Antimony

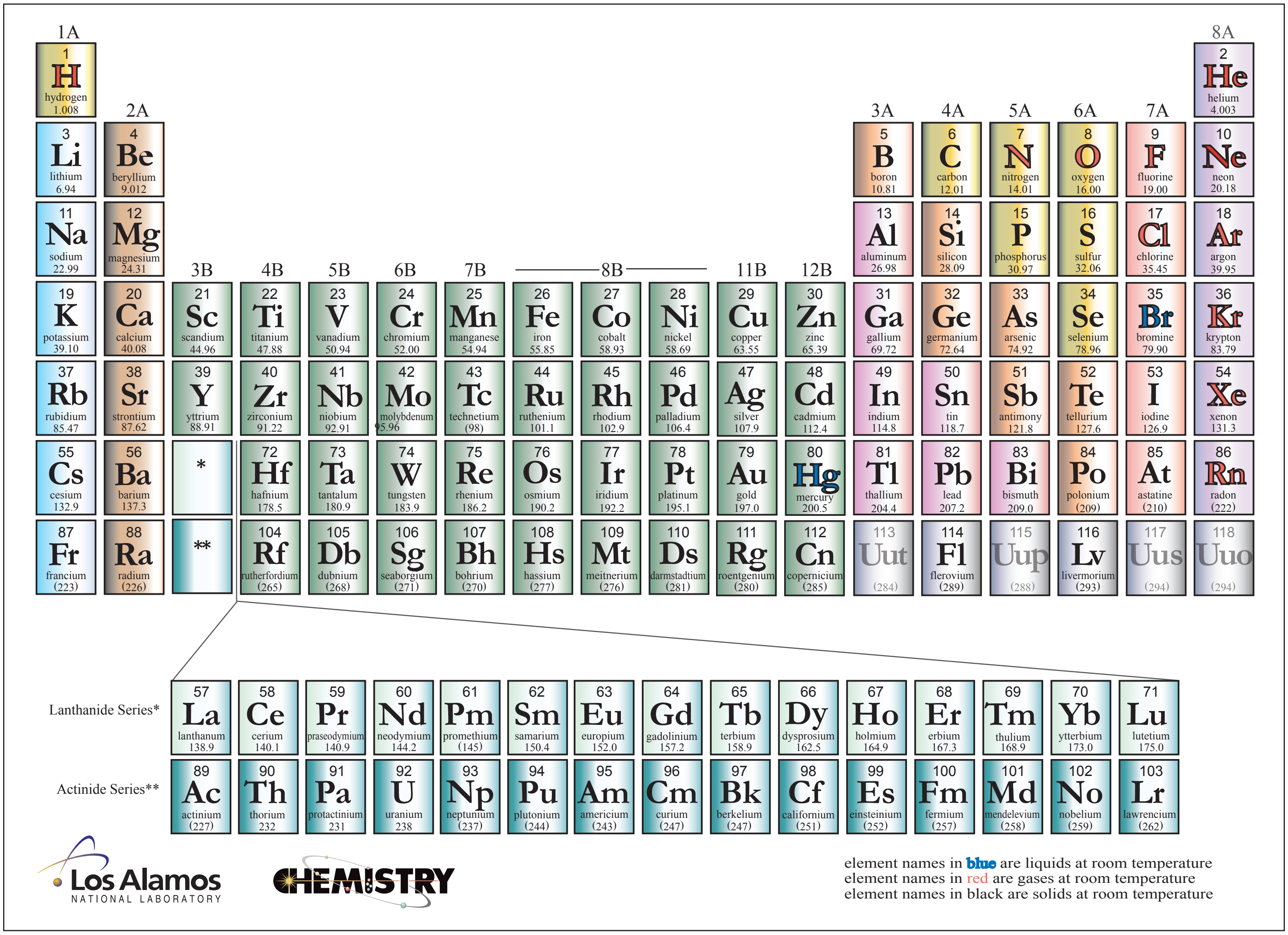
Chapter C of

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

Professional Paper 1802–C

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

Periodic Table of Elements



1A	2A	3B	4B	5B	6B	7B	8B	8B	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)

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

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

Cover. Underground photograph of the Hibbard stibnite-quartz vein, Lake George antimony deposit, New Brunswick, Canada, 1982. Photograph by Robert R. Seal II, U.S. Geological Survey.

Antimony

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

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

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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/L	microgram per liter
ATSDR	Agency for Toxic Substances and Disease Registry
cm	centimeter
EPA	U.S. Environmental Protection Agency
g/t	gram per metric ton
kg $CaCO_3$/t	kilogram of calcium carbonate per metric ton
km	kilometer
km^2	square kilometer
m	meter
ppb	part per billion
ppm	part per million
WHO	World Health Organization

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By Robert R. Seal II, Klaus J. Schulz, and John H. DeYoung, Jr.

With contributions from David M. Sutphin, Lawrence J. Drew, James F. Carlin, Jr.,[1] and Byron R. Berger[1]

Abstract

Antimony is an important mineral commodity used widely in modern industrialized societies. The element imparts strength, hardness, and corrosion resistance to alloys that are used in many areas of industry, including in lead-acid storage batteries. Antimony's leading use is as a fire retardant in safety equipment and in household goods, such as mattresses. The U.S. Government has considered antimony to be a critical mineral mainly because of its use in military applications. The great majority of the world's antimony comes from China, and much of the remainder is shipped to China for smelting. Antimony resources are unevenly distributed around the world. China has the bulk of the world's identified resources; other countries that have identified antimony resources include Bolivia, Canada, Mexico, Russia, South Africa, Tajikistan, and Turkey. Resources in the United States are located mainly in Alaska, Idaho, Montana, and Nevada. The most significant antimony mineral deposits occur in geologic environments with a thick sequence of siliciclastic sedimentary rocks in areas with significant fault and fracture systems. The most common antimony ore mineral is stibnite (Sb_2S_3), but more than 100 other minerals also contain antimony. The presence of antimony in surface waters and groundwaters results primarily from rock weathering, soil runoff, and anthropogenic sources. Global emissions of antimony to the atmosphere average 6,100 metric tons per year. Empirical data suggest that the acid-generating potential of antimony mine waste is low.

Introduction

Antimony is a brittle, silver-white, shiny metal that has a specific gravity of 6.68 and a melting point of 630.5 degrees Celsius (°C) (Miller, 1973). It is a poor conductor of heat and electricity. Antimony metal is too easily broken to be used by itself, but it imparts strength, hardness, and corrosion resistance to alloys (Miller, 1973). In addition, antimony does not readily oxidize and keeps its luster even in moist air and at elevated temperatures in the range of 100 to 250 °C. At temperatures above its melting point, powdered antimony ignites and burns with a white-green flame. Antimony is resistant to attack by dilute hydrochloric acid and concentrated hydrofluoric acid. Small amounts of antimony (about 0.2 part per million [ppm]) are found in Earth's crust, making antimony about as rare as some of the heavy rare-earth elements (Eyi, 2012). Antimony rarely occurs as the native metal because of its strong affinity for sulfur and such other metals as copper, lead, and silver; it is typically found in sulfides, sulfosalts, oxides, antimonates, and antimonites (Boyle and Jonasson, 1984).

Identified resources of antimony are unevenly distributed around the world. Figure C1 shows the locations of selected antimony mines, deposits, and major occurrences. All the deposits that produce antimony are hydrothermal deposits. The mines that produce antimony fall into two main categories—those that produce antimony as their primary commodity and those that produce antimony as a byproduct of mining for other commodities. Antimony production is dominated by one country, China.

Uses and Applications

Antimony has been an important mineral through much of human history. For example, the ancient Egyptians and early Hindus used stibnite (Sb_2S_3), which is the major ore mineral for antimony, to produce black eye makeup as early as about 3100 B.C. Medieval alchemists thought that antimony could be used to convert lead into gold. Today, antimony is used in lead-acid storage batteries for backup power and transportation; in chemicals, ceramics, and glass; in flame-retardant materials; and in heat stabilizers and plastics (fig. C2; Wang, 1919; Gibson, 1998; Carlin, 2011; Anderson, 2012).

Lead-acid storage batteries (the kind commonly used in automobiles) contain from 4 to 6 percent antimony alloyed with lead; antimony's resistance to corrosion is why so-called "lead" battery terminals are actually made of a lead-antimony alloy (Gibson, 1998). Lead-acid storage batteries account for more than two-thirds of the use of metallurgical antimony,

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[1] Deceased.

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 C1. World map showing locations of selected antimony deposits, mines, and major occurrences. Some symbols represent a single mine or resource, whereas others represent a cluster of deposits in one area. Data are from Laznicka (2010, table 8.4) and Schwarz-Schampera (2014). Also shown are major antimony belts in China (Wu, 1993) and the Bolivian antimony belt, which has approximately 500 antimony-gold deposits (Arce-Burgoa and Goldfarb, 2009).

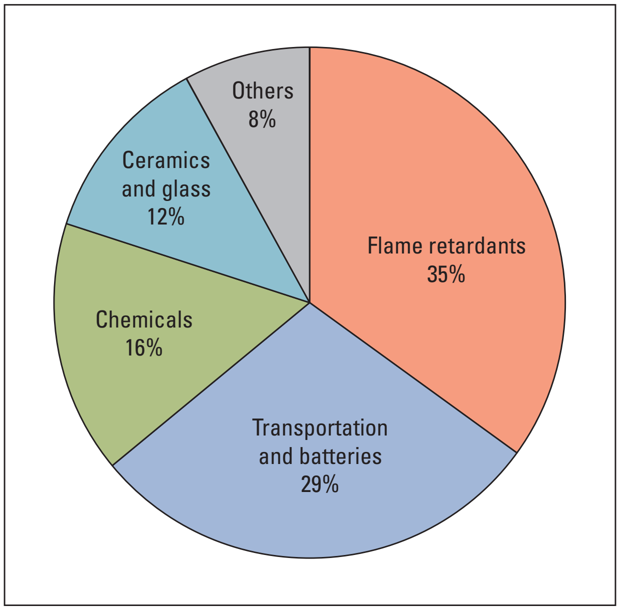

Figure C2. Pie chart showing major end uses of antimony as a percentage of antimony consumption in the United States in 2012. Data are from Carlin (2013b).

much of which is obtained from secondary (scrap) sources (Chegwidden and Bedder, 2012). Very high purity antimony metal (99.999+ percent pure) is used by the semiconductor industry in silicon wafers for making infrared detectors, diodes, and other devices, as well as for other applications. Anti-friction bearings, type metal for mechanical typesetting, solder (as much as 10 percent antimony, but typically much less), and decorative castings of Britannia metal (5 percent antimony) and pewter (7.5 percent antimony in modern products) also contain antimony. Graphite bearings are impregnated with antimony to increase heat tolerance. Antimony is used in nuclear reactors together with beryllium as startup neutron sources. “Antimony black” is finely ground metallic antimony used in bronzing for metals and plaster casts (Miller, 1973).

Antimony in the form of antimony trioxide (Sb_2O_3) is used in the United States mainly as a flame retardant in adhesives, paints, papers, plastics, and sealants. Antimony trioxide is also used as a fire retardant backing on rubber and textile upholstery, typically with bromine- or chlorine-based halogenated compounds (European Flame Retardants Association, 2006). Major markets for flame retardants include electronics, plastics, and fabrics used in making children’s clothing, aircraft and automobile seat covers, and bedding.

Other antimony compounds have a variety of uses. Antimony sulfide will combust in the presence of oxygen. It is a key combustion-supporting ingredient in the manufacture of ammunition primers, detonators, smoke-screen generators, visual range-finding shells, tracer bullets, and the striking surface of safety matches; it also provides the “glitter” effects in fireworks. The rubber industry uses antimony as a vulcanizing agent (Miller, 1973; Gibson, 1998). Antimony is also used in ceramics and glassmaking; for example, with suitable stabilizers and coloring additives, antimony trioxide glass can be made opaque to all visible light except long-wave infrared rays (Miller, 1973). Sodium antimonite (NaO_3Sb) is used as a flame retardant, as well as for removing bubbles from glass (United States Antimony Corp., 2016).

Antimony also has several pharmaceutical uses. Organic antimony compounds, such as antiprotozoal drugs, are used in the treatment of certain parasitic diseases. Potassium antimonyl tartrate ($K_2Sb_2(C_4H_2O_6)_2$) was formerly used as a nauseant and expectorant, although this use has been abandoned because of the compound’s toxicity and because it is difficult to administer (Abdi and others, 2003).

In an analysis of strategic mineral supplies prepared prior to World War II, Roush (1939, p. 238) stated that “Antimony has more uses of a direct military character than other members of the strategic group and probably more important uses than any of the others except mercury.” In addition to serving as a combustion-supporting ingredient, antimony has important additional uses for the military, some of which were first exploited in the Russo-Japanese War of 1905 and, later, by the United States during World War I (Miller, 1973; Anderson, 2012). Antimony is a hardening agent in metals used in ball bearings, bullets capable of penetrating armor plate, and lead shot. It helps to strengthen cable sheaths, chemical pumps, foils, plumbing fixtures and pipes, roofing sheets, and tank linings. During World War II, the fireproofing compound antimony trichloride ($SbCl_3$) saved the lives of many American troops when it was applied to tents and vehicle covers. In a fire, antimony and chlorine recombine to form unstable compounds that remove oxygen from the air, smothering the flames (Gibson, 1998; Eyi, 2012).

Demand, Availability of Supply, and Consumption

Demand and production.—Historically, U.S. consumption of antimony has been primarily for automotive and military uses. In the United States, stibnite deposits and occurrences were first discovered in Nevada in the 1860s, and some antimony ore was produced by 1865. Idaho’s production started in the early 1890s (Miller, 1973). During World War I (fig. C3), the military use of antimony resulted in a shortage that was eased by increased domestic production (driven by higher prices) and by imports from Bolivia (Miller, 1973). Expanded use of storage batteries in automobiles and trucks beginning in the 1930s further increased antimony consumption. In the 1940s, the many military applications for antimony during World War II escalated the demand for antimony; idle domestic mines were reopened, foreign mines expanded production, and secondary antimony recovered from scrap became a major supply source (Miller, 1973). In 1948, domestic mine production of antimony reached a record high of 5,890 metric tons, exceeding the previous high of 5,040 metric tons produced in 1943, owing

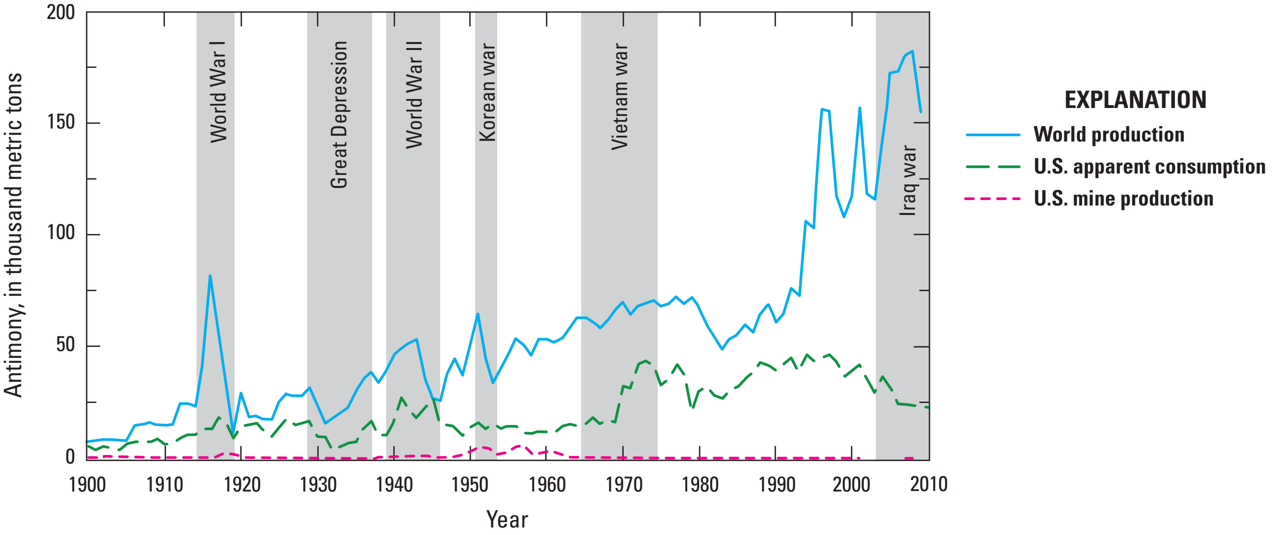

Figure C3. Graph showing world production, U.S. apparent consumption, and U.S. mine production of antimony from 1900 to 2012. Data are from U.S. Geological Survey (2016).

mainly to production from the Yellow Pine Mine in Idaho (Miller, 1973; Butterman and Carlin, 2004). Post-war domestic antimony production had returned to a lower level when the Korean war caused a temporary spike in production in the early 1950s. From the end of the Korean war to 2009, despite nearly unrivaled growth in automobile and truck sales and a building boom in the latter half of the 20th century, domestic mine production of antimony decreased; only in 1970 did it equal or exceed 1,000 metric tons (Miller, 1973; Butterman and Carlin, 2004; U.S. Geological Survey, 2016).

Since about 1984, domestic antimony mine production has been limited to a few companies. In 2001, antimony mining in the United States stopped when the Sunshine silver mine in Idaho stopped producing antimony as a byproduct (Masters, 2007). Domestic antimony mine production was reported in only 1 year between 2001 and 2011 (U.S. Geological Survey, 2016).

From 1900 to 2008, world mine production increased by a factor of more than 24, from 7,710 metric tons in 1900 to 185,000 metric tons in 2008. In 2009, world production decreased to 158,000 metric tons because of the economic recession but increased to 186,000 metric tons in 2011 (U.S. Geological Survey, 2016).

Supply.—In 2013, China produced about 80 percent of the world's supply of antimony. Its leading role in antimony production is greater than it is for any other minor metal (Masters, 2007). In 2006, as consumption of antimony decreased in most countries, China's burgeoning economy also made it the world's leading antimony consumer. However, a reduction in antimony mining and increased domestic consumption led China to look to foreign sources for supply of additional antimony ore and concentrate, including to Canada and Tajikistan, thus further reducing the production of smelted antimony metal and oxide in those countries from which China was importing antimony ores (Masters, 2007). In the United States, there is one active antimony smelter in Thompson Falls, Montana (United States Antimony Corp., 2016).

Consumption.—Apparent consumption of antimony in the United States is sensitive to fluctuations in the economy (fig. C3). In 1997, apparent consumption peaked at 46,600 metric tons, and it has been below that level ever since. In 2009, apparent consumption dropped to 21,200 metric tons, which was the lowest amount since 1979 (U.S. Geological Survey, 2016). The overall decrease in consumption may reflect industry's adjustment to the increase in the price of antimony over time (the price rose from $0.627 per pound in 1999 to $2.80 per pound in 2008); however, the low demand brought about by economic recession is evident in the continued drop in apparent consumption in 2009, despite the decrease in price to $2.36 per pound (Carlin, 2013a).

Strategic and Critical Resource Issues

In 2012, the United States obtained its supply of antimony from imports, particularly from China. In the period 2008 through 2011, the United States obtained 67 percent of its total imported antimony metal, ores and concentrates, and oxide from China; Mexico provided 15 percent; Belgium, 7 percent; Bolivia, 4 percent; and other countries, 7 percent (fig. C4; Carlin, 2013b).

In 2010, two actions by China caused reductions in that country's antimony production. Early in the year, the Government stated that it would not approve any new antimony projects until June 30, 2011. At about the same time, the Government shut down about 100 antimony smelters in its main antimony-producing region—an action that was aimed

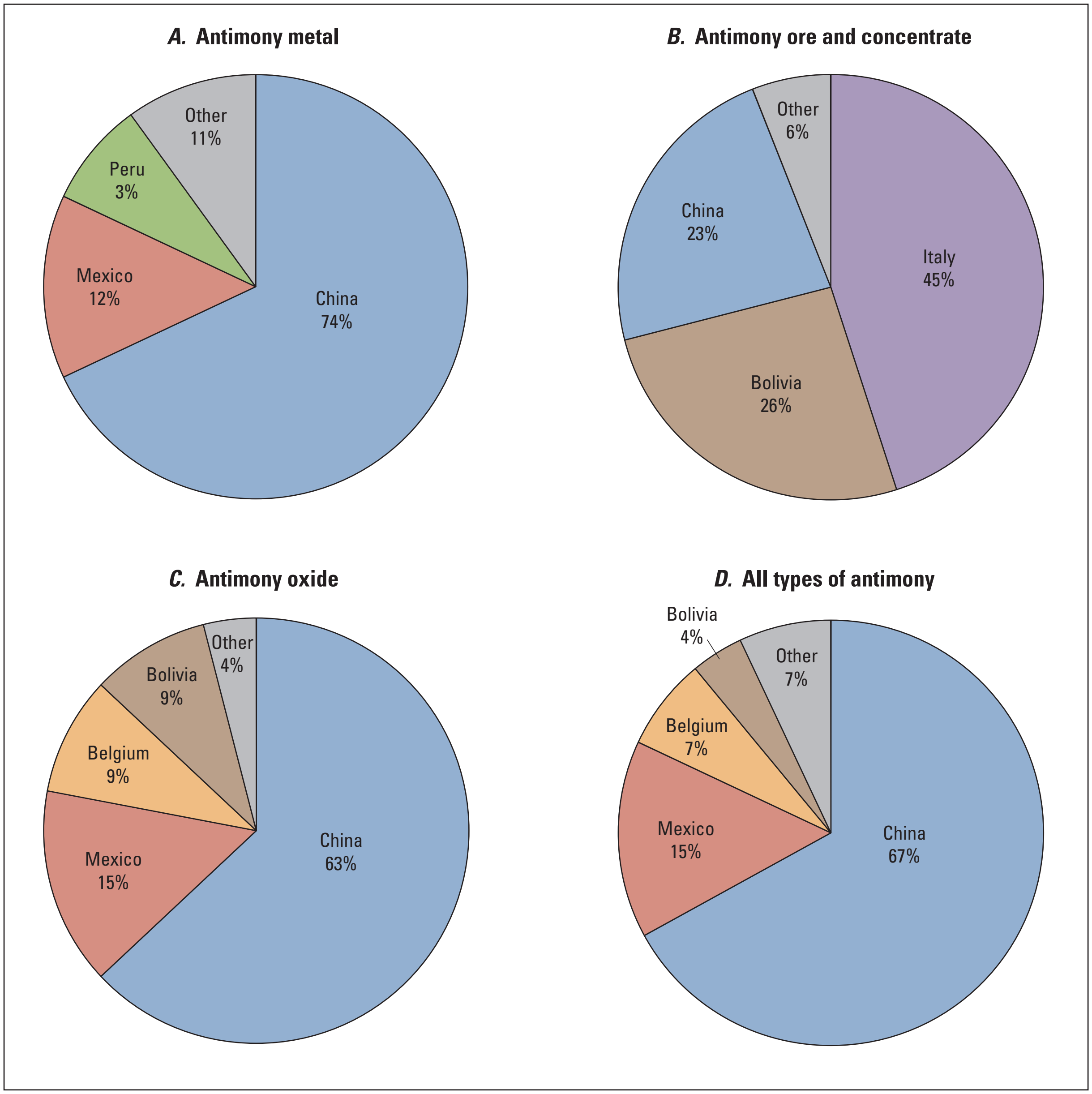

Figure C4. Pie charts showing percentages of contained antimony in U.S. imports for the period 2008–11, by source country. Data are from Carlin (2013b). *A*, Antimony metal; *B*, Antimony ore and concentrate; *C*, Antimony oxide; and *D*, All types of antimony.

at closing illegal mines and curbing pollution (Carlin, 2011). As recently as 2003, China had about 400 antimony producers, but by the end of 2011, that number had been reduced to about 14 to 18 qualified companies (Chegwidden and Bedder, 2012). In 2011, most ores and concentrates from Australia, Canada, Russia, and Tajikistan were exported to smelters in China, and Chinese antimony metal production had become increasingly dependent on these imports (Chegwidden and Bedder, 2012; Connelly and Rosart, undated).

If antimony supplies become limited, then compounds of chromium, tin, titanium, zinc, and zirconium could be substituted for antimony compounds in paint, pigments, and enamels; calcium, copper, selenium, strontium, sulfur, and tin can be substituted for antimony to harden lead and to replace antimony in lead-acid batteries, with enhanced performance in some cases (Eyi, 2012); and a number of organic compounds could be used as fire retardants. Such substitutes could make changes in production techniques and factory equipment necessary, however, and these substitutes have their own critical supply issues or could be more expensive to use. Barring market manipulation by a few dominant producers, recycling, mining, and smelter production are expected to meet the demand for antimony and antimony compounds for the foreseeable future.

Geology

Geochemistry

The name antimony comes from the Greek words *anti* (opposed) and *monos* (solitude), meaning "against being alone," because antimony is most commonly found in nature in combination with other elements (Gibson, 1998). Antimony is a chalcophile element, meaning that it combines readily with sulfur; it also commonly combines with other metals, such as copper, lead, and silver, in a class of minerals known as sulfosalts (Miller, 1973). Although its concentration in continental crust (0.2 ppm) is very low (Taylor and McLennan, 1995), it occurs in mineral deposits in concentrations ranging from trace amounts to major amounts (>10 percent) of economic importance. It occurs either as distinct antimony-bearing sulfide minerals (for example, stibnite), sulfosalt minerals (for example, tetrahedrite), rare antimonides (for example, aurostibite), or as a minor or trace constituent in sulfides (such as arsenopyrite and pyrite), arsenides, and sulfosalts. Antimony occurs in anomalous concentrations in the deposits of many metallic minerals, including those of base metals (such as copper, lead, and zinc) and precious metals (such as gold, silver, and platinum-group elements; Boyle and Jonasson, 1984). Because of its association with so many types of mineral deposits, antimony is a significant pathfinder element in geochemical prospecting surveys (Boyle and Jonasson, 1984).

Mineralogy

Antimony is found in more than 100 minerals (Boyle and Jonasson, 1984), of which 46 are listed in table C1 (Eyi, 2012). The most common antimony ore mineral is stibnite, which may contain traces of other metals, including copper, iron, gold, lead, and silver (Pohl, 2011). Stibnite occurs in numerous mineral deposit types (Cox and Singer, 1986). Antimony ore may also carry undesirable elements, such as arsenic and mercury (Pohl, 2011). Other antimony-bearing minerals, such as boulangerite (a lead-rich mineral), bournonite, gudmundite (an iron-rich mineral), jamesonite, polybasite, pyrargyrite, tetrahedrite (a copper-rich mineral), and valentinite are or have been of minor economic importance as sources of antimony (Miller, 1973; Eyi, 2012). Aurostibite is common in gold deposits enriched in antimony (Boyle and Jonasson, 1984). Metallic accessory minerals commonly found with primary antimony ores are arsenopyrite, chalcopyrite, galena, gold, pyrite, pyrrhotite, sphalerite, and silver; common gangue minerals are quartz (predominantly), calcite, and barite (Miller, 1973). The most common supergene antimony minerals are bindheimite, kermesite, nadorite, senarmontite, and stibiconite (table C1).

Deposit Types

Antimony occurs in a variety of deposits of various ages, including epithermal veins, pegmatites, and replacement and hot-spring deposits (Miller, 1973). Ore-grade concentrations of antimony are not common, but antimony mines can be divided into the following two broad categories: primary antimony producers and byproduct antimony producers. This distinction also corresponds to the empirical differences between simple stibnite deposits and complex polymetallic deposits (Schwarz-Schampera, 2014). Simple quartz-stibnite vein and replacement deposits account for most of the current and recent mine production. They can form in several different types of hydrothermal systems, including the peripheral parts of orogenic gold deposits, intrusion-related gold deposits, porphyry copper and molybdenum deposits, polymetallic mesothermal vein deposits, and sediment-hosted Carlin-type gold deposits (Hofstra and others, 2013). They can also occur alone with no apparent association with other mineral deposits.

The most significant simple quartz-stibnite deposits include those in Bolivia, Canada, China, Russia, and South Africa. Important or representative deposits from these countries include the Kharma (Bolivia), Beaver Brook and Lake George (Canada), Xikuangshan (China), Sarylakh and Sentachan (Russia), and Consolidated Murchison (South Africa) deposits. The Yellow Pine deposit in Idaho and the U.S. Antimony Mine in Montana are the most important deposits that fit within this category in the United States (fig. C1).

The Cordillera Oriental in Bolivia contains more than 500 known antimony-gold deposits, which are typified by the Kharma deposit. The Kharma deposit consists of fissure veins dominated by stibnite with subordinate amounts of other sulfides (pyrite, arsenopyrite, and sphalerite) and sulfosalts (plagionite, fülöppite, and veenite), and minor amounts of aurostibite (Dill and others, 1995). The gold content is generally low (about 1 ppm) and the gold is difficult to recover. Quartz is the main gangue mineral, accounting for up to 90 percent of the veins, followed by siderite and calcite. The vein system is found in a fault zone that cuts Paleozoic fine-grained clastic rocks (argillites), which were deformed and later intruded by granitic rocks from the Permian to Jurassic Periods.

The two prime examples of simple stibnite deposits in Canada are the Beaver Brook deposit in central Newfoundland (Lake and Wilton, 2006) and the Lake George deposit in New Brunswick (Scratch and others, 1984; Seal and others, 1988). These two deposits share many geologic similarities. Both occur in fractures of fault systems hosted by Ordovician to Silurian siliciclastic sedimentary rocks, and they are both located near Siluro-Devonian granitic intrusions. The Beaver Brook deposit contains resources of 2.12 million metric tons at an average grade of 4.41 percent

Table C1. Selected antimony minerals.

[Source: Anderson (2012). *, mineral is mentioned in the text of this chapter]

Mineral name	Chemical formula
Andorite	$AgPbSb_3S_6$
Annivite	$Cu_{12}(Sb,Bi,As)_4S_{13}$
Arite	$Ni(As,Sb)$
Aurostibite*	$AuSb_2$
Berthierite*	$FeSb_2S_4$
Berthonite	$Cu_7Pb_2Sb_5S_{13}$
Bindheimite*	$Pb_2Sb_2O_6(O,OH)$
Bolivianite	$Ag_2Sb_{12}S_{19}$
Boulangerite*	$Pb_5Sb_4S_{11}$
Bournonite*	$PbCuSbS_3$
Breithauptite	$NiSb$
Cervantite	Sb_2O_4
Cylindrite	$Pb_3Sn_4Sb_2S_{14}$
Dyscrasite	Ag_3Sb
Falkmanite	$Pb_3Sb_2S_6$
Famatinite	Cu_3SbS_4
Franckeite	$Pb_5Sn_3Sb_2S_{14}$
Freibergite	$(Cu,Ag)_{12}Sb_4S_{13}$
Geocronite	$Pb_5(As,Sb)_{12}S_8$
Gudmundite*	$FeSbS$
Horsfordite	Cu_6Sb
Jamesonite*	$Pb_4FeSb_6S_{14}$
Kermesite*	Sb_2S_2O
Livingstonite	$HgSb_4S_7$
Meneghihite	$Pb_4Sb_2S_7$
Nadorite	$PbSbO_2Cl$
Native antimony	Sb
Polybasite*	$(Ag,Cu)_{16}Sb_2S_{11}$
Pyrargyrite*	Ag_3SbS_3
Ramdohrite	$Ag_2Pb_3Sb_3S_9$
Romeite	$(Ca,Fe,Mn,Na)_2(Sb,Ti)_2O_6(O,OH,F)$
Senarmontite*	Sb_2O_3
Stenhuggarite	$CaFeSbAs_2O_7$
Stephanite	Ag_5SbS_4
Stibiconite*	$Sb_3O_6(OH)$
Stibiobismuthinite	$(Bi,Sb)_4S_7$
Stibiocolumbite	$SbNbO_4$
Stibiodomeykite	$Cu_3(As,Sb)$
Stibioluzonite	$Cu_3(Sb,As)S_4$
Stibiotantalite	$SbTaO_4$
Stibnite*	Sb_2S_3
Sulfo-antimonite	$Ag_2Pb_7Sb_8S_{20}$
Tellurobismuthite	$(BiSb)_2Te_3$
Tetrahedrite*	$Cu_{12}Sb_4S_{13}$
Ullmannite	$NiSbS$
Valentinite*	Sb_2O_3
Zinckenite	$PbSb_2S_4$

antimony (Lake and Wilton, 2006; Tallman and Evans, 1994). The Lake George deposit consists of two orebodies totaling slightly less than 2 million metric tons at average grades ranging between 3 and 4.2 percent antimony (Seal and others, 1988). The mineralization at both deposits is dominated by quartz-stibnite veins with lesser amounts of carbonate minerals (calcite or dolomite) and minor amounts of pyrite. Arsenopyrite and native antimony are important accessory phases at Lake George (Scratch and others, 1984; Seal and others, 1988). At Lake George, the veins range in thickness from 0.5 to 1.5 meters (m) (Scratch and others, 1984; Seal and others, 1988). The predominant alteration assemblages at Lake George are siliceous and phyllic; the siliceous alteration typically extends to less than 5 centimeters (cm) from the edge of the vein, whereas the phyllic alteration can extend to more than 10 m from the vein (Seal and others, 1988).

The Xikuangshan deposit in Hunan Province, China, is China's leading source of antimony (Panov and No, 1989; Wu, 1993; Fan and others, 2004) and has been worked since the 16th century (Eyi, 2012). The deposit consists of four large orebodies and several smaller ones. The deposit replaces Devonian carbonate rocks and consists predominantly of stibnite with trace amounts of pyrite, pyrrhotite, and sphalerite. The primary gangue minerals are quartz and calcite along with some secondary barite and fluorite (Wu, 1993; Fan and others, 2004). The ore is mostly in two stratiform, 2.5- to 5-m-thick mineralized beds or lenses that extend for several hundred to thousands of meters within a 45-m-thick carbonate sequence. The deposit covers an area of approximately 16 square kilometers (km^2), has an average grade of 4 percent antimony, and contains more than 2 million metric tons of antimony (Yang and others, 2006). Quartz-stibnite and calcite-stibnite ore assemblages account for more than 90 percent of the ore; barite-quartz-stibnite and fluorite-quartz-stibnite assemblages contain relatively minor amounts of ore (Fan and others, 2004). The dominant alteration that accompanied mineralization was silicification; there is also some sericitic, argillic, and pyritic alteration (Yang and others, 2006). Igneous rocks are notably absent in the vicinity of the Xikuangshan deposit (Wu, 1993). In addition to simple quartz-stibnite deposits, China also has important antimony-gold-tungsten deposits (Wu, 1993).

The largest antimony deposits in Russia are the Sarylakh and the Sentachan antimony-gold deposits in the Yakutiya region of eastern Russia. Estimates of the resources contained in these deposits vary. GeoProMining Ltd. reported that these two deposits contain 5 percent of the world's antimony reserves with an average grade of 14 percent antimony (Nossoff, 2012). The company also estimated that the Sarylakh deposit contains 10 grams per metric ton (g/t) gold and that the Sentachan deposit contains 32 g/t gold. Bortnikov and others (2010, p. 339) estimated that the Sarylakh deposit contains 180,000 metric tons of antimony ore grading 20 percent antimony along with 40 metric tons of gold ore grading 8 g/t gold, and that the Sentachan deposit contains 110,000 metric tons of antimony ore grading 30 percent antimony along with 20 metric tons of gold ore grading 35 g/t gold. Baltukhaev and Solozhenkin (2009) reported that the two deposits contain 200,000 metric tons of antimony with grades of 12 to 18 percent antimony at Sarylakh and 24.6 percent antimony, 38.2 g/t gold, and 13.4 g/t silver at Sentachan. Another source (Porter GeoConsultancy Pty Ltd., 2010) reported ore grades at Sentachan to be 25 percent antimony, 37 g/t gold, and 13.4 g/t silver, and resources at Sarylakh to be 2.17 million metric tons at grades of 6 percent antimony and 6 g/t gold, for a total of 130,000 metric tons of contained antimony.

The Sarylakh and Sentachan deposits are hosted by deformed Triassic siliciclastic sedimentary rocks (sandstones, siltstones, and shales) that later were intruded by granitic rocks. The area was also subject to related volcanic activity. The deposits, which are separated by 400 kilometers (km), are located along a major regional fault zone (Bortnikov and others, 2010). The orebodies are controlled by faults and are dominated by quartz and stibnite. Important, although less abundant, minerals include ankerite, arsenopyrite, berthierite, bournonite, chalcopyrite, chalcostibite, galena, native gold, pyrite, and sphalerite. The antimony mineralization and the gold mineralization are paragenetically distinct from one another at these deposits (Bortnikov and others, 2010). At Sentachan, the mineralized zones reach a maximum thickness of 6 m; at Sarylakh, the thickness varies from 0.8 to 17 m.

In South Africa, the Consolidated Murchison Mine is the most important antimony deposit on South Africa's Antimony Line, and it is representative of mineralization along a significant Archean shear zone (Jaguin and others, 2012). Mineralization is predominantly hosted by quartz-muscovite schists and occurs as quartz-carbonate veins bearing stibnite and berthierite with associated pyrite and arsenopyrite (Muff, 1978).

The Yellow Pine deposit in Valley County, Idaho, contains the largest antimony resource in the United States (Miller, 1973) and produced intermittently from 1932 through 1992. Mining in the area began when gold was discovered in 1900; antimony recovery with gold was first recognized in 1929 (Palencia and Mishra, 1986, p. 9). The antimony occurs partly in small high-grade quartz-stibnite veins, rarely more than a foot wide, and in large low-grade zones of disseminated stibnite in shear zones in quartz monzonite of the Idaho batholith (White, 1940). Two periods of mineralization are recognized (White, 1940): the first consists of pyrite, arsenopyrite, and gold; the second consists of antimony and silver. The Yellow Pine deposit was being re-evaluated in 2014 as part of the Stibnite Gold project (formerly known as Golden Meadows project) (Huss and others, 2014).

The U.S. Antimony Mine in western Montana is the second largest simple quartz-stibnite vein deposit in the United States. It had significant production in the past, but was closed in 1983; the mine's production and reserves are estimated to be nearly 15,400 metric tons of antimony (Hofstra and others, 2013). The deposit is located on the north side of a major east-west-trending wrench fault system (the Lewis and Clark line). The quartz-stibnite veins occur near the contact between quartzite and phyllite in the uppermost Prichard Formation. The veins can be as large as 1 km long and 1 m wide and contain 60 percent stibnite; accessory sulfide minerals include arsenopyrite, pyrite, sphalerite, and chalcopyrite (Hofstra and others, 2013). Additional potentially important byproduct sources of antimony include the polymetallic veins at the Sunshine silver mine in the Coeur d'Alene mining district, Idaho.

Resources and Production

Identified Resources

In 2013, the largest identified resources of antimony were located in Bolivia, China, Mexico, Russia, South Africa, and Tajikistan. Resources in the United States are located mainly in Alaska, Idaho, Montana, and Nevada. World reserves total about 1.3 million metric tons of contained antimony (table C2). One-third of these reserves are located in China (Guberman, 2014).

In a study of large deposits of several mineral commodities, Laznicka (1999) noted that the world’s 24 giant and supergiant antimony deposits contained a total of 6.97 million metric tons of antimony. Laznicka estimated the total global endowment to be between 7.1 and 7.5 million metric tons of antimony.

There are abundant identified antimony resources available, but the bulk of those resources are in a few very large deposits that are not evenly distributed across the globe. Today’s market favors large deposits that are conducive to high-volume bulk-mining techniques. The United States and the countries of the Western Hemisphere appear to have mostly small deposits that are uneconomic to mine under current and foreseeable conditions.

In 2012, Midas Gold Corp. (the owner) contracted for a preliminary economic assessment to be done of the indicated and inferred mineral resources at the Golden Meadows project in Idaho to demonstrate the potential for positive economic returns and identify areas requiring additional work. A subsequent prefeasibility study of the project (renamed the Stibnite Gold project) was completed in 2014. The property includes three zones of gold-antimony-silver mineralization within an area of significant historical mining activity. Past production was reported from the Hanger Flats (1928–38), Yellow Pine (1938–92), and West End (1978–97) deposits (Huss and others, 2014, p. 6-7–6-9). Conventional open pit methods were being considered for mining the three deposits, all of which are located within 3 km of each other and may in fact represent one large mineralized zone. The 2014 study estimated indicated and inferred resources to be about 130 million metric tons at grades of about 1.6 g/t gold and 0.06 percent antimony (Huss and others, 2014, p. 1-10).

Additional Resources

Antimony resources that may be mined in the future are likely to be those tied directly to deposits of precious metals, copper, lead, and (or) zinc, similar to those from which most domestic antimony has historically been recovered as a byproduct or coproduct. Gold is an important joint product with antimony, but gold-antimony veins are commonly mined just for their gold. Because the presence of antimony makes gold more difficult and more expensive to process (the antimony interferes with the heap-leaching agent by consuming oxygen and hindering the effect of cyanide on the gold ore), some amount of gold ore that has a high antimony grade may be stockpiled (Eyi, 2012).

Table C2. Estimated world production and reserves of antimony in 2013, in metric tons of antimony.

[e, estimated; NA, not available; n.r., not reported]

Country	Production[1, e]	Reserves[2]
Australia	3,275	n.r.
Bolivia	5,081	310,000
Burma	9,000	n.r.
Canada	76	n.r.
China	120,000	[3]460,000
Kyrgyzstan	1,200	n.r.
Mexico	294	n.r.
Russia	8,700	350,000
South Africa	2,400	27,000
Tajikistan	4,675	50,000
Turkey	4,600	n.r.
Other countries	NA	[4]150,000
World total	159,000	1,300,000

[1] From Guberman (2015).

[2] From Guberman (2014) and National Bureau of Statistics of China (2014).

[3] In 2009, the Chinese Ministry of Land and Resources reported reserves of 2,460,000 metric tons; however, high-grade antimony reserves in Lengshuijiang, Hunan Province, China, are near exhaustion (Chegwidden and Bedder, 2012, p. 5).

[4] Includes estimated reserves for countries listed as “n.r.” above.

A post-World War II evaluation of domestic mined resources concluded that “the United States has no deposits, from which the ore is mined principally for antimony, that are large enough or rich enough to compete with foreign sources in normal times” (Shaum and others, 1948, p. 53). This situation has not changed since that report was completed. If the United States could no longer import antimony in quantities to meet its needs, then additional domestic production may be obtainable from base- and precious-metal deposits and from areas of identified base-metal, gold, silver, and tungsten mineralization (Miller, 1973). These sources may include undiscovered resources in parts of the United States and other nations of the Western Hemisphere, as well as Australia, South Africa, and other trading partners of the United States. Table C3 lists some potential near-term sources of antimony ore and concentrate (Chegwidden and Bedder, 2012).

Enhanced recovery of antimony from precious-metal deposits may represent the most readily available source of antimony if demand were to increase rapidly. The Sunshine silver mine in Idaho was a significant producer of byproduct antimony from a deposit of silver-rich tetrahedrite (a common ore mineral in silver deposits). The mine stopped recovering antimony before its closure in early 2001 (Carlin, 2003). In addition, antimony can be recovered as a byproduct from some base-metal refining, for example, from Mississippi Valley-type lead deposits in the United States.

Table C3. Potential additional sources of antimony ore and concentrate, by country.

[Sources: Chegwidden and Bedder (2012, p. 10) and Huss and others (2014)]

Country	Notes
Australia	The Hillgrove Mine, which closed in late 2015, might be reopened. Other deposits in New South Wales and Western Australia are being evaluated.
Bolivia	The San Antonia de Turiri Mine may be developed.
Burma	Exports of antimony concentrates increased from 1,200 metric tons in 2002 to 14,100 metric tons in 2011. There may be capacity for a further increase in output.
Canada	At least three companies have been exploring antimony deposits in Newfoundland and Labrador, the Yukon Territory, and New Brunswick.
China	Tibet may increase output.
Mexico	U.S. Antimony Corp. expected to increase production from Los Juarez deposit in Coahuila State.
Russia	In the Far East, increased production may come from Sentachanskoe and Ilinskoe; new deposits, such as Udereiskoe and Zhipkoshinskoe, were being developed in eastern Siberia.
South Africa	There may be recovery of production at the Consolidated Murchison Mine.
Tajikistan	Output reached about 8,000 metric tons per year of concentrate from a plant with a capacity of 30,000 metric tons per year; there may be potential for a further increase in output. The mercury content of the ore is a concern.
Turkey	Possible new production in projects near Gediz in Kütahya Province as well as Niğde and Izmir Provinces.
United States	Midas Gold Corp.'s Stibnite Gold project in central Idaho is a large low-grade gold-antimony property that includes the Hanger Flat, Yellow Pine, and West End deposits.

Exploration for New Deposits

Most undiscovered primary antimony deposits will likely be located in geologic settings similar to those where antimony deposits are known to occur. From what is known about where these deposits form, rocks of any age that were deposited in the world's sedimentary basins on active continental margins are permissive for the occurrence of antimony deposits, especially rocks in those basins with known antimony deposits. In the United States, these types of sedimentary rocks located in the Cordillera of Alaska, and in California, Idaho, Montana, and Nevada would be prime targets. Areas within large-scale shear zones and strike-slip fault zones, such as those in Nevada, are potentially favorable areas for antimony fissure-vein deposits. In Arkansas, California, Idaho, Montana, Nevada, Washington, and other States, rocks near to, on trend with, and similar to those with known antimony occurrences could be explored for additional undiscovered antimony deposits.

The empirical association of hydrothermal antimony deposits with fine-grained sedimentary rocks, especially carbonaceous shales or their metamorphosed equivalents, may be a reflection of the antimony enrichments commonly found in these types of rocks. The continental crust averages 0.2 ppm antimony (Taylor and McLennan, 1995), yet average shales contain 1.5 ppm (Li and Schoonmaker, 2003), and black shales average 5.0 ± 0.5 ppm (Ketris and Yudovich, 2009). Although the source, transport, and concentration mechanisms will likely vary among deposit types, a fertile source region may be essential to the formation of economic deposits. Further, Pitcairn and others (2006) demonstrated a significant depletion in antimony and other elements (arsenic, gold, mercury, molybdenum, silver, and tungsten) with increased metamorphic grade in the Alpine and Otago schists of New Zealand. These findings suggest that high-grade metamorphism (>400 °C) may mobilize antimony into hydrothermal fluids that may form quartz-antimony veins at lower temperature under favorable conditions. The combination of siliciclastic sedimentary rocks and an egress pathway for hydrothermal fluids from high-temperature source regions is common to most of the significant simple quartz-stibnite deposits described in the Geology section above. An association with major structural fault systems that could access deeper regional metamorphic fluids is found at the Xikuangshan deposit (China), the Sentachan and Sarylakh deposits (Russia); the Antimony Line (South Africa), and the U.S. Antimony Mine (Montana). In contrast, igneous heat sources associated with more local fault and fracture zones are found at the deposits in Bolivia and at the Lake George and Beaver Brook deposits in Canada.

Historically, very little prospecting has been directed solely toward antimony (Miller, 1973). Most exploration that resulted in the incidental discovery of an antimony deposit has been the result of prospecting for another mineral commodity, such as copper, gold, lead, and silver. Exploration for antimony deposits usually includes techniques commonly employed to find other mineral deposits, such as geochemical soil and rock sampling, ground geophysical surveying, geologic mapping, and drilling. Surveys of mercury-vapor haloes in soil are helpful for identifying sulfide deposits of antimony, the base metals, mercury, gold, and tin (Fursov, 1990).

Environmental Considerations

Sources and Fate in the Environment

Environmental aspects of antimony have been summarized by Rish (2004). The environmental aqueous chemistry of antimony has been reviewed by Filella and others (2002a, b). Antimony in waters results primarily from rock weathering, soil runoff, and anthropogenic sources. Global emissions of antimony to the atmosphere average 6,100 metric tons per year, which includes 3,500 metric tons per year from anthropogenic sources (energy production, mining, smelting, and waste incineration) and 2,600 metric tons per year from natural sources (including, in order of contribution to atmospheric antimony, dust, volcanoes, sea aerosols, forest fires, and biogenic sources; Filella and others, 2002a). Seawater contains approximately 0.2 part per billion (ppb) dissolved antimony, and uncontaminated surface waters (streams, rivers, and lakes) contain less than 1 ppb (Filella and others, 2002a). In surface water, pentavalent antimony species (Sb^{5+}) dominate over trivalent species (Sb^{3+}) (Filella and others, 2002b). The solubility of antimony in water at room temperature reaches 90 ppm in oxygenated waters, 13 ppm in anoxic waters, and 1.2 ppm in anoxic and sulfidic waters (Tourky and Mousa, 1948; Krupp, 1988).

Data are available for antimony concentrations in soils and plants. In their national geochemical survey of soil in the United States, Smith and others (2013) report concentrations of antimony that range from less than 0.05 to 630 ppm, with a mean value of less than 0.9 ppm. Filella and others (2002a) summarized published data for sediments that ranged from less than 0.005 ppm in uncontaminated areas to up to 12,500 ppm in areas around a smelter. Antimony concentrations in plants do not show a strong correlation with soil concentrations; plant concentrations range from less than 0.1 to 500 ppm (Boyle and Jonasson, 1984; Rish, 2004).

Antimony is mined primarily from quartz-stibnite vein deposits. Modern environmental baseline characterization studies of antimony deposits have not been reported; however, Ritchie and others (2013) report background (upstream) concentrations of antimony in surface water and sediments from mineralized areas of the historic Kantishna Hills district in Alaska that range from 2.7 to 4.2 ppb and from 91 to 968 ppm, respectively. Austria (1971) reported antimony concentrations of soils up to 500 ppm in the vicinity of the Lake George antimony deposit in New Brunswick, Canada.

Mine Waste Characteristics

Information on antimony mine waste is extremely limited. Historically, small, high-grade (about 35 to 70 percent antimony) deposits have been mined, but modern production comes from larger, lower grade deposits, which have a median tonnage of 0.09 million metric tons, a maximum tonnage of 3 million metric tons, a median grade of 3.6 percent antimony, and a maximum grade of more than 7.0 percent antimony (Bliss and Orris, 1986a–c). The Xikuangshan deposit in Hunan Province, China, which is the world's largest antimony deposit, is an anomaly. The deposit, which has an average grade of 4 percent antimony, is estimated to contain more than 2 million metric tons of antimony (Yang and others, 2006).

The mineralogical character of the ores greatly influences the geochemistry of the mine waste. The ores are typically predominantly stibnite and quartz, with subordinate amounts of calcite, pyrite, arsenopyrite, and native antimony, hosted mostly by siliciclastic or carbonate sedimentary rocks (Wu, 1993). The most common secondary antimony minerals in mineral deposits are kermesite (Sb_2S_2O), senarmontite (Sb_2O_3), and stibiconite ($Sb_3O_6(OH)$). Thus, the elements of greatest environmental concern are predominantly antimony and arsenic.

The acid-generating potential of mine waste is expressed in terms of the amount of calcium carbonate it would take to neutralize it; it is measured in kilograms of calcium carbonate per metric ton (kg $CaCO_3$/t) of mine waste (Price, 2009; International Network for Acid Prevention, 2011). The acid-generating potential resides primarily in pyrite. Mine waste can also have acid-neutralizing potential, which resides in carbonate minerals, such as calcite, and in some silicate minerals, such as feldspars.

Limited data are available on the acid-generating potential of antimony mine waste. Klimko and others (2011) investigated the acid-generating potential of mill tailings at two abandoned stibnite mines in Slovakia. One had a neutral pH (7 to 8), whereas the other had an acidic pH (3 to 5). Acid-base accounting results indicated that the neutral tailings had an acid-generating potential that was negligible as well as a modest acid-neutralizing potential (70 to 120 kg $CaCO_3$/t of tailings). In contrast, the acidic tailings had a low acid-generating potential (0.8 to 2.8 kg $CaCO_3$/t) and a low acid-neutralizing potential (16 to 18 kg $CaCO_3$/t) that was nonetheless higher than the acid-generating potential. The acid-neutralizing potential to acid-generating potential ratios ranged between 5.7 and 22.6, which suggests a low potential for acid generation. The presence of carbonate minerals, such as calcite, and only minor amounts of pyrite in the mine waste from antimony deposits in general suggest that the acid-neutralizing potential is likely to exceed the acid-generating potential of the mine wastes (Price, 2009; International Network for Acid Prevention, 2011).

Mine-drainage data from abandoned antimony mines support this conclusion (Wilson and others, 2004; Casiot and others, 2007; Majzlan and others, 2007), although some sites can generate acid drainage. Ritchie and others (2013) and Eppinger and others (2002) found low pH (2.5 to 5.6) in pore water and seeps from tailings piles in the abandoned mines in the Kantishna district, Alaska, but the receiving creeks immediately downstream of the mines had near-neutral pH (6.1 to 8.3).

Human Health Concerns

Belzile and others (2011) have summarized the general aspects of antimony exposure to humans. The Agency for Toxic Substances and Disease Registry (ATSDR) has developed a toxicological profile for antimony (Agency for Toxic Substances and Disease Registry, 1992). In general, trivalent antimony (Sb^{3+}) is more toxic than pentavalent antimony (Sb^{5+}). In humans, antimony can result in diseases of the liver, respiratory and cardiovascular systems, and skin (Wu and others, 2011). Compared to trivalent arsenic, trivalent antimony is 5 times less cytotoxic and 10 times less genotoxic (Rish, 2004).

The U.S. Environmental Protection Agency (EPA) (2009) has set a maximum contaminant limit of 6 ppb for antimony and 10 ppb for arsenic for drinking water. The World Health Organization (WHO) drinking water guideline is 20 ppb for antimony and 10 ppb for arsenic (World Health Organization, 2008). In the Xikuangshan mining district, which includes three mines that produce from China's largest antimony deposit and an associated smelter, Wu and others (2011) found 100 percent of drinking water samples collected in a roughly 300-km^2 surrounding area exceeded the maximum contaminant limit of 6 ppb for antimony set by the EPA. Concentrations ranged from 8.1 to 152 ppb antimony. They concluded that mine drainage and smelter wastes were the dominant sources. In contrast, the arsenic concentration of most samples was below the maximum contaminant limit. Wu and others (2011) also investigated the dietary intake of antimony by local residents and found that their daily intake exceeded WHO guidelines and were several orders of magnitude higher than those found in other parts of the world, none of which approached the WHO tolerable daily intake guideline. The greatest sources in the daily dietary uptake were rice (33 percent), vegetables (26 percent), drinking water (19 percent), and meat and poultry (19 percent) (Wu and others, 2011).

The concentrations of antimony and arsenic in soils in the Xikuangshan mining district also exceed EPA regional screening levels (U.S. Environmental Protection Agency, 2015). Wang and others (2010) collected 23 soil samples within 15 km of the mines. Antimony concentrations ranged from 10 to 2,159 ppm, of which 96 percent exceeded the EPA residential soil regional screening level for antimony (39 ppm). More than 80 percent of soil samples also exceeded EPA residential guidelines for arsenic. Local exceedances of the residential guidelines were also found for cadmium, chromium, lead, manganese, and mercury.

Ecological Health Concerns

National ambient-water-quality criteria with respect to freshwater organisms are not available from the EPA for antimony; however, Suter (1996) presents both acute and chronic ecological screening benchmarks for antimony. The acute toxicity value is 985 ppb (also expressed as 985 micrograms per liter [μg/L]) and the chronic toxicity value is 104 ppb. No guidelines are available for sediment.

Information about surface water impacts from antimony mines is limited to an active mining district in China and several small abandoned mines throughout the world. Several sources of mine drainage data are available. In their study of the abandoned Goesdorf antimony mine in Luxembourg, Filella and others (2009) compiled mine drainage data for antimony mines from around the world (Australia, Italy, New Zealand, Scotland, and Slovakia). Majzlan and others (2007) presented mine-drainage data from the Pezinok Mine in Slovakia. Eppinger and others (2002) and Ritchie and others (2013) investigated surface water quality in the Kantishna district, Alaska. Casiot and others (2007) provide additional data from an antimony mine in France. Data are also available from New Zealand (Wilson and others, 2004). Collectively, the pH of surface water downstream of mines is near neutral (6.2 to 8.5), which is a reflection of the low acid-generating potential of the ore and mine waste and the significant acid-neutralizing potential provided by carbonate minerals in the mineralized assemblages.

Ponded water on mine waste, pore water in tailings, and seeps from mine waste in the Kantishna district in Alaska have been documented as having low pH (2.5 to 5.6) (Eppinger and others, 2002; Ritchie and others, 2013). Information on the dissolved concentrations of sulfate (<0.5 to 2,115 ppm) and iron (<10 to 3,000 ppb) in mine waters and surrounding surface waters is limited (Casiot and others, 2007), but their concentrations are moderate, which is a reflection of the typically limited pyrite contents of these ores. Dissolved antimony concentrations range from less than 0.3 to 55,000 ppb, and dissolved arsenic concentrations range from less than 1 to 3,509 ppb. Thus, mine drainage from antimony mines can locally exceed both acute and chronic ecological guidelines for antimony and arsenic. Information on other trace elements is lacking, with exception of surface waters in the vicinity of the Slate Creek deposit in the Kantishna district. All trace element concentrations were in the subparts-per-million range (<1.0 ppm), except for iron (<170 ppm), manganese (<6.5 ppm), aluminum (<3.7 ppm), and zinc (<1.6 ppm), all in mine waters (Eppinger and others, 2002).

The geochemistry of mine waters and surface waters in the Xikuangshan mining district in China was investigated by Liu and others (2010). The samples included stream waters in the district, seepage from waste piles, and mine water. The pH of the samples was comparable to those from the abandoned mines discussed above and ranged from 7.7 to 8.3. Dissolved sulfate concentrations in surface water samples were significantly higher at Xikuangshan (46 to 1,267 ppm) than those at an abandoned mine in France (Casiot and others, 2007). Dissolved antimony concentrations at Xikuangshan (330 to 11,400 ppb) were significantly higher than most values from abandoned mines elsewhere in the world.

Mine Closure

The nature of mine closure for antimony mines depends primarily on the method of mining. Most antimony deposits are exploited as underground mines. The most common solid waste from underground mines is mill tailings, which are disposed in some sort of tailings storage facility.

The long-term fate of tailings storage facilities depends upon the nature of the tailings and the method by which the facility is constructed. Some facilities can be regraded, capped, and revegetated. These facilities may have seepage and, depending upon the acid-generating potential of the material, may require some form of water treatment. Some of the tailings could be placed back in the mined-out workings, depending upon how the orebody was mined; however, the entire volume of tailings cannot be placed back in the mine workings because of the volume expansion caused by crushing and milling the ore.

Problems and Future Research

A major problem facing the countries that depend upon stable and secure supplies of a critical mineral commodity such as antimony for their industry and defense needs is the uneven distribution of resources and production around the world. Finding new resources in countries other than China could be a challenge for antimony-consuming nations. Knowledge of how quickly the United States and the rest of the world could develop additional production by adding capacity to existing mines, by reactivating nonoperating mines, or by bringing newly discovered deposits online is essential to understanding the effect of supply shortfalls in the event that China, which is the dominant producer, was to reduce antimony exports. Since 2011, production of antimony in China has declined and its antimony reserves may be declining as well (Guberman, 2015).

Although antimony occurs in several different deposit types of various ages, ore-grade concentrations of antimony are not common, and economically minable deposits of stibnite are generally small and discontinuous. This makes exploration for antimony deposits challenging. Detailed geologic studies would be required to understand the tectonic history of ancient continental margins and sedimentary basins as well as the relation of antimony deposits to that history in order to enhance the possibility of delineating areas that are prospective for undiscovered antimony resources.

From an environmental perspective, no clear case study of the behavior of antimony and related trace elements in a modern mine setting using current best practices exists. The toxicity of aqueous antimony species to aquatic organisms is a notable gap in knowledge. Knowledge of the toxicity of antimony in sediments is also limited.

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For more information concerning this report,
please contact:

Mineral Resources Program Coordinator

U.S. Geological Survey

913 National Center

Reston, VA 20192

Telephone: 703–648–6100

Fax: 703–648–6057

Email: minerals@usgs.gov

Home page: https://minerals.usgs.gov

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