Barite (Barium)

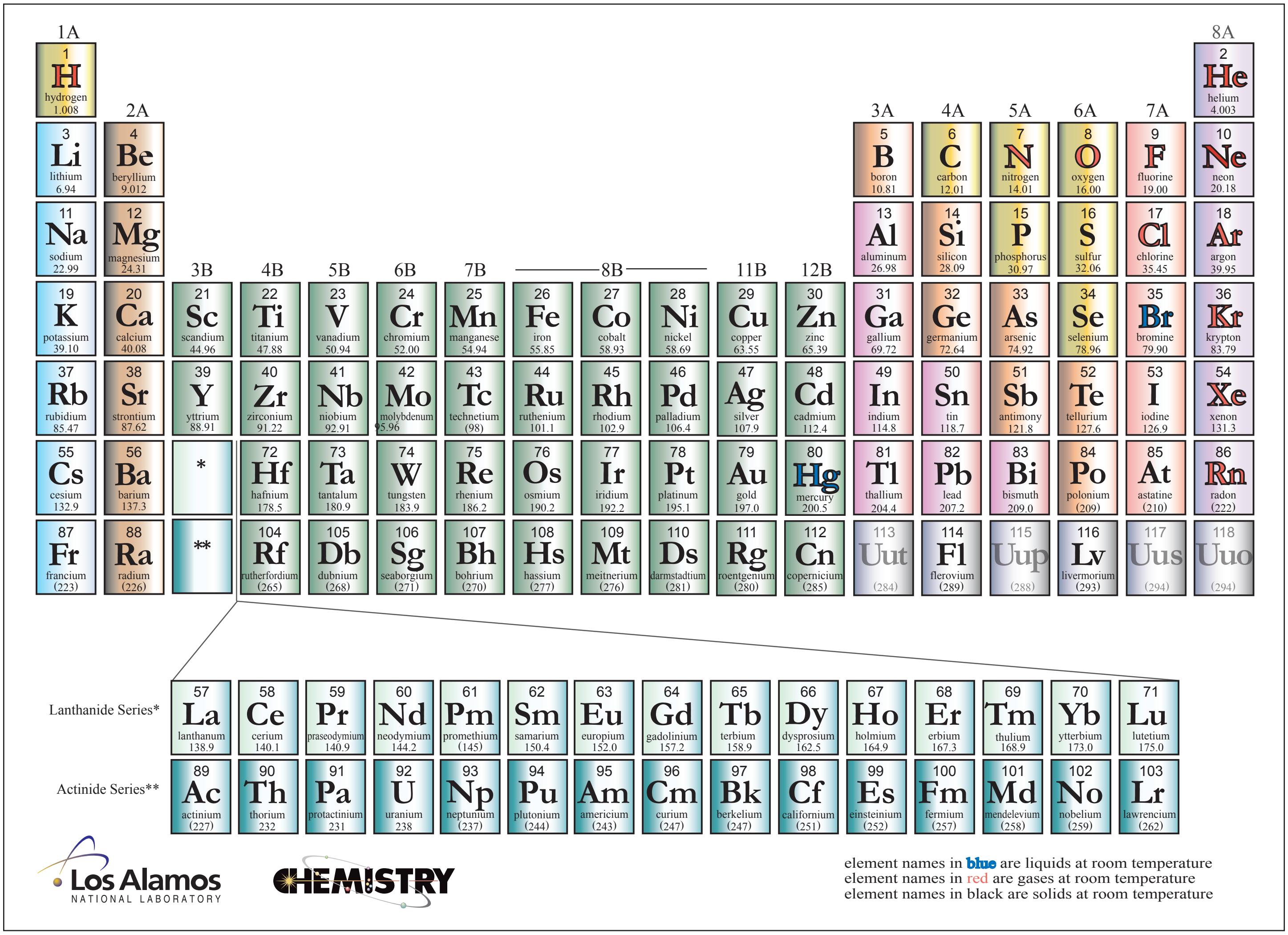
Chapter D of

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

Professional Paper 1802–D

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)

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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. Barite. Photograph from mineral collection of Brigham Young University Department of Geology, Provo, Utah.

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

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

Professional Paper 1802–D

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

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Figures

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

API	American Petroleum Institute
cm	centimeter
g/cm^3	gram per cubic centimeter
PbS	lead sulfide (galena)
ppb	part per billion
ppm	part per million
SG	specific gravity
ZnS	zinc sulfide (sphalerite)

Barite (Barium)

By Craig A. Johnson, Nadine M. Piatak, and M. Michael Miller

Abstract

Barite (barium sulfate, $BaSO_4$) is vital to the oil and gas industry because it is a key constituent of the mud used to drill oil and gas wells. Elemental barium is an additive in optical glass, ceramic glazes, and other products. Within the United States, barite is produced mainly from mines in Nevada. Imports in 2011 (the latest year for which complete data were available) accounted for 78 percent of domestic consumption and came mostly from China.

Barite deposits can be divided into the following four main types: bedded-sedimentary; bedded-volcanic; vein, cavity-fill, and metasomatic; and residual. Bedded-sedimentary deposits, which are found in sedimentary rocks with characteristics of high biological productivity during sediment accumulation, are the major sources of barite production and account for the majority of reserves, both in the United States and worldwide. In 2013, China and India were the leading producers of barite, and they have large identified resources that position them to be significant producers for the foreseeable future. The potential for undiscovered barite resources in the United States and in many other countries is considerable, however. The expected tight supply and rising costs in the coming years will likely be met by increased production from such countries as Kazakhstan, Mexico, Morocco, and Vietnam.

Barium has limited mobility in the environment and exposed barium in the vicinity of barite mines poses minimal risk to human or ecosystem health. Of greater concern is the potential for acidic metal-bearing drainage at sites where the barite ores or waste rocks contain abundant sulfide minerals. This risk is lessened naturally if the host rocks at the site are acid-neutralizing, and the risk can also be lessened by engineering measures.

Introduction

Barite (barium sulfate, $BaSO_4$) is an industrial mineral commodity that is used primarily in the drilling of oil and gas wells. The mineral commodity is also referred to as baryte or barytes. It is a key constituent of drilling mud, which is the fluid pumped into the oil or gas well to lubricate the bit and drill stem, remove rock chips, prevent collapse of well walls, and prevent blowouts if overpressured strata are encountered. Barite has an unusual combination of properties—high density, softness, and chemical inertness—that make it exceptionally well suited for this purpose. Other minor uses of the mineral include its use as an additive for friction materials, paints, plastics, rubbers, and other products; feedstock for chemical manufacturing; and shielding in X-ray and gamma-ray applications. Barium, which constitutes 59 percent of barite by weight, is used in ceramic glazes, enamels, optical glass, primers, signal flares, steel hardeners, welding fluxes, and a variety of other products. The mineral witherite (barium carbonate, $BaCO_3$) is another source of barium that accounts for only a small fraction of current production. The barium in witherite is more highly concentrated than in barite (barium constitutes 70 percent of witherite, by weight). Furthermore, barium is more easily liberated from witherite than it is from barite because witherite is readily dissolved by acids. On the other hand, witherite normally occurs in deposits that are smaller and more discontinuous than barite deposits, and they are thus more difficult to mine.

Barite is a critical mineral commodity because of its uses in the exploration for and development of petroleum and natural gas resources. Drilling activity accounts for nearly 95 percent of domestic consumption and about 90 percent of global consumption. Economic deposits of barite are relatively common and are found in many countries. Although prices have risen substantially in recent years, the commodity remains relatively inexpensive. Thus, it is unlikely that the oil and gas industry will have a need for substitutes in the short term. All the likely substitutes (celestite, hematite, ilmenite, and magnetite) present significant drawbacks. The principal strategic concern with respect to barite is that adequate supplies be available at low cost in the geographic regions that are currently being explored for oil and gas resources and in geographic regions that will be explored in the future.

Until 1950, output of barite from U.S. mines equaled or exceeded domestic consumption. In succeeding years (fig. D1), domestic consumption outpaced production from U.S. mines by a steadily increasing margin, so that by 1980,

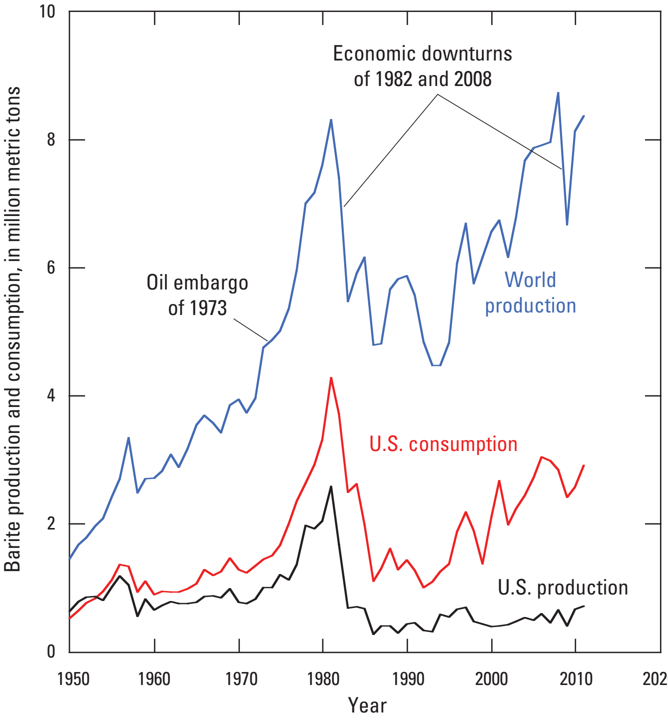

Figure D1. Graph showing barite world production, U.S. production, and U.S. consumption from 1950 to 2011. Data are from Kelly and Matos (2013).

imports accounted for some 46 percent of U.S. consumption. Barite production declined precipitously during the economic downturn of 1982. Since then, output from U.S. mines has remained relatively low, and increases in demand have been satisfied mainly by imported barite. In 2011 (the latest year for which complete data were available), import reliance was 78 percent (Miller, 2013).

Historically, domestic barite has come from mines in Arkansas, Georgia, Illinois, Missouri, Tennessee, and Nevada. At present, barite is produced primarily from mines in Nevada that exploit high-grade deposits; this barite requires only crushing, sizing, and jigging to meet the American Petroleum Institute (API) specifications for use in the oil industry. The API has two specifications for drilling-grade barite that differ only in specific gravity (SG)—4.1 SG and 4.2 SG. Both specifications correspond to a barite content of about 90 weight percent. The 4.1 SG specification was introduced in 2010 at the request of Nevada barite producers to extend Nevada's barite reserves and avoid the major capital investments that would be required to continue producing 4.2 SG material. The majority of barite now mined and processed in Nevada is 4.1 SG material. Deposits that are lower in grade or that contain deleterious gangue minerals can require more involved and more expensive beneficiation procedures, including wet grinding, magnetic separation, and froth flotation.

The active U.S. mines are open pit operations. They produce neither coproducts nor byproducts, so mine output depends exclusively on the economics of barite. At some mines in other countries, fluorite (CaF_2, also known as fluorspar), galena (PbS), sphalerite (ZnS), and (or) gold- or silver-bearing minerals are present and are recovered, so production at some locations can depend partly on the economics of other mineral commodities. Drilling activity in the Great Plains of the United States, in the Western United States, and in Western Canada are the major markets for barite produced from Nevada mines. Drilling activity in the Gulf of Mexico and in the eastern and midwestern parts of the United States relies heavily on imported barite, mainly from China.

A wealth of information on the geology and geochemistry of barite can be found in previous overviews by de Brodtkorb (1989), Clark and others (1990), Brobst (1973, 1994), Harben and Kuzvart (1997), Hanor (2000), and Jewell (2000). Information on barite as a mineral commodity has been provided by Ampian (1985), Coffman and Kilgore (1986), Harben (2002), Mills (2006), Roskill Information Services, Ltd. (2006), and Miller (2012).

Geology

Geochemistry

Barium occurs in the geologic environment mainly as the divalent cation Ba^{2+}. This ion is larger than most other divalent cations, and, consequently, barium is not easily accommodated in common rock-forming minerals. During fractional crystallization of silicate magmas, barium becomes concentrated in the residual silicate liquid. It is also concentrated in silicate liquids produced by partial melting. The barium content of average upper continental crust is estimated to be 0.0624 weight percent (Rudnick and Gao, 2003). Granitic rocks typically have somewhat higher barium content than average continental crust, and basaltic rocks typically have somewhat lower barium content. The range of barium content of shales spans approximately the same range as the barium content of granitic rocks.

Barium substitutes extensively for the nearly-as-large Pb^{2+} and Sr^{2+} cations in minerals that contain these elements, and less extensively for the somewhat smaller Ca^{2+} and K^+ ions; substitution for K^+ requires a coupled substitution to maintain charge balance. In common igneous rocks, barium is present as a trace or minor element in potassium feldspar and mica where it substitutes for K^+. Less extensive substitution is seen for Ca^{2+} in amphibole, apatite, calcite, plagioclase feldspar, and pyroxene. In common sedimentary rocks and hydrothermal deposits, barium occurs mainly in barite or organic matter. The presence of trace amounts of barite in many sedimentary rocks reflects the fact that sulfate (SO_4^{2-}) is the stable form of sulfur in most Earth-surface environments, and the formation constant for barite (barium sulfate, $BaSO_4$) is quite large. Although barite is highly stable in oxidizing (sulfate-stable) environments, it can be readily dissolved in reducing hydrogen sulfide (H_2S) stable environments. This attribute has important implications for the formation of barite deposits and for environmental aspects of barite mining.

Mineralogy

Barite is typically white or colorless. Crystals tend to be tabular and have habits that reflect the orthorhombic symmetry of the barite lattice. Fibrous, nodular, and massive forms are also common. The mineral has a hardness of 3 to 3.5 on the Mohs scale, which is about the same hardness as copper, and it has a density of 4.48 grams per cubic centimeter (g/cm^3), which is roughly twice that of common rocks. Barite has multiple good cleavages.

Natural barite is relatively pure, generally showing only minor replacement of barium by strontium (less than 7 percent) or lead. The relative purity is convenient from a resource perspective because commercially important properties that depend on mineral chemistry, such as density and solubility, can be expected to vary little no matter where the barite is found. Most barite deposits have low impurity levels because (a) deposits typically form as precipitates from aqueous fluids, and (b) barium partitions more strongly into the sulfate mineral than strontium, lead, and other potential impurities. Calcium replacement of barium is also restricted in natural occurrences.

Deposits of barite invariably contain gangue minerals, the abundance and identity of which vary from one deposit type to another. The most common gangue minerals are quartz or other forms of silica (chert, drusy quartz, and jasperoid), sulfide minerals (galena, marcasite, pyrite, and sphalerite), clay minerals, carbonates (calcite and siderite), and iron oxides. Organic matter can also be present at concentrations up to several weight percent.

Witherite is colorless. Crystals commonly take the form of pseudohexagonal dipyramids. Witherite has a hardness of 3.5 on the Mohs scale and a density of 4.3 g/cm^3. It is readily distinguished from barite by the fact that it effervesces in cold acids. The mineral typically contains small amounts of strontium and calcium substituting for barium. Witherite is normally found in veins within sedimentary rocks where it is associated with galena and, less commonly, anglesite, barite, and barytocalcite. Witherite can also form as an alteration product of barite and can itself be altered to barite.

Other barium minerals are known, but none occur in deposits as large, concentrated, and widespread as barite. Although these are not currently mined, some may merit consideration as future sources of barium, particularly where they occur in deposits that have other valuable minerals. Noteworthy examples are benstonite ($(Ba,Sr)_6(Ca,Mn)_6Mg(CO_3)_{13}$), which is a secondary mineral in various barium-rich rocks (Hood and Steidl, 1973); sanbornite ($BaSi_2O_5$), which occurs in metasomatic zones associated with granitic rocks in the Big Creek-Rush Creek district of California (Alfors and others, 1965); and celsian ($BaAl_2Si_2O_8$), which is locally abundant in a metamorphosed barium deposit near Aberfeldy, Scotland (Coats and others, 1980). Other minerals that can contain significant barium are todorokite ($(Na,Ca,K,Ba,Sr)_{0.3-0.7}(Mn,Mg,Al)_6O_{12}\bullet 3.2-4.5H_2O$), which is a common constituent of deep-sea ferromanganese nodules, and romanechite ($BaMn_9O_{16}(OH)_4$), which is a mineral currently mined for manganese.

Deposit Types

Barite deposits can be classified into the following four groups on the basis of physical characteristics, geochemical characteristics, and geologic setting: (1) bedded-sedimentary; (2) bedded-volcanic; (3) vein, cavity-fill, and metasomatic; and (4) residual. This classification scheme resembles schemes that have been used previously (Brobst, 1958; Clark and others, 1990), but it has been modified somewhat to accommodate newly discovered deposits and results of more recent geologic studies. The locations of deposits or districts that are either relatively large or representative of the four groups are shown in figure D2. Numerous other deposits, both mined and unmined, have also been identified (Roskill Information Services, Ltd., 2006).

Bedded-Sedimentary Deposits

Bedded-sedimentary deposits are stratiform bodies of massive or near-massive barite within sedimentary successions that typically contain organic-rich shale, mudstone, or chert. The deposits can be quite large, with resources up to tens of millions of tons, and they tend to occur in districts rather than as isolated occurrences. The barite beds vary in thickness from centimeters to 100 meters or more and can extend for kilometers along strike. The barite can be dark in color, reflecting the presence of organic carbon, and it commonly occurs in one of the following four forms: massive, laminated, nodular, or rosette. Gangue minerals include clays, iron oxides (hematite, limonite, or magnetite), quartz, and pyrite or other sulfide minerals. Beneficiation can be simpler than for ores from other deposit types. Bedded-sedimentary deposits are the major source of worldwide barite production, and they also account for the majority of world reserves.

The bedded-sedimentary type of barite deposit can be associated with stratiform sulfide mineralization of sufficient quantity and grade that the districts are better known as resources for lead, zinc, or other metals. In principle, sulfide mineralization could be employed as an exploration guide to undiscovered barite deposits, but the economics normally favor the reverse: barite is employed as a guide to sulfide deposits. The nature of the association between barite and sulfides varies considerably. Barite and sulfide crystals can be intergrown, as in the Red Dog deposit in Alaska (Kelley and others, 2004); barite and sulfide layers can be thinly interbedded, as in the Tom and Jason deposits in the Selwyn basin of northwestern Canada (Goodfellow, 2004); or discrete barite bodies can lie adjacent to sulfide deposits, as in the Meggen and Rammelsberg deposits in Germany (Krebs, 1981; Large and Walcher, 1999), the Ballynoe and Silvermines deposits in Ireland (Mullane and Kinnaird, 1998), and the Aggeneys-Gamsberg district in South Africa (McClung and others, 2007). Barite deposits can also occur in the same district as stratiform sulfide deposits but be separated from them by distances of hundreds or thousands of meters, as in the Tea, Gary, Moose, Pete, and Oro barite deposits of

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 D2. World map showing locations of selected barite deposits and districts, color-coded by deposit type. Where districts contain more than one deposit type, the symbol reflects the dominant type. Citations for published descriptions of the deposits are given in the text or are as follows: Camamu (Cassedanne, 1989); Chaillac (Sizaret and others, 2009); Chiganak (Vinogradov and others, 1978); Dorreh Kashan (Yaghubpur, 2003); Flinders Range (McCallum, 1990); Gertrudis-Jagua (Maynard and others, 1995); Isparta (Kiran Yildirim, 2010); Jameson Land basin (Thomassen, 2007); La Helvecia (de Brodtkorb and others, 1989); Lasbela-Khuzdar (Ahsan and Mallick, 1999); Neuquen-Mendoza (de Brodtkorb and others, 1989); Nghê An (Kusnir, 2000); northern Thailand (Hahn and others, 1986), Harben and Kuzvart, 1997); Rosebery (Solomon and others, 1969); Sardinia (Padalino and others, 1989); and Zhayrem (Gauert, 2001).

the Selwyn basin (Lydon and others, 1985; Butrenchuk and Hancock, 1997) and the Anarraaq, Gull Creek, Moil, and Su barite deposits of the Red Dog district (Johnson and others, 2004). Other bedded-sedimentary barite deposits occur without sulfides. Examples of these include the deposits of the Ouachita Mountains of Arkansas (Zimmermann and Amstutz, 1989), the Nevada barite belt (Papke, 1984), the Cutaway basin in Alaska (Schmidt and others, 2009), the Sonora area of Mexico (Poole and others, 1991), the Cuddapah district in India (Neelakantam and Roy, 1979), and the Qinling and Jiangnan regions in southern China (Wang and Li, 1991; Wang, 1996).

Bedded-sedimentary barite associated with sulfide mineralization owes its origin to subsea-floor fluid flow systems that can span lateral distances of hundreds of kilometers or more; these flow systems are directly or indirectly related to the flow systems that give rise to the metal sulfide deposits (Lydon and others, 1985; Emsbo, 2000). The fluids typically migrate through pore spaces in buried sediments and sedimentary rocks toward extensional fault zones located along the margins of depositional basins. Barite deposits form where the ascending fluids, which carry Ba^{2+} ions scavenged from organic matter or from trace barite in the underlying sediments, encounter and mix with sulfate-bearing pore fluids or seawater. Where the mixing occurs within the sediment, barite precipitates as interstitial cement or replacements of preexisting minerals, such as calcite. Where the mixing occurs by fluid seepage onto the sea floor, barite particles form in the water column and then accumulate on the sediment surface. Because barite is not decomposed by seawater, preexisting deposits can be reworked by sea-floor erosion, and the barite can become reconcentrated in submarine channels.

The origin of bedded-sedimentary barite that lacks sulfide mineralization is more controversial. This deposit type has been attributed to an oceanographic process that operates beneath waters with high biological productivity (Jewell, 2000). Decomposition of sinking organic matter promotes anoxic conditions by consuming dissolved oxygen, and it also releases organic-bound barium. The released barium combines with seawater sulfate to form barite, which accumulates on the sea floor at the interface between anoxic and oxic water masses. An alternative proposal (Lydon and others, 1985) holds that the deposits form at sea-floor vents for fluids whose chemical composition, temperature, or oxidation state are not conducive to sulfide precipitation. This proposal has been strengthened by the discovery of barite deposits on the modern continental margins at locations where sedimentary formation waters are emerging from fault-controlled seeps (Torres and others, 2003; Clark and others, 2004; Koski and Hein, 2004; Johnson and others, 2009).

Bedded-sedimentary barite deposits form in marine basins in association with sediments characteristic of high biological productivity. The deposits are most common in sedimentary strata of early or middle Paleozoic age, but they have also been found in strata of Archean, Proterozoic, and Mesozoic age. Concentrations of barite nodules have been identified in Cenozoic age rocks (Bogoch and others, 1987; Stamatakis and Hein, 1993), but there are no identified deposits of Cenozoic age that are of sufficient grade and size to consider mining. The presence or absence of sulfide mineralization has been proposed to reflect different tectonic settings for the depositional basins, one of which is underlain by continental crust—a source of zinc and lead (Maynard and Okita, 1991). This proposal has been controversial (Turner, 1992), but tectonic setting undoubtedly influences sulfide formation in some way because it can affect important parameters of the ore-forming process, including the availability of heat to drive fluid movement, the nature of the fault systems that serve as channels for flow, and the structure and oxidation state of the overlying basin.

Bedded-Volcanic Deposits

Bedded-volcanic deposits are stratiform bodies of massive or near-massive barite within stratigraphic successions containing igneous rocks—typically both felsic and mafic volcanic varieties—and sedimentary rocks. The barite can occur in large high-grade deposits (up to 90 percent $BaSO_4$) or can be intergrown or interbedded with copper, lead, zinc, or gold- or silver-bearing sulfide minerals. The deposits tend to occur in districts, and individual barite ± sulfide bodies can be closely spaced enough that both barite and metals are exploited by a single mining operation. Barite resources at individual mines can range up to millions of tons. Gangue minerals are typically clays, quartz, or sulfides. Whereas bedded-volcanic deposits have been significant sources of barite in the past (in Japan, for example; Marumo, 1989), they are presently a minor source compared with bedded-sedimentary deposits.

Examples of bedded-volcanic deposits are the kuroko-type deposits of northern Honshu and southern Hokkaido, Japan (many of which are better known for their copper, lead, precious metals, and zinc; Marumo, 1989), the Barite Hill deposit in the Carolina slate belt of South Carolina (Clark and others, 1999), and deposits that occur in a belt extending westward from the Madneuli deposit in the Republic of Georgia through Turkey and Bulgaria to northern Algeria (Kekeliya and others, 1984; Migineishvili, 2005).

Bedded-volcanic barite deposits form at submarine volcanic centers at divergent, convergent, and, in some cases, transform plate boundaries (Marumo, 1989; Herzig and others, 1993; Hein and others, 1999). Barium is scavenged from the volcanic edifice and underlying rocks by seawater that is heated by magmas and circulated by convection. In convergent-margin volcanic-arc settings, additional fluid may be supplied to the convection system by crystallizing magmas. Barite deposits form where the hot barium-bearing fluids are expelled onto the sea floor and encounter cold sulfate-bearing seawater. Like the bedded-sedimentary deposits, the bedded-volcanic deposits have analogs on the modern sea floor, but these are located near active submarine volcanoes mostly away from continental margins (Kusakabe and others, 1990; Urabe and Kusakabe, 1990).

Vein, Cavity-Fill, and Metasomatic Deposits

Barite deposits included in the vein, cavity-fill, and metasomatic classification occupy faults, breccia zones, solution-collapse, or other fluid-permeable structures in which barite has either filled open spaces or replaced adjacent rock. The deposits are commonly tabular and extend along structures, often discontinuously, that can be traced for hundreds or thousands of meters. The vein deposits can attain thicknesses of several tens of meters. Gangue minerals include carbonates (calcite, siderite), fluorite, quartz, and pyrite or other sulfide minerals. The deposits tend to occur in districts or in linear distributions. This deposit type has been a source of high-purity barite for use in fillers and ceramics, which generally requires a grade of at least 95 percent $BaSO_4$. In some mining operations, barite is a byproduct or coproduct of fluorite, lead, or zinc production. The economic advantage of producing barite as a byproduct or coproduct from deposits of this type tends, however, to be offset by higher mining costs because underground mines or large open pits are required to exploit ore zones that commonly have steep dips.

Examples of vein barite deposits are found in the Culpeper, Hartford-Deerfield, and Newark basins in the Eastern United States (Robinson and Woodruff, 1988), the North Pennine and South Pennine orefields of England (Ixner and Vaughan, 1993), and the Greater Caucasus in the Republic of Georgia (particularly the Chordi deposit) (Tvalchrelidze and Shcheglov, 1990). Some vein barite deposits are located in districts that are better known for their lead-zinc sulfide deposits (Mississippi Valley-type), as in the Pennine orefields. A direct association with Mississippi Valley-type sulfide mineralization is characteristic of cavity-fill barite deposits, such as those of the Central Missouri and Southeast Missouri districts, the Sweetwater district of Tennessee (Leach, 1980; Kaiser and others, 1987), and the Jbel Irhoud and Zelmou deposits of Morocco (Valenza and others, 2000). Cavity-fill deposits are more irregular in form; they tend to be restricted to a particular sedimentary stratum or sequence of strata. District-wide zoning is apparent in rare cases, as in the South Pennine orefield where a region of barite-dominant deposits is bounded on the east by a region of fluorite-dominant deposits and on the west by a region of calcite-dominant deposits.

Metasomatic barite deposits included in this grouping are associated with alkalic or carbonatite complexes. The best example in the United States is found at Mountain Pass in California, where a body of rock that has been mined for rare-earth elements contains approximately 20 to 25 percent barite (Castor and Nason, 2004). The barite is not presently recovered. The Araxá deposit, which lies within the alkaline-ultramafic Barreiro complex in Minas Gerais, Brazil, is capped by a 150- to 230-meter-thick regolith that has been leached of carbonate minerals and contains approximately 20 percent barite (Woolley, 1987). The Mau Xe deposit in northern Vietnam is another carbonatite-associated deposit that is composed of about 51 percent barite (Kusnír, 2000). These deposits are resources for other mined commodities that are more valuable than barite—rare-earth elements for Mountain Pass and both rare-earth elements and niobium for Araxá and Mau Xe. Thus, any barite production from them would be as a byproduct or coproduct. The same is likely to be true for other examples of this deposit type.

In detail, deposits of the vein, cavity-fill, and metasomatic category have diverse origins, but they share a basic genetic attribute—the ore constituents are transported by one or more high-temperature fluids (100 degrees Celsius or hotter) that are channeled along structurally controlled pathways. Depending on the specific location, the source of ore constituents varies from predominantly sedimentary rocks to predominantly igneous rocks, as has been shown for the deposits of central Europe (Dill and Nielsen, 1987). Barite associated with carbonatite complexes is of igneous origin but can be either a precipitate from hydrothermal fluids or a crystallization product of a carbonate melt. The mechanism by which fluids were heated also varies from one location to another. The fluids that formed the U.S. midcontinent deposits were heated as they circulated to deep levels in an extensional tectonic setting where the geothermal gradient was elevated, whereas the fluids that formed the central Europe deposits were heated by igneous intrusions (Dill and Nielsen, 1987). In carbonatite-associated deposits, heat was supplied by intruded carbonatite magma. The tectonic settings are also diverse. Many vein deposits are found in narrow rift basins that contain red beds and other terrigenous sedimentary rocks, whereas cavity-fill deposits are commonly found in carbonate platforms that developed along the margins of marine basins. Carbonatites are unusual rocks that originate by low degrees of partial melting of mantle material beneath continental rifts.

Residual Deposits

Residual barite deposits are poorly consolidated materials that form by weathering of preexisting deposits. Clay minerals, quartz, and unweathered rock fragments are typically present in the deposits. Iron oxides, metal sulfides, and sulfide weathering products may also be present. Within the United States, residual deposits are found in the Cartersville area of Georgia (Reade and others, 1980), the Southeast Missouri district (Leach, 1980; Kaiser and others, 1987), and the Sweetwater district of Tennessee (Kesler, 1996). These deposits formed by weathering of cavity-fill barite mineralization contained in limestone or dolostone host rocks. Residual barite deposits can also form from weathering of other deposit types. For example, barite-hematite gossan at the Mount Lyell Mine in western Tasmania was produced by weathering of bedded-volcanic barite and sulfide mineralization (Solomon and others, 1969). At Araxá, Brazil, the defined ore reserve is a weathered regolith leached of carbonate minerals (Woolley, 1987). At Mount Lyell and Araxá, weathering resulted in residual enrichment of barite and upgrading of the deposit.

Resources and Production

Reserves

Barite reserves tend to be defined only a few years prior to production because (a) drilling activity—the major market for barite—fluctuates in ways that are difficult to forecast farther in advance, and (b) the ease of extraction and ore processing allows for faster and less expensive mine startup than for many other mined commodities. Consequently, there is a general tendency for mined reserves to be replaced regularly by new reserves. A boom in oil and gas exploration resulting from a combination of increasing global demand for oil and gas, high oil prices, and expanded use of hydraulic fracturing in development of unconventional oil and gas resources has resulted in dramatically increased global consumption of barite. Reserves of high-grade barite are being depleted, but they exceed demand by a large margin, both in the United States and worldwide. Thus, this mineral commodity is unlikely to become severely depleted in the foreseeable future.

Problems with costs of current sources of supply are evident, however. Consumers have become dependent on low-cost barite supplied by China and India, which together accounted for about 65 percent of world production in 2011. Prices for Chinese and Indian barite have risen substantially in recent years, with prices for barite from China increasing nearly sixfold in the past 10 years. Consumers are seeking alternative sources of low-cost barite to reduce the dependence on China and India for supplies. Global barite resources are extensive, but the exploration and development of these resources may not proceed in direct response to changes in the price or supply of the commodity. In recent years, even while barite prices rose steeply, little exploration took place. Currently, however, indications are that exploration and development work is expanding domestically and internationally in such countries as Kazakhstan, Liberia, Mexico, and Zimbabwe.

An additional consideration is that transportation is a major factor in the total cost of barite (Coffman and Kilgore, 1986). Long transport distances can add substantially to the overall price of the commodity, particularly if shipping is by rail or truck rather than by sea. Thus, supplies of low-cost barite for oil and gas producers depends partly on the proximity of barite mines to the drilling activity and whether transportation can be by low-cost ocean shipping.

Solutions to problems of tight supply and rising costs will likely include increased production from such countries as Kazakhstan, Mexico, Morocco, and Vietnam, and new production from nontraditional sources, such as Greenland and Zimbabwe. Other solutions that have been proposed include developing application-appropriate specifications and grades in order to preserve existing barite resources, using blended weighting agents, expanding the use of managed-pressure drilling techniques, and implementing recycling (Newcaster, 2012). Barite consumption is forecast to increase by about 30 percent by 2016, with likely fluctuations in the availability of supply.

Other Identified Resources

Recent production from existing mines, by country, is shown in figure D3. Total world production averaged 7.97 million metric tons per year for the 5-year period starting in 2007. China was the leading producer (4,020 thousand metric tons per year, or 50 percent of global production), India was second (1,190 thousand metric tons per year, or 15 percent), Morocco was third (630 thousand metric tons per year, or 7.9 percent), and the United States was fourth (574 thousand metric tons per year, or 7.2 percent). The top eight countries accounted for about 92 percent of global production.

In 2011, output from U.S. mines was 710,000 metric tons (Miller, 2013). For the foreseeable future, Nevada mines are expected to be the major domestic producers. Current producers have gathered extensive data on Nevada barite resources to plan future mining activities, and at least one producer was expanding production capacity. Renewed production is possible from Arkansas, which last mined barite in the early 1980s and has identified economic deposits in the Ouachita National Forest that could be developed. In addition, important new resources have been identified during the past 20 years in northern Alaska. These are bedded-sedimentary barite deposits at the Red Dog district in the western Brooks Range and in the Cutaway basin in the central Brooks Range. The barite endowment of the Red Dog district could be in excess of 1 billion metric tons (Kelley and Jennings, 2004). These deposits are not currently mined, and most lie far from roads or other existing infrastructure; however, they are in close proximity to a region of active oil and gas exploration on the north slope of Alaska and to possible future exploration

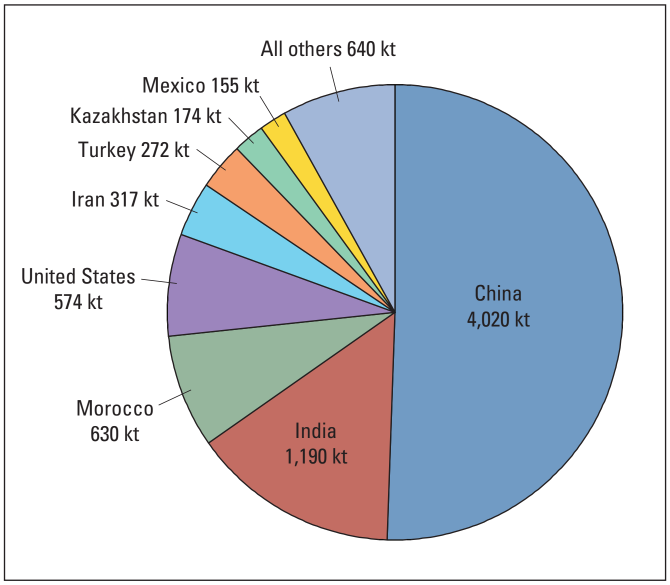

Figure D3. Pie chart showing average annual barite production for the period 2007–11, by country and amount (in thousand metric tons [kt]). World production during this 5-year period averaged 7.97 million metric tons per year. Data are from Miller (2012).

in Arctic regions of North America, Europe, and Asia. The Cutaway basin deposits lie within the National Petroleum Reserve–Alaska.

The largest identified resources of barite on a global scale are found in the Qinling and Jiangnan regions of southern China and the Cuddapah district of India. Tonnage estimates have varied widely, but all suggest that the amounts of barite available for mining are quite large. For example, recent estimates for one of the larger deposits in China, the Gangxi deposit in Hunan Province, have ranged from more than 80 million metric tons (Roskill Information Services, Ltd., 2006) to 453 million metric tons grading between 63.6 and 77.3 percent $BaSO_4$ (Kamitani and others, 2007). The compilation of published data by Kamitani and others (2007) lists seven barite deposits in southern China that exceed 5 million metric tons. The Mangampeta deposit in the Cuddapah district in India has been estimated to contain 73.4 million metric tons with a specific gravity of 3.8 or greater, 50 percent of which has a specific gravity of 4.2 or greater (Clark and Basu, 1999).

Undiscovered Resources

The potential for the discovery of new barite resources in the United States and in many other locations in the world is considerable. Bedded-sedimentary deposits are probably the most attractive target for exploration because they have the potential to produce mud-grade barite with minimal ore processing. In addition, the most common geologic setting for this deposit type—organic-rich chert-mudstone-shale successions of early to middle Paleozoic age—exists in many regions of the world. Barite is easily overlooked or misidentified, so there is good potential for unrecognized deposits in recognized districts. Figure D2 provides a guide to a number of districts with current or past production from bedded-sedimentary deposits, but many others likely occur.

Another potential source is byproduct barite or barium at mineral deposits that will be mined in the future primarily to recover other mineral commodities. Foremost among these are carbonatite deposits, which are potential sources of rare-earth elements and several other mineral commodities, and barite-dominant hydrothermal deposits in relatively shallow water along active volcanic arc systems.

Exploration for New Deposits

Exploration for barite deposits has traditionally been carried out by direct examination of outcrop or by chemical analysis of stream sediment in areas where the geologic setting is favorable. Barium in stream sediment, in both the fine size fraction and the heavy-mineral fraction, has proven to be a good guide to bedded mineralization (Coats and others, 1981).

Geophysical methods have been used to delineate deposits or to identify barite accumulations that are shallowly buried. Gravity methods exploit the large density contrast that exists between massive barite bodies and most of the rock types that enclose them (Uhley and Scharon, 1954; Schmidt and others, 2009). Very-low-frequency electromagnetic methods have also provided useful information where barite, which has low resistivity, is contained in conductive host rocks (Coats and others, 1981).

Environmental Considerations

Barium Behavior in the Environment

Barium has limited mobility in the environment because it tends to form insoluble compounds under common Earth-surface conditions and does not form soluble organic complexes. The barium released from minerals during weathering tends to precipitate as barite (barium sulfate, $BaSO_4$), witherite (barium carbonate, $BaCO_3$), or other minerals, or to adsorb onto clay minerals, oxides, or hydroxides. Barite is practically insoluble in oxidizing environments and is highly resistant to weathering. The solubility of most barium compounds increases as conditions become reducing or acidic (Jaritz, 2004).

Barium in the environment comes mostly from natural rock weathering, but anthropogenic contributions can be important, particularly emissions related to copper smelting, steel production, and automobile manufacturing (Reimann and de Caritat, 1998). Combustion of coal and diesel and incineration of waste both release barium-bearing particulates to the atmosphere (Agency for Toxic Substances and Disease Registry, 2007). In the United States, atmospheric barium concentrations have been reported to range from 0.00015 to 0.95 microgram per cubic meter (U.S. Environmental Protection Agency, 1984). Barium concentrations in soil usually reflect the composition of the underlying bedrock, but dispersal of fly ash or sludge from landfills and application of phosphate fertilizers can lead to elevated levels of barium in the soil (International Programme on Chemical Safety, 2001; Kabata-Pendias and Mukherjee, 2007). Surface soils (top 5 centimeters [cm]) in the conterminous United States average 518 parts per million (ppm) barium with values ranging from less than 5 to 4,770 ppm (parts per million equals grams per metric ton; 1 ppm equals 0.0001 percent; Smith and others, 2013).

The concentration of barium in natural waters is controlled by the solubility of barium compounds, the tendency of barium to adsorb onto particulates, and the availability of dissolved sulfate or carbonate to form insoluble salts (Agency for Toxic Substances and Disease Registry, 2007). The concentration of barium in surface waters ranges from 7 to 15,000 parts per billion (ppb) (Jaritz, 2004).

Gaillardet and others (2003) reported a worldwide river water average of 23 ppb. Suspended solids and sediments commonly contain more barium than the water. The global average for barium in suspended river sediment is 522 ppb (Viers and others, 2009). A study of the Rhine River near Darmstadt showed a barium concentration of 480 ppb in the suspended material compared with 39 ppb in the water (Hoffmann and Lieser, 1987). Barium in seawater averages 6 ppb, which is lower than the concentration in most freshwater because barite tends to precipitate as freshwater enters the ocean (Jaritz, 2004). The barium content in seawater varies among different oceans and with latitude and depth (International Programme on Chemical Safety, 2001).

The contents of barium and other elements in waters, sediments, and soils in the vicinity of barite deposits can be above average, depending on the type of deposit, the extent of the outcrop of ore and overburden, the climate, and other factors. Barium can be leached by groundwaters in some locations, such as in regions of Kentucky, northern Illinois, New Mexico, and Pennsylvania, where the presence of barite in bedrock has given rise to relatively high barium concentrations in groundwater (Agency for Toxic Substances and Disease Registry, 2007).

Barite in drilling muds can be recycled in some situations. The procedure involves removing barite from the mud by centrifuging and returning it to the active drilling system; this recycling of barite can help ensure compliance with fluid discharge requirements in environmentally sensitive areas. For the most part, barite is recycled only because drilling mud is continuously circulated through a reserve pit to allow cuttings to settle, and the mud is then reused during the drilling of a particular well.

The U.S. Environmental Protection Agency classifies oil and gas drilling fluids as “special wastes,” which are exempt from amendments to the Resource Conservation and Recovery Act (P.L. 94–580) issued by Congress in 1980. As a result, the methods for handling and disposal of oilfield waste fluids vary from one State to another (McFarland and others, 2009). Various methods are employed to dispose of drilling fluids containing barite, including onsite burial, landfill disposal, land application, salt cavern injection, and disposal at sea. The most common practice on land is onsite burial. After well completion, the fluid is pumped into the reserve pit, allowed to dry, and then either mixed with soil from the pit berms or simply covered with soil. At other locations, drilling fluids are transported to a landfill or are land-applied, which allows naturally occurring microbes in the soil to metabolize, transform, and assimilate the waste constituents. Salt cavern injection involves pumping waste drilling fluids into cavities in underground salt deposits. Specific regulations apply to ocean disposal of drilling fluids, particularly for fluids that are oil based or synthetic (Drilling Waste Management Information System, undated).

Barium in electronic devices and other manufactured products is not recovered. Recycling supplies less than 1 percent of worldwide barium consumption (Graedel and others, 2011).

Mine Waste Characteristics

The solid wastes produced at barite mines vary widely in volume, mineralogy, and chemistry because of the variation in the types and sizes of deposits, in the compositions of the host rock and gangue, and in the ore processing methods. At bedded deposit mines, barite of high purity can often be obtained with minimal processing. Waste from operations of this type consists of host rock and gangue minerals. Common host rock types include alluvium, black shale, chert, dolostone, limestone, mudstone, and siltstone; igneous rocks can be important in some locations. Common gangue minerals include carbonates, clays, iron oxides, quartz, and minor sulfide minerals. Sulfide minerals are typically sparse enough that waste rock piles and tailings impoundments have low potential for acid drainage, as at the Argenta Mine in Nevada (U.S. Bureau of Land Management, 2010). In locations where bedded deposits are hosted by dolostone or limestone, the potential for acid drainage is lessened by the capacity of these rock types to neutralize acidity. This phenomenon may be responsible for the lack of acidity in groundwaters in the vicinity of the Mangampeta Mine in India (Nagaraju and others, 2006a). Waste rock can be of sufficiently high quality that the material is suitable for use as aggregate. On the other hand, wall rocks exposed in open pits can be acid-generating (U.S. Bureau of Land Management, 2010), in which case, pit lakes that develop after mine closure warrant remediation. In addition, soils developed on waste piles can have elevated concentrations of barium and other metals contained in the host rocks, as in the region surrounding the Mangampeta Mine in India where soils locally contain significant amounts of boron, chromium, and nickel (Raghu, 2001).

Vein barite deposits and bedded barite closely associated with massive sulfide mineralization normally require froth flotation to separate barite from fluorite, galena, pyrite, sphalerite, or other minerals. At these operations, waste rock and tailings can have higher sulfide contents and correspondingly greater potential for acidic metal-bearing drainage. The acid-neutralization capacity of host rocks and gangue minerals can be a significant control of acid drainage. Granite host rocks, for example, have less acid-neutralizing capacity than limestones or dolostones. At mines where carbonate rocks are important constituents of the bedrock, acid drainage can be lessened naturally, such as at the Magnet Cove copper-lead-zinc-gold-barite mine in Nova Scotia, where surface waters are acidic only very locally (Whitehead and Macdonald, 1998). Unlike copper, iron, lead, manganese, zinc, and many other metals, barium is not particularly mobile in acid drainage because barite resists dissolution. Dispersal of barium from mining operations is mainly by physical erosion and transport of barite particles.

Human Health Concerns

No adverse human health effects have been linked to barite mining in the United States. In general, the toxicity of barium depends on its chemical form. Soluble barium compounds, such as barium chloride, barium hydroxide, and barium nitrate, can be toxic to humans, animals, and plants, whereas barium sulfate (barite) is effectively nontoxic because the barium is not bioaccessible. In fact, barium sulfate is routinely ingested by patients undergoing gastrointestinal X-rays (Jaritz, 2004). Barium carbonate is only slightly soluble in water, but it is toxic to humans because it dissolves in the gastrointestinal tract (Agency for Toxic Substances and Disease Registry, 2007). There is no evidence that barium compounds are carcinogenic or cause genotoxicity in humans or animals, although the available data are limited (International Programme on Chemical Safety, 2001).

The barium content of drinking water, food, and soils is rarely high enough to present a human health concern. Dietary intake of barium is mostly from drinking water. The maximum contaminant level for drinking water in the United States is 2.0 ppm (U.S. Environmental Protection Agency, 2009), whereas the World Health Organization guideline is 0.7 ppm (World Health Organization, 2004). Drinking waters in the United States have a median barium concentration of 0.043 ppm, and more than 90 percent of U.S. cities were found to contain less than 0.1 ppm (Dufor and Becker, 1964). High concentrations of barium in drinking water can result in gastrointestinal disturbances and muscular weakness, and lead eventually to high blood pressure and cardiovascular disease (Agency for Toxic Substances and Disease Registry, 2007; Health Canada, 2012). For barium concentrations up to 10 ppm, however—which have been observed in certain regions of the United States, including Illinois and Iowa (Brenniman and others, 1981)—the links to high blood pressure and cardiovascular risk factors have been called into question (Wones and others, 1990). In some situations, food can be a significant source of dietary barium. Dairy and meat products tend to be lower in barium than vegetables, but Brazil nuts, seaweed, fish, and some plants can be high in barium (Jaritz, 2004; Agency for Toxic Substances and Disease Registry, 2007). Consumption of vegetables grown on barite-contaminated garden soils has been suggested as a human exposure pathway near a barite mine in northwestern Croatia (Frančišković-Bilinski and others, 2007). For soils, the noncancer screening level is 1,500 ppm in residential settings and 19,000 ppm in industrial settings (U.S. Environmental Protection Agency, 2012). The level for industrial settings is many times higher than the 4,770 ppm maximum concentration reported in a survey of soils in the conterminous United States (Smith and others, 2013), but the level for residential settings is exceeded by some of the reported soil concentrations.

The individuals at greatest risk of barium exposure are workers at mines, ore processing plants, and manufacturing facilities for barium-containing products. Epidemiological studies have reported cases of baritosis stemming from dust exposure during mining and grinding of barium ores (Pendergrass and Greening, 1953; Doig, 1976; Seaton and others, 1986). Baritosis is a benign lung disease that does not result in medical disability and appears to be reversible on a time scale of several years (Seaton and others, 1986). In the United States, workplace exposure to soluble barium compounds is limited to 500 micrograms of barium per cubic meter of air per 8-hour period (Occupational Safety and Health Administration, 2013). Some barite deposits contain enough quartz that respirable silica can be a concern at mine and mill sites. Risks can be mitigated, however, by using dust masks and water sprayers or other dust suppression techniques (Mills, 2006).

Ecological Health Concerns

No adverse toxicological effects of barium on plants or wildlife have been reported near barite mines or elsewhere. Barium accumulates only slightly from soil to plant and from plant to animal (International Programme on Chemical Safety, 2001); however, high soil barium contents have been shown to inhibit growth in some terrestrial plants (International Programme on Chemical Safety, 2001). For the United States, a soil screening guideline of 500 ppm has been proposed for phytotoxicity (Efroymson and others, 1997), but this benchmark has only limited data to support it. Some soluble barium compounds are toxic to animals; for example, barium carbonate—the mineral witherite where it occurs naturally—is sufficiently toxic that it is used as a rodenticide (Jaritz, 2004).

In the aquatic environment, barium can have toxic effects on some organisms (water fleas, or *Daphnia magna*), but limited data suggest that the risk to fish and aquatic plants is likely to be less. Barium accumulates only slightly in aquatic life (Reimann and de Caritat, 1998). Suter (1996) proposed secondary acute and chronic water-quality benchmarks for freshwater biota of 69.1 and 3.8 ppb, respectively, but these values were determined using fewer data than normally required to establish levels. Lethal concentrations for water fleas and freshwater amphipods (*Hyalella azteca*; 50 percent mortality in laboratory tests) are greater than 1,000 ppb, which is significantly higher than the proposed benchmark (Borgmann and others, 2005).

Ecological health concerns associated with the mining and processing of barite ores arise more from disturbance of host rocks and associated minerals than from the barite itself. The carbonaceous shales or siltstones associated with many bedded-sedimentary barite deposits typically contain minor amounts of pyrite (1 to 2 weight percent on average) and significant amounts of some metals (chromium, manganese, vanadium, and zinc typically exceed 100 ppm) (Quinby-Hunt and others, 1989). Weathering of these lithologies in waste rock piles can potentially lead to acidic metal-bearing drainage, the release of which can have deleterious effects on aquatic life. The same potential would exist at barite mining operations that treat sulfide-bearing ores and produce sulfide-bearing tailings. As discussed, the presence of acid-neutralizing rocks would tend to lessen this problem.

Drilling mud is disposed of at or near the drilling site. Dispersal of this material can have deleterious effects on plants, including slowed growth of both seeds and plant, and reduction in yields, although these effects could also relate to other constituents of drilling mud (Ferrante, 1981). Barite alone has been shown to cause toxicity to freshwater fish only at very high concentrations (Ferrante, 1981). In some jurisdictions, such as Alaska, restrictions are placed on the metal content of the barite used in drilling mud (less than 3 ppm cadmium and less than 1 ppm mercury; Harben, 2002).

Mine Closure

Most active barite mines worldwide, and all active mines in the United States, are open pit operations. After mining ceases, open pits can be left open and fenced. A pit lake will form if the depth of the excavation exceeds the depth of the water table. The lake water may or may not be acidic and metal-bearing depending on the abundance of sulfide minerals and the acid-neutralizing capacity of rocks exposed in the pit walls and immediate vicinity. Poor water quality may require that the lake be drained and the water treated, followed by backfilling of the pit. Openings to any underground workings are typically sealed.

Waste rock piles, mill sites, and other surface disturbances are graded and contoured. The area is typically revegetated by seeding or planting. At least one scrub species (*Prosopis juliflora*) grows prolifically and sequesters barium and metals (Nagaraju and others, 2006b). For some waste rock and tailings, a possible alternative to grading and revegetation is removal and sale of the material for use as aggregate or fill. This has been common practice at barite mines in France, Germany, Spain, and the United Kingdom (European Commission, 2009).

Problems and Future Research

Several unresolved questions regarding the origin of bedded-sedimentary barite deposits have implications for exploration. Perhaps the most important is whether the barium is derived from organic matter that decomposes as it sinks to the floor of a sedimentary basin or from fluids ascending faults or other structurally controlled pathways toward the basin floor. The correct answer to this question may differ from one district to another and will dictate whether new deposits are likely to be sought in locations where water column oxic-anoxic transitions intersected the basin floor or in the vicinity of basin-bounding faults.

Other outstanding questions regard the relationship of barite deposits to deposits of other useful minerals. The reason that there is a close spatial and temporal relationship between bedded-sedimentary barite deposits and zinc-lead-silver sulfide deposits in some sedimentary basins but not in others is not fully understood. Evidence has been presented that bedded-sedimentary barite deposits are one member of a large family of mineral deposits in sedimentary basins that includes not only lead-zinc-silver deposits but also deposits of gold, phosphate rock, vanadium, and several other mineral commodities (Emsbo, 2000; Emsbo and others, 2005). If predictable relationships are identified among these deposit types on the basis of accurate models for their origin, then explorers could likely be able to identify stratigraphic intervals in sedimentary basins that present the highest probability of new discoveries for a variety of mineral commodities.

Finally, if pursued, advances in mineral processing could make it possible for barite to be profitably recovered as a coproduct or byproduct where ores are being mined for zinc, lead, rare-earth elements, or other mineral commodities. These advances could help meet the broader goal of increasing the efficient use of mined materials and reducing the amount of mining and ore processing waste that requires remediation.

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