a fine-grained granitic rock. In contrast, the Hellroaring Creek prospect, which is located west of the city of Kimberley in the Province of British Columbia, Canada (fig. E6*A*), is a chemically and mineralogically simple lithium-pegmatite body that has indicated resources of 500,000 metric tons grading 0.1 percent beryllium oxide (Soloviev, 2011). In this case, the pegmatite intrudes an overlying granitic stock, and pockets of beryl are distributed in both granite and pegmatite (fig. E6*B*). The pockets have a relatively simple mineralogy of beryl (with crystals up to greater than 30 cm in length), muscovite, and quartz. The prospect is located in an extensive trend of rare-metal granites, pegmatites, and related deposits of the Cordilleras of North America (fig. E6*A*). These range from small and uneconomic beryl pegmatite deposits of Idaho and Montana (Stoll, 1950) to significant beryllium deposits of Seward Peninsula, Alaska (for example, the Lost River skarn deposit).

Skarn and Greisen-Hosted Beryllium-Fluorine Deposits

Beryllium-bearing skarn and greisen deposits occur in association with many large rare-metal-enriched granitic and syenitic plutons. These deposit types, which form by metasomatic replacement processes in the mineralized contact zone between the intruding pluton and the country rock, typically have phenakite, bertrandite, and helvite-group minerals. Skarns form by high-temperature alteration of carbonate country rocks, and greisens form by alteration of rocks of alumino-silicate compositions. They often display a distinctive texture of rhythmically banded replacements containing alternating light and dark layers of beryllium minerals, fluorite, magnetite, and silicates. Fluorine-beryllium skarn and greisen deposits associated with, for example, tin deposits of the Seward Peninsula, Alaska, such as the Lost River beryllium skarn deposit (Alexsandrov, 2010), and those in Russia's Far East, such as the Yermakovskoye deposit in the Kizhinginskiy Khrebet [Kizhinginskiy Ridge] area of the Republic of Buryatia, are localized in the contact aureoles of carbonate rocks intruded by high-silicon (leucocratic), fluorine-rich granites (Reyf, 2008). The beryllium is contained in veins and vugs in fluorite and calc-silicate altered limestone and argillized granite. Beryl, helvite-group minerals, and phenakite occur along with calcite, fluorite, garnet, quartz, topaz, tourmaline, zinnwaldite (a lithium-mica), and sulfide minerals. Skarn deposits near Changning City in Hunan Province, China (Lin and others, 1995), may supply some of the beryl currently mined in China. Beryllium-fluorine skarn and greisen deposits of this type are deep, high-pressure analogs of carbonate-hosted beryllium deposits, and, where present, may represent the roots of volcanogenic beryllium systems (fig. E6).

Carbonate-Hosted Beryllium Deposits

Carbonate-hosted beryllium deposits form in carbonate rock sequences where rare-metal and lithophile-enriched volcanic rocks intrude and mineralize carbonate rocks, depositing beryllium minerals in replacement fronts (fig. E6). These types of beryllium deposits occur near Sierra Blanca, Texas, and Aguachile, Mexico. At Sierra Blanca, beryllium-rich fluorite deposits occur in association with peralkaline-metaluminous volcanic rock sequences. The deposits occur within Cretaceous limestones beneath an intrusive contact with an overlying rhyolite laccolith. The rhyolite laccoliths of Round Top Mountain near Sierra Blanca are strongly peraluminous and have anomalous beryllium and fluorine contents (Rubin and others, 1987, 1988, 1990). The rhyolites also contain elevated amounts of Li, Nb, Rb, rare-earth elements (REEs), Th, Y, Zn, and cryolite. The beryllium mineralization at Aguachile occurs as replacements and fillings in limestone that was brecciated when it was intruded by a rhyolite dike near the ring fault of a caldera; the rhyolite is peraluminous, although related igneous rocks are peralkaline (McLemore, 2010a). Bertrandite is present with calcite and quartz in fluorite-rich deposits in limestone, and the principal orebody has approximately 0.3 percent beryllium oxide.

At the present time, no domestic carbonate-hosted beryllium deposits are known to be economic; however, they can be important indicators of the potential presence of volcanogenic beryllium deposits. For example, a number of small and irregularly shaped beryllium-rich zones are present in carbonate rocks located stratigraphically beneath the bedded tuff that hosts world-class volcanogenic beryllium ores at Spor Mountain (McLemore, 2010a; Materion Corp., 2012a, b).

Volcanogenic-Hosted Beryllium Deposits

Beryllium deposits of the volcanogenic type (Barton and Young, 2002; Foley and others, 2012, and references therein) form by replacement of carbonate fragments found in lithic tuff, which is a rock composed of compacted volcanic ash, glass, and rock fragments. Host rocks are typically rare-metal-enriched volcanic rhyolite lavas and related tuffs and ash flows that are metaluminous to peraluminous in composition and enriched in fluorine and other lithophile-elements (Be, Ce, Li, Rb, REEs, Sn, Th, Tl, and U) (fig. E7*A*). The classic tectonic setting is an extensional environment where young igneous rock sequences overlie older dolomite, limestone, quartzite, and shale sequences. The deposits form as the result of magmatic processes that produce fluorine-, beryllium-, and gas-rich rhyolite melts. Degassing of the melts causes explosive volcanism that rips up carbonate and another rock fragments as magmas vent to the surface through fractures in the limestone sequences. The hot magma interacts with groundwater, which causes a hydrovolcanic eruption that dumps fine ash, beryllium-rich volcanic glasses, and fragments of carbonate and other rock in wedged-shaped base surge deposits that thin away from the vent structures (fig. E7*B*; Burt and others, 1982). This mix of magmatic and hydrothermal fluids is capable of leaching beryllium from the volcanic glass and precipitating it as bertrandite when the hydrothermal fluid encounters carbonate fragments in the tuff. Beryllium is removed from devitrifying glass as a fluoride complex in the cooling fluid. Upon encountering carbonate rock, calcium from the rock fragment and fluorine from the fluid combine to form the mineral fluorite, and the beryllium reacts with silica in the fluid to make bertrandite; this leads to essentially simultaneous deposition of fluorite and bertrandite. These post-magmatic processes play an important role in the development of economic volcanogenic beryllium deposits because they concentrate the beryllium into high-grade ore zones. The size and grade of a volcanogenic beryllium deposit is thought to be related to the distribution of carbonate lithic-rich zones in the host beryllium tuff and the duration and efficiency of the mineralizing hydrothermal system.

Volcanogenic ores of beryllium are produced at Spor Mountain, Utah, from elongate deposits in Miocene-aged tuffs composed of glass, ash, carbonate fragments, and other rock fragments (fig. E7*B*). The bertrandite occurs as submicroscopic grains mixed with fine-grained fluorite, opal, and calcite in layered nodules that replace carbonate in the tuff (fig. E7*C*; Lindsey, 1998). The median concentration of unaltered glass melt (59 ppm beryllium) in Spor Mountain tuff (Adams and others, 2009) is about eight times that left in intensely altered glass (7 ppm beryllium), which suggests that almost 90 percent of the original beryllium in the glassy tuff matrix was redeposited in the mineralized carbonate rock fragments.

Only a small number of volcanic rocks and beryllium deposits of this type are known, and most are subeconomic (table E3; fig. E1). These include domestic rare-metal-bearing volcanic occurrences at The Honeycombs (more commonly

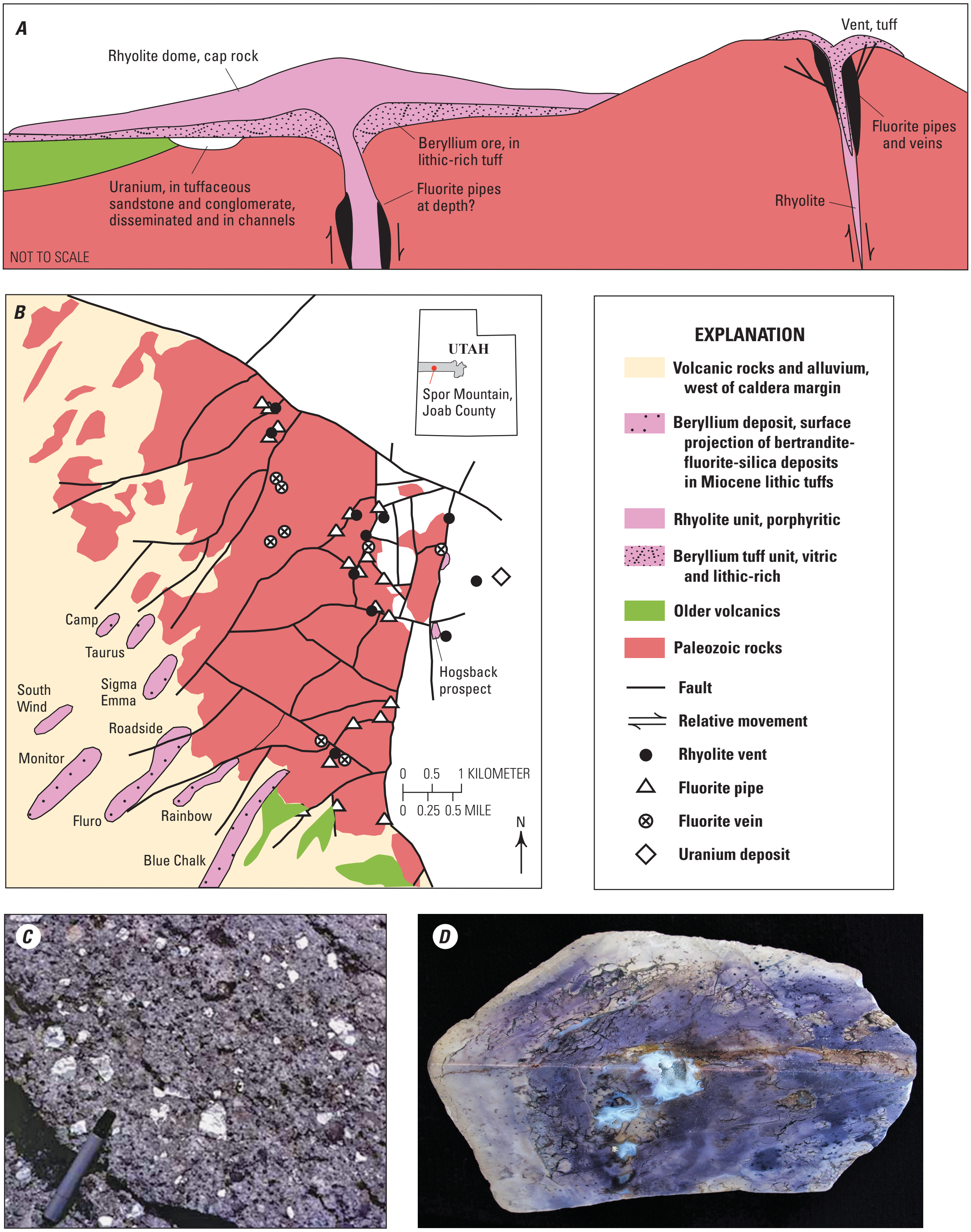


Figure E7. *A*, Generalized geologic cross section showing the setting of volcanogenic beryllium deposits and related deposit types relative to volcanic vent structures, host tuff, and overlying cap rocks. *B*, Gelogic map of Spor Mountain area, Utah, showing the distribution of beryllium deposits, fluorite pipes, carbonate rocks, and volcanic rocks. Modified from Lindsey (1998) and Foley and others (2012). *C*, Photograph of beryllium tuff at Spor Mountain showing dolomite clasts (white) replaced by fluorite, clay, chalcedonic quartz, and manganese oxide. *D*, Photograph of nodule from the Spor Mountain tuff showing an interior of opal and purple fluorite and an outer zone of opal and fluorite; nodules can contain as much as a few percent beryllium oxide (BeO) as bertrandite. The nodule shown is about 20 centimeters wide. Photographs *C* and *D* are by D.A. Lindsey, U.S. Geological Survey.

known as Honeycomb Hills), Utah, and at the Apache Warm Springs volcanogenic beryllium deposit at the Ojo Caliente No. 2 mining district, New Mexico. The Honeycombs are two small eroded domes of topaz-bearing alkali rhyolite and tuff located about 30 kilometers (km) (20 miles) west of Spor Mountain; the prospect contains small amounts of beryllium and fluorite. Similar prospects throughout New Mexico and Utah are also small and of low grade (McLemore, 2010a). Globally, rare-metal metallogenic provinces favorable for volcanogenic beryllium deposits are restricted to a small number of locations, including the peralkaline Niobium tuff of the State of Western Australia, which contains the Brockman deposit (table E3) (Ramsden and others, 1993; Taylor and others, 1995a, b); the Macusani tuff of the Peruvian Altiplano (Pichavant and others, 1988a, b); and peraluminous to peralkaline volcanic rocks of the Teg-Ula deposit in Govi-Altay Province, Mongolia (Kovalenko and Yarmolyuk, 1995), and in Shixi, Zhejiang Province, China (Lin, 1985). At the Brockman deposit, beryllium occurs in low-grade lenses of Nb-REE-Ta-Zr mineralization associated with the pyroclastic eruption of a Paleoproterozoic magma enriched in volatiles. The tuff hosts rare-metal deposits with proven reserves of about 4.3 million metric tons containing 0.44 percent Nb_2O_5 and 50 to 1,500 ppm beryllium. Beryllium-bearing ash-flow tuffs also occur in the vicinity of the town of Macusani in the Puno Region of southeastern Peru (Pichavant and others, 1988a, b). The highly peraluminous rocks that compose the Neogene volcanic field near Muscani may be a northernmost expression of the Bolivian tin belt. The tuffs contain elevated concentrations of beryllium (about 15 to 37 ppm) but no known beryllium deposits. Deposits and occurrences of beryllium in Mongolia and Siberia, Russia, reportedly are hosted by fluorine-rich igneous suites, such as those typically associated with volcanogenic beryllium deposits. The deposits are mostly associated with granite and are of the skarn or greisen type. In Mongolia, however, the central Gobi volcanic zone contains fluorine-bearing rhyolite, beryllium-rich tuff, and REE-rich alkaline volcano-plutonic rocks that compose part of a late Mesozoic rare-metal metallogenic belt within the Transbaikal-Mongolian rare-metal province (Kovalenko and Yarmolyuk, 1995).

Nonmagmatic-Related Beryllium Deposits

Beryllium minerals also occur in a variety of nonmagmatic hydrothermal, metamorphic, and sedimentary environments; in most cases, these occurrences are subeconomic. Shear-zone deposits form in metamorphic terranes by local redistribution of materials during deformation. Metamorphic host rocks may include felsic metavolcanics, metasedimentary rocks, marbles and metabasites, and, thus, shear-zone deposits are found in blackwall (mafic rock), greisen, skarn, and vein settings. They are uncommon occurrences of beryl and phenakite and are typically mined as gem emerald (Grundmann and Morteani, 1989). Basinal brine deposits consist of greisens and veins formed by replacement of aluminosilicate host rock by low-temperature basinal brines with unsubstantiated or unknown connections to magmatic systems. Classic examples include the emerald deposits of Muzo and Chivor, in the Department of Boyacá, Colombia, where beryl and euclase are exclusively mined as gemstones. Placer deposits containing beryl are common and historically have provided both industrial beryllium ore and gemstones (Sinkankas, 1981). Deposits of this type are known in the State of Minas Gerais, Brazil, and in Madagascar and Sri Lanka. Nonmagmatic deposits can be a source of industrial beryl; however, most are mined as gemstones of beryl-type minerals, such as aquamarine, chrysoberyl (variety alexandrite), and emerald, as well as euclase, phenakite, and tugtupite (table E2). Gemstones are a distinct mineral commodity and are not covered in this chapter, but they are covered elsewhere (see, for example, Olson, 2016).

Resources and Production

Identified resources of beryllium worldwide have been estimated to be more than 80,000 metric tons (Jaskula, 2013a). About 65 percent of these are in U.S. resources of bertrandite, and the rest are in resources of beryl in other countries. Beryllium grades and resource tonnages for volcanogenic beryllium deposits, LCT pegmatites, and selected other deposit types are shown for the purpose of general comparison in figure E8. World beryllium reserves are not sufficiently well delineated to report consistent figures for all countries.

Domestic Resources

Domestic carbonate-hosted and volcanogenic deposits of beryllium occur in New Mexico, Texas, and Utah. The deposits range in size from small (Iron Mountain in New Mexico) to world class (Spor Mountain in Utah) (table E4; fig. E8).

Exploration sites thought to host the large deposits are described below. It is unlikely that other domestic beryllium deposits will be mined in the near future because the Spor Mountain deposit contains sufficient beryllium reserves to meet expected demand.

Spor Mountain, Utah.—At yearend 2011, Materion Corp. (2011) reported proven domestic reserves of bertrandite at Spor Mountain of 5.75 million dry tons at an average grade of 0.265 percent beryllium (about 0.8 percent beryllium oxide). The bertrandite contains about 15,200 metric tons of beryllium. Figure E8 shows ore grade and tonnage estimates for Spor Mountain based on a cutoff grade of 0.23 percent beryllium.

Lost River, Alaska.—The Lost River Mines, which are located in the western part of Seward Peninsula, were mined intermittently for tin from 1904 through 1955. Near the mines, a limestone of Early Ordovician age is partly replaced by silicate minerals and cut by numerous veinlets containing silicates, ore minerals, and fluorite. A granite pluton and dikes

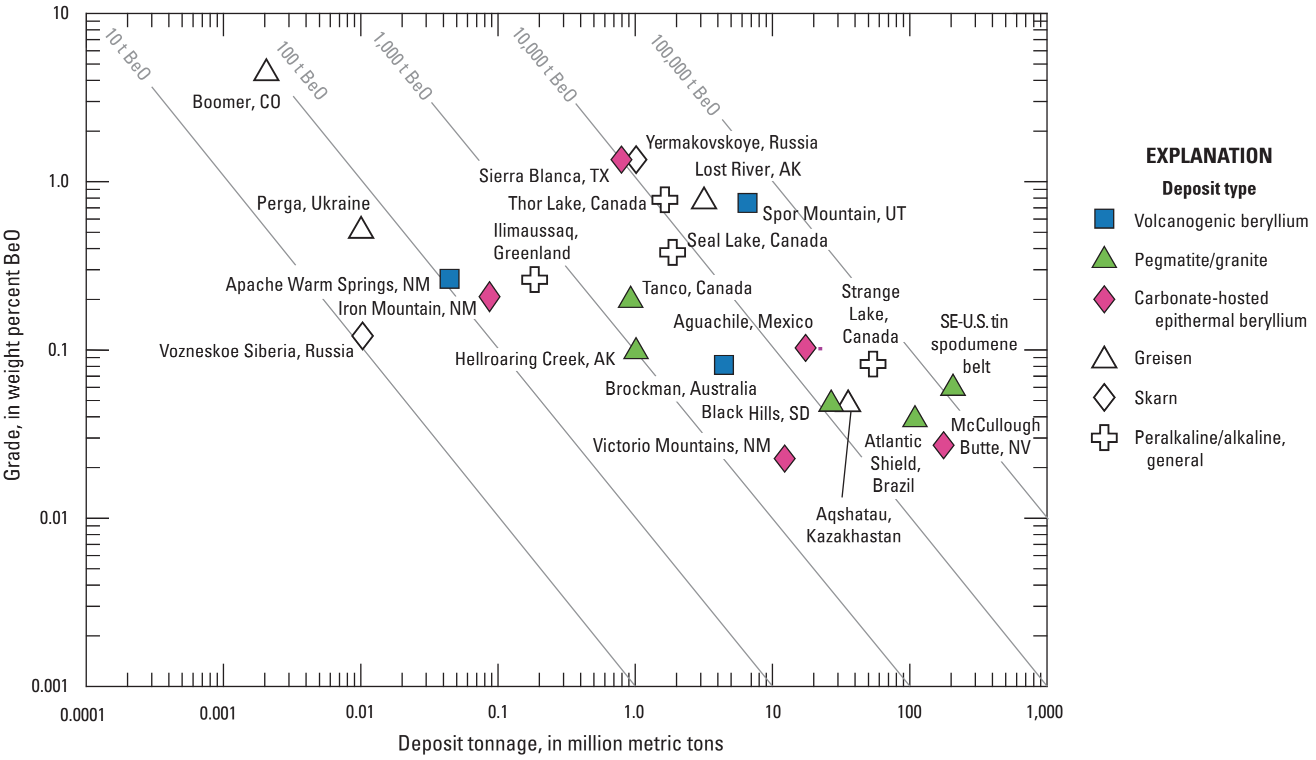


Figure E8. Graph showing general estimates (using data from table E4) of grade and tonnage for a variety of beryllium (Be) deposits, districts, and belts that have a potential for minable beryllium resources. Diagonal lines are isolines of contained beryllium oxide, in metric tons (t). The available data for deposits of these types are sparse; some of the deposit information has been compiled using poorly documented past production, reserve, and resource information—data types that are typically not combined for use in a single plot of grade versus tonnage. BeO, beryllium oxide. Locality: AK, Alaska; CO, Colorado; NM, New Mexico; NV, Nevada; SD, South Dakota; SE-U.S., Southeastern United States; TX, Texas; UT, Utah

that underlie the deposit are greisenized. The fine-grained ore of diaspore, euclase, fluorite, mica, tourmaline, and white chrysoberyl forms replacement veins, pipes, and stringer lodes in limestone. The beryllium content of the bulk ore ranges from 0.11 to 0.54 percent (0.31 to 1.50 percent beryllium oxide); high-grade nodules of chrysoberyl, diaspore, fluorite, and mica contain as much as 6 percent beryllium oxide (Sainsbury, 1963, 1964a, b; Dobson, 1982).

Apache Warm Springs, New Mexico.—Exploration for volcanic-hosted beryllium deposits in New Mexico has focused on the Sierra Cuchillo and San Mateo Mountains, which extend across Socorro and Sierra Counties (McLemore, 2010b, undated). Bertrandite at the Apache Warm Springs property at Sierra Cuchillo occurs in small quartz veins and stringers in fractures and disseminations in a 28-million-year-old rhyolite and ash-flow tuff showing intense alteration to clay minerals. Drilling by BE Resources Inc. of Toronto, Ontario, Canada, identified mineralized zones in altered rhyolite; however, assays from 13 exploration boreholes revealed grades of beryllium oxide well below the cutoff grades determined from the company's beryllium oxide benchmarking project (BE Resources Inc., 2011). In addition, beryl has been produced from New Mexico pegmatites in Grant, Mora, Rio Arriba, San Miguel, and Taos Counties, and the majority of the beryl production (about 770 metric tons of beryl) came from the Harding pegmatite in Taos County.

Sierra Blanca, Texas.—Beryllium-fluorine mineralization at Round Top Mountain, Sierra Blanca, is found with fluorite and replaces limestone adjacent to rhyolite (Rubin and others, 1988). The Sierra Blanca rhyolite is one of six laccoliths of similar age (36.2 ± 0.6 mega-annum [Ma]) (Henry, 1992). Cyprus Beryllium Corp. reported resources and reserves of 850,000 metric tons averaging 1.5 percent beryllium oxide (0.5 percent beryllium), although the reported data were not compliant with National Instrument (NI) 43–101 guidelines (Rubin and others, 1990).

Tin-Spodumene Belt, North Carolina and South Carolina.—Pegmatite dikes in the tin-spodumene belt of North Carolina and South Carolina contain an average of about 0.05 percent beryllium oxide (Griffitts, 1973). The pegmatites also contain cassiterite, columbite, feldspar, mica, and spodumene. Resource estimates for the entire tin-spodumene belt suggest 747,000 metric tons of beryl (111,400 metric tons of beryllium oxide) (Griffitts, 1954, p. 10). Individual pegmatite districts (for example, Bessemer City and Kings Mountain, North Carolina) have in the range of 36,000 metric tons of beryl (equivalent to about 5,400 metric tons of beryllium oxide). Little beryl is found in the Piedmont province outside of the tin-spodumene belt.

Black Hills, South Dakota.—The Tin Mountain district in the Black Hills includes more than 24,000 pegmatites associated with the peraluminous Harney Peak granite of Paleoproterozoic age. Only about 2 percent of pegmatites in the district are zoned, and these have been mined for muscovite, potassium-feldspar, and rare metals, such as Be, Cs, Li, Nb, Ta, and Sn. The most highly differentiated pegmatites, such as at the Tin Mountain and the Bob Ingersol Mines, are dikes with lepidolite, petalite, and spodumene mineralization (Krogstad and others, 1993; Walker and others, 1986; Sirbescu and Nabelek, 2003).

International Resources

Pegmatite beryl deposits are found throughout the world (figs. E1 and E8). The more significant global exploration sites for nonpegmatite beryllium resources are as follows:

Yermakovskoye, Russia.—The Yermakovskoye beryllium deposit occurs in a large block of carbonate rock with a sedimentary sequence preserved in a field of gabbroic plutons, alkali granite, and leucogranite. The phenakite-microcline-fluorite ores formed at about 225 Ma by replacement of limestone (Kislov and others, 2010; Lykhin and others, 2010). The deposit has an average grade of 1.3 percent beryllium oxide (about 0.5 percent beryllium) and may be the largest beryllium deposit in Russia (Reyf, 2008), although as of 2011, no beryllium was being produced from this deposit. East Siberian Metals Corp. (a subsidiary of Metropol Group) and JSC Ulba Metallurgical Plant of Kazakhstan reportedly had completed a predesign phase for resuming mining and the technical design for a processing plant. The new plant would produce beryllium hydroxide for delivery to China, Japan, and Kazakhstan for metal and alloy processing. Russia is not known to produce any domestic beryllium metal currently; imports from Russia are most likely sourced from Kazakhstan (Jaskula, 2013b).

Thor Lake, Northwest Territories, Canada.—The Thor Lake rare-metals group of deposits, and specifically the North T deposit, reportedly host one of the highest grade beryllium resources known in the world. An NI 43–101-compliant resource estimate prepared by Wardrop Engineering Inc. of Canada in 2007 confirmed an indicated resource in one sub-zone of the North T deposit of greater than 450,000 metric tons grading 0.98 percent beryllium oxide. The primary beryllium ore mineral in the North T deposit is phenakite. The owner, Avalon Rare Metals Inc., saw no near-term economic potential for the North T beryllium deposit and had no immediate plans to initiate development (Avalon Rare Metals Inc., 2013).

Production and Supply

The recent annual worldwide production of beryllium (mainly from China, Mozambique, Portugal, and the United States) was estimated to be 260 metric tons in 2011. Of that output, more than 235 metric tons of contained beryllium was derived from deposits at Spor Mountain (Jaskula, 2013a, b). In 2011, pegmatite beryllium deposits accounted for about 25 metric tons of contained beryllium. Global trends show an increase in estimated production of beryllium for the United States and China for the period 2000 through 2012 (fig. E9). During pegmatite mining for other minerals, beryl is frequently stockpiled for processing at a later time. World production and the United States share of world production have a high degree of uncertainty because China, which is known to be a significant producer, does not report its beryl production.

Countries that produce beryl ore include Brazil, China, Madagascar, Mozambique, and Portugal. Nigeria, Kazakhstan, and Uganda may also produce beryl ore, but information is inadequate to make reliable estimates of output. Nations that produced gemstone beryl may also have produced some beryl ore for industrial use. The United States is the world's leading producer of bertrandite ore, and Materion Corp., which was the sole domestic producer, accounted for 91 percent of estimated world beryllium ore production in 2011. China, Kazakhstan, and the United States are the only countries known to process beryllium ores and concentrates into beryllium products. Materion Corp. has manufactured products in the form of foil, rods, sheets, and tubes, and a variety of other customized shapes at plants in Elmore, Ohio, and Fremont, California, and beryllium oxide ceramic products at a plant in Tucson, Arizona.

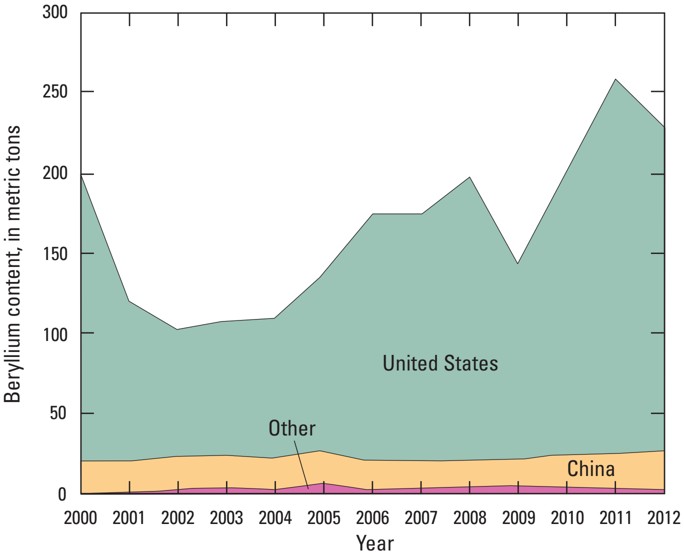


Figure E9. Graph showing estimated global production of beryllium for 2000–11. The layers of the graph are placed one above the other, forming a cumulative total. Data are from U.S. Geological Survey (2007–15).

In the United States, Materion converts bertrandite from open pit mines in Utah and imports beryl ore (at a ratio of 90 percent bertrandite to 10 percent beryl) into beryllium hydroxide at operations near Delta, Utah, in an effort to extend its domestic bertrandite reserves. Because beryl has fewer impurities than bertrandite, Materion also processes imported beryl alone as a means of producing very high purity beryllium (Stephen Freeman, President, International Business Development, Materion Corp., oral commun., January 10, 2013). Some of the beryllium hydroxide is shipped to Elmore, Ohio, where Materion converts it into the primary feed material used to make beryllium metal products, including beryllium-copper master alloy (BCMA), metal, or oxide; in the past, some of the primary feed material was sold to NGK Insulators, Ltd. of Japan. Materion ceased producing beryllium metal in 2000 when its facility was closed owing to obsolescence. Since that time, the company has obtained beryllium metal from the National Defense Stockpile and through imports from Kazakhstan.

In 2011, Materion built a new primary beryllium facility in partnership with the DOD to ensure the availability of high-quality domestic beryllium metal to meet critical defense needs. Under its Defense Production Act Title III Program, the DOD invested in a public-private partnership with Materion to build a new $90.3 million primary beryllium facility in Elmore, Ohio. The construction was completed in 2011. Materion provided assets, research and development, and technology valued at approximately $23.2 million to the project; the balance was funded by the DOD. Plant capacity was reported to be 73 metric tons per year of high-purity beryllium metal; approximately two-thirds of the facility's output is to be allocated for defense and Government-related end uses, and the remaining output is to go to the private sector (Metal Bulletin, 2010; Materion Corp., 2012a).

Kazakhstan's Ulba Metallurgical Plant, which was a subsidiary of JSC National Atomic Company "Kazatomprom," reported that it supplied about 26 percent of the world's beryllium products in 2011 compared with 3 percent in 1999. The Ulba Metallurgical Plant reportedly produced these products from stockpiled beryllium concentrate imported mainly from Russia. The concentrate stockpile, which was built up before the breakup of the Soviet Union, was forecast in 2003 to be sufficient to support production for about 30 years (Metal Bulletin, 2003; McNeil, 2006; Kazatomprom JSC, 2012).

More recent reports (2015) indicated that only a few years of supply remain in the concentrate stockpile. In 2015, it was estimated that the Ulba Metallurgical Plant produced about 90 metric tons of beryllium contained in beryllium-copper alloys, beryllium oxide ceramics, and beryllium metal. Owing to anticipated demand for beryllium, Russia is in the process of resuming mining and constructing a processing plant at the Yermakovskoye deposit in the Siberian Republic of Buryatiya. The new plant will produce beryllium hydroxide for export to the Ulba Metallurgical Plant in Kazakhstan, as well as to China and Japan for processing into beryllium metal and beryllium alloys. The annual mining and processing capacities are estimated at 25,000 metric tons per year of bertrandite ore and 130 metric tons per year of beryllium hydroxide. In 2015, Russia announced it would produce its own beryllium metal on a commercial scale by 2020.

China's Shuikoushan Non-Ferrous Metals Co., Ltd. processed beryllium ores and produced beryllium products in various forms at its 6th Smelting Plant in Songbai, Changning City, Hunan Province. The plant had an estimated production capacity of 150 metric tons per year of beryllium oxide and 1,500 metric tons per year of BCMA (McNeil, 2006). Fuyun Hengsheng Beryllium Industry Co., Ltd.'s refinery (a joint venture among Xinjiang Nonferrous Metals Industry Group, Xinjiang Henghe Investment Co., Ltd., and Xinjiang Nonferrous Metals Industry Group Nonferrous Metals Co.) was designed to produce 100 metric tons per year of beryllium oxide and 800 metric tons per year of BCMA. The refinery is located in Fuyun County in northwestern Xinjiang Uygur Autonomous Region (China Non-Ferrous Metal Import & Export Xinjiang Corp., undated). In 2015, it was estimated that China produced about 65 metric tons of beryllium contained in beryllium-copper alloys, beryllium oxide ceramics, and beryllium metal at these two plants. Approximately 20 metric tons of the beryllium was sourced from domestic ore and 45 metric tons was obtained from ore derived from foreign sources, most likely Kazakhstan's Ulba Metallurgical Plant.

Exploration for New Deposits

Early exploration methods to map the occurrence of deposits in highly evolved felsic rocks and fluorine-rich hydrothermal systems used a neutron-sourced gamma ray spectrometer capable of rapid semiquantitative field analysis of the beryllium contents of rocks (Meeves, 1966). Current exploration and assessment methods are based on identifying favorable geotectonic settings, beryllium-bearing magmatic rock suites, and local and regional alteration patterns that might target economic mineralization (Foley and others, 2012). Magnetic, gravity, and seismic data are useful in identifying large-scale igneous suites in favorable geotectonic settings that have a potential to contain volcanogenic beryllium deposits. Rhyolitic rocks rich in fluorine and beryllium that show evidence of explosive volcanism, such as unsorted carbonate rock fragments in breccias and vent structures capable of tapping the sources of rhyolitic magma and mineralizing fluids at depth, are a favorable volcanic host rock. The richest beryllium ore zones may be associated with mineralized carbonate-fragment-rich deposits of tuff. The presence of fluorite and uranium deposits suggests the presence of fluids capable of transporting sufficient amounts of beryllium to form a deposit (Lindsey, 1975). Hydrothermal alteration minerals, especially the presence of abundant lithium-smectite, and geochemical halos of elements, including Be, Ce, F, Ga, Li, Nb, and Y, occur in rocks surrounding deposits (Lindsey and others, 1973). Economic deposits are likely to be made up of many small mineralized lenses that, as a whole, may cover 50 square kilometers or more but that individually may cover only hundreds of square meters. For example, the surface expression of the Apache Warm Springs deposit is approximately 10 meters by 40 meters—comparable in size to one of the smaller individual deposits at Spor Mountain.

Exploration for beryl-rich LCT pegmatites is typically carried out within major known pegmatite fields where field relations are clear and discoveries of new pegmatite bodies may be readily mined (Bradley and McCauley, 2013). In areas where bedrock is well exposed, pegmatites stand out because they are light-colored, have large crystals, and are resistant to weathering relative to surrounding country rocks. An initial exploration step is the identification of appropriate granitic rock types, although, because pegmatites can invade any rock type, the absence of granite in surface exposures does not eliminate the potential occurrence of LCT pegmatites. In areas where exploration has been minimal, first-order criteria, as established in Bradley and McCauley (2013), are an orogenic hinterland (mountain-building) setting, rocks having metamorphic grades suggesting conditions of medium pressure and medium to high temperatures, and the presence of evolved granites and common granitic pegmatites. Pegmatites that show a regional mineralogical and geochemical zoning pattern concentric about the inferred parental granite are favorable for beryl. Exploration and assessment for LCT pegmatites are guided by a number of important field and laboratory observations. Because beryl is associated with the highly fractionated pegmatite zones and because these may constitute only 1 to 2 percent of a field, mineralogical and geochemical variations in granite-pegmatite zones are important (Selway and others, 2005). For example, beryl reportedly shows color changes from green-brown to pink-white, with increasing fractionation in more evolved bodies (Trueman and Černý, 1982). Also, mapping of chemical changes in specific minerals, such as increasing rubidium in potassium feldspar, increasing lithium in white mica, increasing manganese in garnet, and increasing tantalum and manganese in columbite-tantalite, may be used to locate LCT pegmatite bodies within larger fields of common pegmatite. Many LCT pegmatites show haloes of alkali elements (cesium, lithium, and rubidium) in surrounding wall rocks and soils that have been used to locate buried rare-metal pegmatites (Galeschuk and Vanstone, 2005, 2007). In weathered environments, anomalies of As, Be, Sb, and Sn and resistant minerals, such as cassiterite, in soils may also indicate LCT pegmatite (Smith and others, 1987).

Exploration for new deposits is limited in North America because domestic beryllium production is dominated by a single producer (Materion Corp.) that effectively controls the relatively small and specialized domestic beryllium market—a market that cannot readily accommodate new competition on the raw material supply side. Many new discoveries of volcanic-hosted bertrandite are extensions of known deposits. Further exploration and mining of beryl from pegmatite is unlikely in the United States given the current high costs associated with labor-intensive beryl extraction.

Environmental Considerations

Sources and Fate in the Environment

The behavior of beryllium in the environment is dominated by its low solubility in water and that it is commonly found in solid form. Natural beryllium in the atmosphere is mostly from dust sources, including windblown dust and volcanic eruptions. The main anthropogenic source of beryllium in the atmosphere is from the combustion of coal and fuel oil, followed by beryllium processing and municipal waste combustion (National Research Council, Committee on Beryllium Alloy Exposures, 2007). Globally, the atmospheric content of beryllium varies between 0.3 and 300 parts per trillion (ppt) (0.1 to 100 nanograms per cubic meter [ng/m^3]) (Kabata-Pendias and Mukherjee, 2007). Beryllium concentrations in air in rural areas of the United States ranged from 0.08 to 0.2 ppt (0.03 to 0.06 ng/m^3) and in urban areas ranged from less than 0.3 to 18 ppt (0.1 to 6.7 ng/m^3); up to 224 ppt (82.7 ng/m^3) was reported in the vicinity of a beryllium processing plant in Pennsylvania (Bruce and Odin, 2001). The average upper crustal abundance of beryllium is 1.9 ppm (Hu and Gao, 2008) and natural soils are reported to contain between 0.48 to 3.52 ppm beryllium (Kabata-Pendias and Mukherjee, 2007). In the conterminous United States, the concentration in surface soils (0 to 5 cm depth) averages 1.3 ppm and ranges from less than 0.1 to 17.3 ppm (Smith and others, 2013).

In waterways, the natural weathering of rocks and soils, deposition of atmospheric beryllium, and industrial wastewater effluents are the main sources of beryllium. The mobility of beryllium in the aqueous environment is limited because of the poor solubility of most beryllium compounds and its affinity to bind with clay minerals and organic compounds; beryllium commonly resides in sediment or soils. Beryllium mobility is enhanced under acidic water conditions and may be found as a dissolved cation (beryllium^{2+}) or may form soluble fluorine and organic complexes (Kabata-Pendias and Mukherjee, 2007). At near-neutral pH, which is typical of most surface and groundwaters, beryllium is controlled by the formation of beryllium hydroxide, which is a low solubility phase. Globally, rivers commonly contain between less than 0.008 and 0.6 ppb beryllium and have an average of 0.009 ppb beryllium (Gaillardet and others, 2003). Surface waters in the United States have a mean concentration of 0.07 ppb beryllium; groundwaters contain comparably low concentrations, and seawater contains even lower concentrations (Eckel and Jacob, 1988; Bruce and Odin, 2001). Beryllium concentrations in industrial effluents are several orders of magnitude higher and range from 30 to 170 ppb (Bruce and Odin, 2001).

Pre-mining baseline geochemical data for beryllium deposits are sparse. LCT pegmatite deposits may exhibit enrichments in B, Cs, F, Li, and Rb in surrounding soils and waters. These enrichments form as surrounding country rock is hydrothermally altered as a result of pegmatite emplacement (Bradley and McCauley, 2013), and they can persist in soils that develop when the rocks are weathered. For example, the Tanco pegmatite in Canada has alteration halos of lithium and rubidium over the buried deposit (Trueman and Černý, 1982). In general, volcanogenic beryllium deposits may have enriched halos of F, Li, Mo, Nb, REEs, Sn, Ta, Th, U, and W in surrounding volcanic rocks and mineralized tuff; therefore, soils and waters in the vicinity may contain anomalous concentrations of the elements (Foley and others, 2012). The stream waters near the Yermakovskoye deposit in Russia contain naturally elevated concentrations of Cu, F, Fe, Hg, Mn, Mo, and Zn (Kislov and others, 2010). The solubility of beryllium minerals is low under most naturally occurring conditions; thus, beryllium contents are not expected to be anomalous in waters draining beryllium deposits, although soils may be enriched.

Mine Waste Characteristics

Mine waste is material that is generated during ore extraction and processing at the mine site as part of the mining operation; it has no economic value. The volume and characteristics of the mine waste depend on the deposit type exploited and its size, whether multiple mineral commodities are being recovered, and the mining and processing methods used. Mine waste also includes waste generated in the chemical conversion of concentrated beryllium ores to beryllium hydroxide at the mine site. Additional processing steps to convert beryllium hydroxide to beryllium metal, oxides, or alloys also create waste; this type of waste is not discussed in this paper because these operations are commonly conducted at processing plants distant from the mine sites. In general, the mining of beryl and bertrandite ores creates mine waste that is similar in composition to the rocks that host the beryllium-containing minerals because the ores grades are low (table E4).

The ore from the bertrandite deposit at Spor Mountain, Utah, contains about 1 percent or less bertrandite; therefore, nearly all of the mined and processed ore becomes waste. Mining at Spor Mountain occurs with a stripping ratio of overburden to ore of 23:1, which indicates that significant amounts of overburden also have to be disposed of (Hawkins, 2001). At Spor Mountain, the composition of the mineralized tuff and the overlying rhyolite is likely representative of the bulk geochemical characteristics of the waste material. Quaternary alluvium overlying the mineralized tuff and rhyolite is mainly Pleistocene sediments of Lake Bonneville. The geochemical characteristics of the mineralized tuff at Spor Mountain have been summarized by Lindsey (1975), and, for the most part, reflect the rhyolitic protolith ($Si > Al > K > Ca \approx Na > Fe \approx Mg$) with trace-element enrichments in beryllium, fluorine, lithium, thorium, and uranium relative to unmineralized counterparts. The mineralogy of the tuff is dominated by clays, cristobalite, potassium-feldspar, and quartz; calcite and dolomite clasts are locally important. Fluorite and manganese oxides are locally abundant in the ore assemblages, and uranium is thought to be bound in fluorite and opal (Lindsey, 1981). The lack of sulfide minerals and the presence of carbonate minerals as clasts suggest that the waste material is net-alkaline (has a pH greater than 7); this measure indicates that the rocks will not contribute acid to surrounding bodies of water as they weather.

At the Yermakovskoye Mine site in Russia (fig. E1), future mining and processing of the ore reserves is expected to extract 8.5 million cubic meters of rock from an open pit operation and to produce 830,000 cubic meters of tailings during its approximate 20-year mine life (Kislov and others, 2010). The ore minerals of fluorite (about 20 percent fluorite), bertrandite, and phenakite are associated with albite, calcite, dolomite (about 12 percent carbonate), microcline, and quartz with minor amounts of sulfides, including galena, pyrite, and sphalerite. Mine tailings from production that ended in 1989 contains up to 241 ppm beryllium, which is well above background concentrations in the area, which are between 1.5 and 9.9 ppm beryllium (Kislov and others, 2010). The reopening of this mine site as proposed would include a processing facility that would use flotation to separate the sulfides, which would create sulfide-rich tailings, followed by beryllium and fluorite flotation, which would create additional tailings. The sulfur content of the ore is up to 0.37 percent sulfur, including the contribution from pyrite, which can generate acid upon weathering. Sulfide tailings could be potentially acid generating, but the high carbonate content of other mine waste may help neutralize the acid generated.

Beryl in pegmatites can be associated with a range of host rock types, but, in general, processing of pegmatite ores generates mill tailings of relatively simple mineralogy. Enriched zones of beryl (approximately 2 percent) usually are associated with muscovite, plagioclase, potassium-feldspar, and quartz and may be from zones in which amblygonite, feldspar, and spodumene are recovered (Sabey, 2006). Beryl has also been found in quartz veins that contain cassiterite, molybdenite, wolframite, and other minerals. Enriched-beryl zones commonly consist of a few thousand tons of rock, with the largest containing up to 1 million metric tons. When it was in operation, the Tanco Mine generated tailings that were predominantly feldspar with some mica, quartz, pollucite, and spodumene when the ore was processed to recover spodumene and tantalum (Solylo, 2012). Tailings produced after beryl separation would likely be compositionally similar. Additional insight into the mineralogy of mine waste from pegmatite deposits was gained from experiments conducted on recovering beryl from several small operations that were mining spodumene in Arizona, Colorado, New Mexico, and Canada. Quartz and feldspar tailings from gangue as well as mica-schist tailings from overburden were generated. Also, in a later processing step to concentrate the beryl, apatite and iron-bearing gangue minerals, including garnet, pyroxene, and tourmaline, were separated with a magnetic separator, which generated additional waste (Bhappu and Fuerstenau, 1964). Other research on recovering beryl from the former Foote Mine near Kings Mountain, North Carolina, generated predominantly feldspar and quartz tailings along with separate

Table E4. Location, grade, tonnage, and other data for selected beryllium deposits of the world.

[Compiled from Griffitts (1954, 1973), Barton and Young (2002), Sabey (2006), Secher and Appel (2007), Brush Engineered Materials, Inc. (2009), and McLemore (2010a). Be, beryllium; BeO, beryllium oxide; %, percent; —, no data]

Deposit	Location	Country	Deposit type	Resource (metric tons)	Contained BeO (metric tons)	Grade (% BeO)	Grade[1] (% Be)
Aguachile	Coahuila	Mexico	Carbonate-hosted	17,000,000	—	0.1	0.036
Apache Warm Springs	New Mexico	United States	Volcanogenic	43,060	—	0.26	0.094
Aqshatau	Aqshatau	Kazakhstan	Greisen	16,000	—	0.03 to 0.07	0.02
Atlantic shield	Brazil	Brazil	Pegmatite/granite	106,000,000	—	0.04	0.015
Black Hills	South Dakota	United States	Pegmatite/granite	—	13,000	0.05	0.02
Boomer, Lake George	Colorado	United States	Greisen	<1,000 to 3,000	—	2.0 to 11.2	2.3
Brockman	Western Australia	Australia	Volcanogenic	4,300,000	—	0.08	0.03
Gold Hill	Utah	United States	Veins	—	5,000	—	0.5
Hellroaring Creek	British Columbia	Canada	Pegmatite	—	1,000	0.1	0.036
Ilimaussaq (general)	Ilimaussaq	Greenland	Peralkaline intrusion	—	20,000	—	0.18
Iron Mountain	New Mexico	United States	Carbonate-hosted	1,000	—	0.2 to 0.7	0.18
Kvanefjeld	Ilimaussaq	Greenland	Peralkaline intrusion	180,000	—	—	0.1
Lost River	Alaska	United States	Skarn	3,000,000	10,000	0.3 to 1.75	0.36
McCullough Butte	Nevada	United States	Carbonate-hosted	175,000,000	47,000	0.027	0.01
Mt. Wheeler	Nevada	United States	Veins	—	1,000	0.75	0.27
Rodenhouse Wash	Utah	United States	Pegmatite/granite	1,000,000	—	0.5	0.18
Seal Lake	Northwest Territories	Canada	Peralkaline intrusion	—	6,800	0.35 to 0.4	0.14
Sheeprock	Utah	United States	Greisen	1,000,000	—	0.01 to 0.1	0.02
Sierra Blanca	Texas	United States	Carbonate-hosted	—	11,300	0.5 to 1.9	0.36
Spor Mountain	Utah	United States	Volcanogenic	6,425,000	—	0.266 to 0.720	0.18 to 0.26
Strange Lake	Quebec, and Newfoundland and Labrador	Canada	Peralkaline intrusion	—	42,000	0.08	0.03
Tanco[2]	Manitoba	Canada	Pegmatite/granite	900,000	1,800	0.2	0.07
Thor Lake	Northwest Territories	Canada	Peralkaline intrusion	1,600,000	13,300	0.76	0.28
Tin-spodumene belt, North Carolina and South Carolina	North Carolina and South Carolina	United States	Pegmatite/granite	—	111,000	0.02 to 0.1	0.031
Ukrainian Shield	Ukraine	Ukraine	Greisen	20,000	—	0.4	0.11
Victorio Mountains	New Mexico	United States	Carbonate-hosted	11,900,000	—	0.023	0.01
Vozneskoye	Siberia	Russia	Skarn	10,000	—	0.06	0.02
Yermakovskoye	Siberian Republic, Buryatiya	Russia	Skarn	—	10,000	1.3	0.47

[1] Grade used for constructing figure E9.

[2] Also known as Bernic Lake.

beryl, mica, and spodumene concentrates (Browning, 1961). In addition, discarded spodumene tailings at the mine, which consisted of feldspar and quartz with minor amounts of mica, spodumene (approximately 5 percent), and beryl (approximately 0.5 percent) were reprocessed to recover beryl, spodumene, and, sometimes, feldspar (Browning and others, 1964).

In addition to the waste rock, overburden, and mill tailings generated at beryllium mine sites, converting the concentrated beryllium ores to beryllium sulfate and subsequently to beryllium hydroxide produces additional waste. To remove impurities and waste minerals, the beryllium is extracted, purified, and precipitated using organic or other solutions. The waste solutions and precipitates from various steps are discarded in waste ponds and may be acidic. Waste ponds may be neutralized and diluted to offset high corrosivity and reduce the overall concentrations of Be, Cr, Cu, Se, and cyanide. Waste solutions containing uranium are commonly transferred to separate storage ponds and shipped elsewhere for U-metal recovery. Waters in the ponds are commonly evaporated to generate a solid waste product (U.S. Environmental Protection Agency, 1989). One study that examined the characteristics of red mud solid waste resulting from the fluoride separation process for beryl ore found that it was composed mainly of aluminum, iron, and silicon, with significant amounts of beryllium (Bhat and others, 2002). For example, red mud at a processing facility in India contained 0.4 to 0.6 percent beryllium, and approximately one-half of the beryllium was leached using water (based on laboratory experiments), which suggests that much of the beryllium in red mud is mobile in surficial environments (Bhat and others, 2002).

Human Health Concerns

Beryllium is toxic and a human carcinogen that can impair the function of the blood vessels, endocrine glands, heart, and liver (Taylor and others, 2003; Kabata-Pendias and Mukherjee, 2007). The general population is exposed to beryllium mainly from ingestion of beryllium-containing food and water, with smaller contributions from inhalation of dust (Bruce and Odin, 2001). Ingested beryllium is less likely than inhaled beryllium to cause health concerns because most beryllium that is ingested passes through the body without entering the bloodstream. In contrast, beryllium particles inhaled can dissolve in the lungs and move to the bloodstream or remain in the lungs for up to years after exposure has ceased.

An international guideline value for beryllium in drinking water has not been established because beryllium is “rarely found in drinking water at concentrations of health concern,” according to the World Health Organization (2011, table 8.9, p. 179). For the United States, however, the maximum contaminant level for beryllium in drinking water is 4 ppb (U.S. Environmental Protection Agency, 2009). Beryllium concentrations in excess of this drinking water standard are unlikely because most beryllium compounds and minerals are poorly soluble in water. According to the U.S. Environmental Protection Agency (EPA) (2009), consumption of waters exceeding action levels may lead to intestinal lesions. The average concentration of beryllium in drinking water in the United States is 0.19 ppb (which is significantly less than the guidelines), and ranges from 0.01 to 1.22 ppb (Agency for Toxic Substances and Disease Registry, 2002; Sabey, 2006). As for soils, screening levels based on human health risk in the United States have been established to determine whether levels of contamination at hazardous waste sites warrant further investigation or site cleanup. The noncancer screening level for beryllium in residential soils is 160 ppm, and in industrial soils, it is 2,000 ppm (U.S. Environmental Protection Agency, 2013). As previously stated, the range in beryllium concentrations in surficial soils of the United States are from less than 0.1 to 17.3 ppm (Smith and others, 2013), although orders of magnitude higher concentrations can be found in soils, such as those formed by weathering of beryllium-rich rocks.

Human health concerns from exposure to beryllium are mostly associated with inhaling airborne particles during the mining and processing of beryllium ores and the manufacturing of beryllium-containing products. The occupational threshold exposure level value for beryllium in the atmosphere is 5 ppb (2 milligrams per cubic meter [mg/m^3]) for an 8-hour exposure period and 68 ppb (25 mg/m^3) for a 30-minute exposure period (National Institute for Occupational Safety and Health, 2005). The level of occupational exposure to beryllium inhalation has decreased from early years of beryllium production in the 1930s to modern workday environments (National Institute for Occupational Safety and Health, 2005). Processing facilities implement safety procedures to minimize exposure that include regularly washing hands and laundering clothes; personal safety equipment, such as respirators; and the collection of dusts, fumes, and mists (Petkof, 1985).

Beryllium dust and fumes have been recognized to cause chronic beryllium disease, which is a debilitating and potentially lethal lung disease, and its precursor, beryllium sensitization, which is an immune system disorder. The human health risk is variable among the different sectors of the beryllium industry, and only mining and ore processing that occur at the mine site are considered here. A study of workers from the Spor Mountain Mine and mill reported that beryllium exposure levels during mining and milling were generally less than the threshold exposure level of 5 ppb (2 micrograms per cubic meter [$\mu g/m^3$]) (Deubner and others, 2001). Another study at the site by Stefaniak and others (2008) reported that concentrations in the air among various work areas ranged from 0.003 to 6 ppb (0.001 to 2.1 $\mu g/m^3$). There may be a lower risk of sensitization and of developing chronic beryllium disease from beryllium during mining and ore (both bertrandite and beryl) processing than during other phases of beryllium manufacturing, including the production of beryllium oxide, beryllium ceramics, and copper-beryllium alloys (Deubner and others, 2001, 2011).

Deubner and others (2011) hypothesize that the decreased risk is because the beryllium-containing materials found at the Spor Mountain facility dissolve faster in lung fluid than do other beryllium-containing materials. The physicochemical properties of beryllium, such as chemical composition, particle size, and specific surface area, influence bioavailability and may be more important than the exposure concentration in determining risk of developing beryllium sensitization or chronic beryllium disease (National Research Council, Committee on Beryllium Alloy Exposures, 2007; Stefaniak and others, 2008). In addition, genetic susceptibility is likely an additional risk factor (Taylor, Ding, and others, 2003).

Although inhalation is the main industrial exposure pathway of concern, skin exposure to beryllium may result in it entering the body, contributing to sensitization and causing irritation, lacerations, and chemical ulcers, and granulomas (Epstein, 1991; Day and others, 2006; National Research Council, Committee on Beryllium Alloy Exposures, 2007; Duling and others, 2012). Duling and others (2012) found the beryllium from bertrandite ores from Spor Mountain dissolves in artificial sweat as well as synthetic lung fluids.

Radiation exposure from uranium or thorium associated with volcanogenic beryllium ore may be a human health concern during mining and processing operations, although specific case studies could not be identified. Nonetheless, anomalous amounts of uranium (up to 200 ppm) and thorium (up to 150 ppm) are associated with the beryllium ores at Spor Mountain (Lindsey, 1981). If uranium is concentrated in waste generated from converting ore to beryllium hydroxide, precautions need to be taken when handling the waste.

Ecological Health Concerns

Beryllium is toxic to plants and animals; however, similar to human health concerns, ecological issues are associated mainly with the mining and manufacturing of beryllium. In uncontaminated areas, the concentration of beryllium in plants is commonly low (less than 1 ppm), and soils tend to contain beryllium in forms that are unavailable to plants (Bruce and Odin, 2001; Rossman, 2004). In some cases, beryllium is present as soluble salts in soils (for example, beryllium chloride [$BeCl_2$] and beryllium sulfate [$BeSO_4$]) that are bioavailable and potentially may cause toxic effects, including reduced growth and degradation of some proteins and enzymes, and may inhibit the uptake of calcium, magnesium, and phosphorus. Toxicity of beryllium to plants has been observed for soil concentration ranges of from 10 to 50 ppm (Kabata-Pendias and Mukherjee, 2007). Additionally, soils with concentrations of beryllium between 20 and 40 ppm have been shown to affect the survival and reproduction of soil invertebrates (Kuperman and others, 2006). Also, beryllium, both inhaled and ingested, has been shown to be acutely toxic to mammals in laboratory tests, but information regarding toxicity to wildlife was not found (Bruce and Odin, 2001).

Beryllium in water and stream or lake sediment is not significantly concentrated by aquatic organisms or accumulated within the food chain (Bruce and Odin, 2001). In laboratory tests, beryllium (administered as soluble salts) is acutely toxic to a variety of freshwater fish and water fleas (*Daphnia magna*), but toxicity varied widely depending on the species studied and the test conditions; soft and acidic waters had the highest toxicity associated with the lowest concentrations of beryllium (Bruce and Odin, 2001, and references therein). Water-quality criteria and stream-sediment guidelines for the protection of aquatic life are generally lacking; however, the EPA does provide lowest observable effect limits (LOELs) as guidance for acute and chronic toxicity to aquatic life for beryllium of 130 ppb and 5.3 ppb, respectively (U.S. Environmental Protection Agency, 1980). Also, Suter (1996) suggests secondary acute and chronic aquatic ecosystem guidelines for surface waters of 271 ppb and 5.09 ppb beryllium, respectively. These guidelines are generally higher than the mean concentration of 0.07 ppb beryllium reported for surface waters in the United States (Eckel and Jacob, 1988). In general, the concentrations needed to cause toxicity to aquatic organisms from the dissolution of bertrandite or beryl would likely occur only in soft waters with acidic pH values.

The mining and processing of beryllium ores may enrich waters and soils in potentially toxic trace elements and contaminate the ecosystem at some mine sites. For example, water from the open pit at a previously mined, skarn-related, beryllium-fluorite deposit in Russia (the Yermakovskoye deposit) contained elevated concentrations of some elements, including Cu, Fe, Mn, Mo, Mg, Pb, and Zn, that exceeded local standards for water bodies used for fishery purposes. Additionally, sediment at the bottom of the pit was contaminated with As, Be, Cd, Pb, and Zn, and the concentrations of lead and zinc exceeded values above which effects to aquatic biota are likely. Mine waste piles contained concentrations of beryllium that were above the maximum allowable concentrations (Kislov and others, 2010). The natural background contents of some of the elements, such as Cu, Fe, Mn, Mo, and Zn, in local streams and melt waters were also elevated and above environmental guidelines, which made it difficult to distinguish the contamination from mining compared to pre-mining concentrations associated with the mineralized area. According to Kislov and others (2010), the pasture vegetation in the local area may contain high amounts of beryllium from the deposition of contaminated dust, and the agricultural uses of the land should be limited.

In contrast to the mine site in Russia, the Spor Mountain deposit is characterized by an arid climate, a lack of surface water, and low concentrations of beryllium and uranium in both the volcanic host rock and ore materials. Ecosystem issues related to beryllium mining are not known in the vicinity of the Spor Mountain deposit.

Carbon Footprint

Beryllium has the potential to reduce the carbon footprint from energy production because of its potential for use in wind energy and hydrogen storage and fuel cell applications. IBC Advanced Alloys Corp. of Canada and a Washington, D.C.-based clean-energy consulting company are working to commercialize wind energy applications of beryllium. The use of beryllium is expected to increase wear resistance in wind turbines, and thus reduce the cost of operations (IBC Advanced Alloys Corp., 2013; Jaskula, 2013a). IBC has also collaborated with Hydrogen Link Inc. of Canada to advance research on the use of beryllium in hydrogen fuel storage. Lithium-beryllium hydrides have the highest viable hydrogen capacity at reasonable temperatures and can be used for small-scale applications, such as laptops and other portable devices (IBC Advanced Alloys Corp., 2010).

Mine Closure

The post-mining landscape at beryllium mines depends on the deposit type and size, the mining and processing methods, the climate, and regulations regarding mine closure. Open pits, shafts, and adits from underground operations, processing facilities, and mine and processing wastes may need to be addressed for mine closure; some mines are not reclaimed. For example, remediation efforts were not undertaken when production ceased in 1989 at the Yermakovskoye deposit in Russia (Kislov and others, 2010). The shallow open pit covered a surface area of 277,000 square meters. The pit floor was at least 70 m deep at the deepest part, and the pit contained a few meters of water (Kislov and others, 2010). Future plans for the site included resuming mining and building a processing plant. Construction was expected to begin in 2013 (Jaskula, 2013b). The life of the mine was expected to be 17 to 20 years (Kislov and others, 2010). Eventually, mine closure will involve stabilizing disturbed surfaces, reclaiming soils, waters, and stream sediments at and near the mine site, and addressing any issues associated with the open pit, waste-rock piles, and tailings.

Similar remediation efforts may also be undertaken at the Spor Mountain Mine after mining there ceases. The mining operations thus far have created several elongated open pits created to exploit the large sheet-like orebodies. Stockpiles of ore and waste piles of overburden material cover areas that are hundreds of meters in diameter.

Beryl is typically mined from small-scale operations using minimal mining equipment, commonly as a byproduct of feldspar and mica mining. Mining of ore is typically in quantities ranging from a few kilograms to hundreds of tons (Sabey, 2006). These types of operations commonly do not have mine closure plans. Some operations where beryl is mined as a byproduct are larger operations, and they leave a landscape of waste rock, tailings, and open pits after mining has ceased. For example, the flooded open pit at the Foote Mine in the Kings Mountain district, North Carolina, is several hundreds of meters in diameter, and waste rock and tailings cover an even larger area that is devoid of vegetation.

Problems and Future Research

Research efforts into understanding the factors that may affect future supplies of beryllium include developing assessment models for new deposits, conducting experimental studies on beryllium at conditions applicable to biochemical processes occurring in surface environments, and devising new and more efficient extraction technologies for both raw ore and recycled products. These are described in more detail below.

Assessment models.—Assessing for beryllium in volcanogenic systems is problematic at present because there is only one known and essentially unique economic deposit. Comprehensive modern geologic and geochemical studies of the exemplary deposit at Spor Mountain and comparative studies of additional regions and related deposit types (carbonate-hosted and fluorite deposits)—for example, the central Gobi volcanic zone in Mongolia, and the REE-rich alkaline volcano-plutonic rocks within the Transbaikal-Mongolian rare-metal province, Siberia—are needed to provide for more widely applicable deposit models and assessment methods. New approaches to evaluating the geologic availability of beryllium are also needed to assess pegmatite resources and other rare-metal systems, such as rare-metal granites, pegmatites, and skarn and greisen rocks of Alaska, where economics may require extraction and recovery of byproducts and coproducts (such as Be, Cs, F, Li, Nb, Si, Ta, and so forth).

Experimental studies.—Thermodynamic data on beryllium in various fluid-melt systems are needed to gain a better understanding of transport mechanisms for beryllium in a magmatic-hydrothermal environment and in fluorine-rich magmatic systems having rare-metal granites and associated beryllium-enriched pegmatites. These data have practical implications for resource and environmental assessment because they are needed to model these specialized geologic environments.

Environmental aspects.—The advent of new technologies and new products that use beryllium in conjunction with other elements, such as beryllium oxide enhanced nuclear fuel pellets, will likely require further study into the possible effects of use and disposal of complex and hazardous alloys, manufactured products, and waste materials.

Extraction technologies.—Improved extraction technologies may eventually be devised to handle materials that are currently below cutoff grades for volcanogenic deposits. Better refining methods may also be developed to separate contaminants (for example, Al, BeO, C, Fe, Mg, and Si) from raw beryllium minerals so that very high purity beryllium metal can be made from any beryllium source mineral.

Recycling.—As production levels and uses increase, the percentage of recycled beryllium from both new and old scrap may be expected to increase if separation technologies are improved.

New markets.—Materials producers will continue to work closely with users, especially the aerospace and defense industries, to meet advances in end-use products and to ensure that new materials are developed to meet high-performance requirements. According to some industry experts, the global beryllium market forecast is for consumption to reach greater than 500 metric tons per year within 5 years and for the growth in consumption to be shaped by upward trends in some important end-use application areas (Global Industry Analysts, Inc., 2012). In particular, growing security concerns are proposed to increase the demand for beryllium in defense applications. Further, the advent of new alloys of beryllium with aluminum is expected to drive the beryllium market in the United States and other countries as new products are developed. If successful, the beryllium oxide enhanced nuclear fuel pellet could increase demand for beryllium substantially.

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