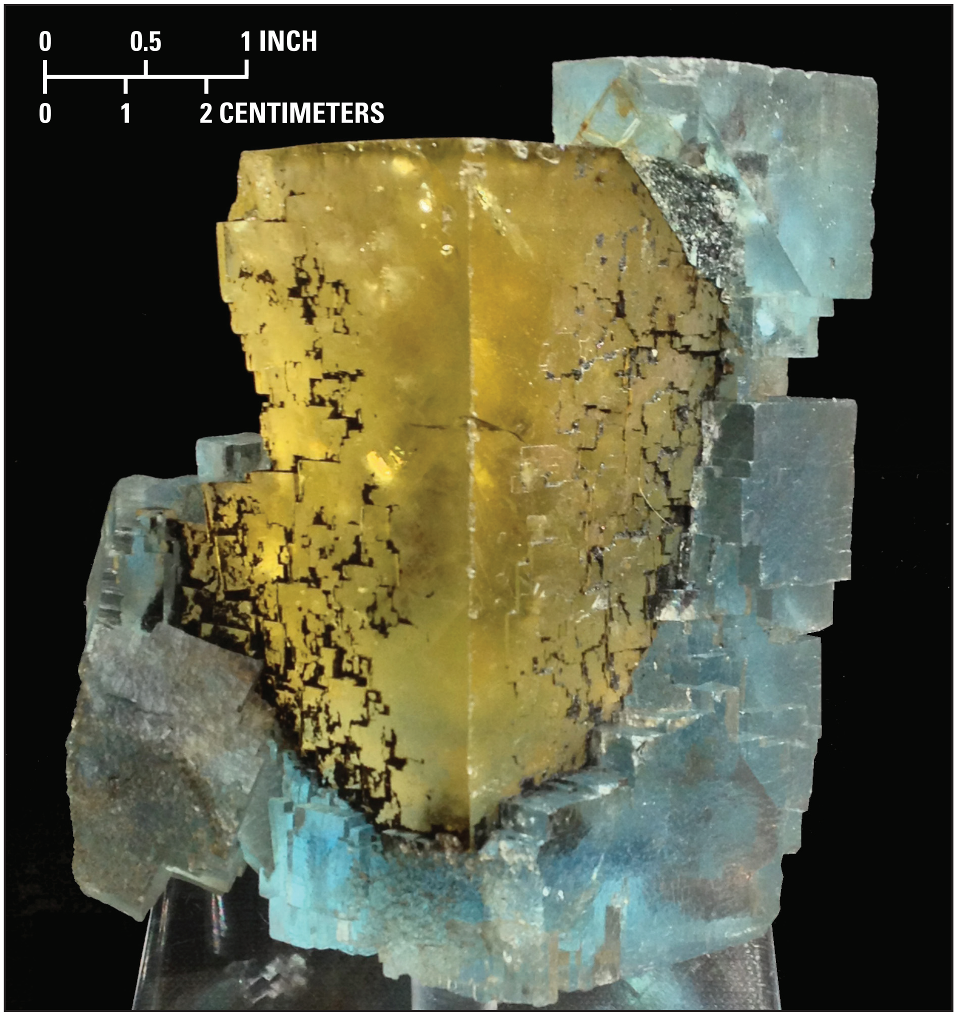
Fluorine

Chapter G of

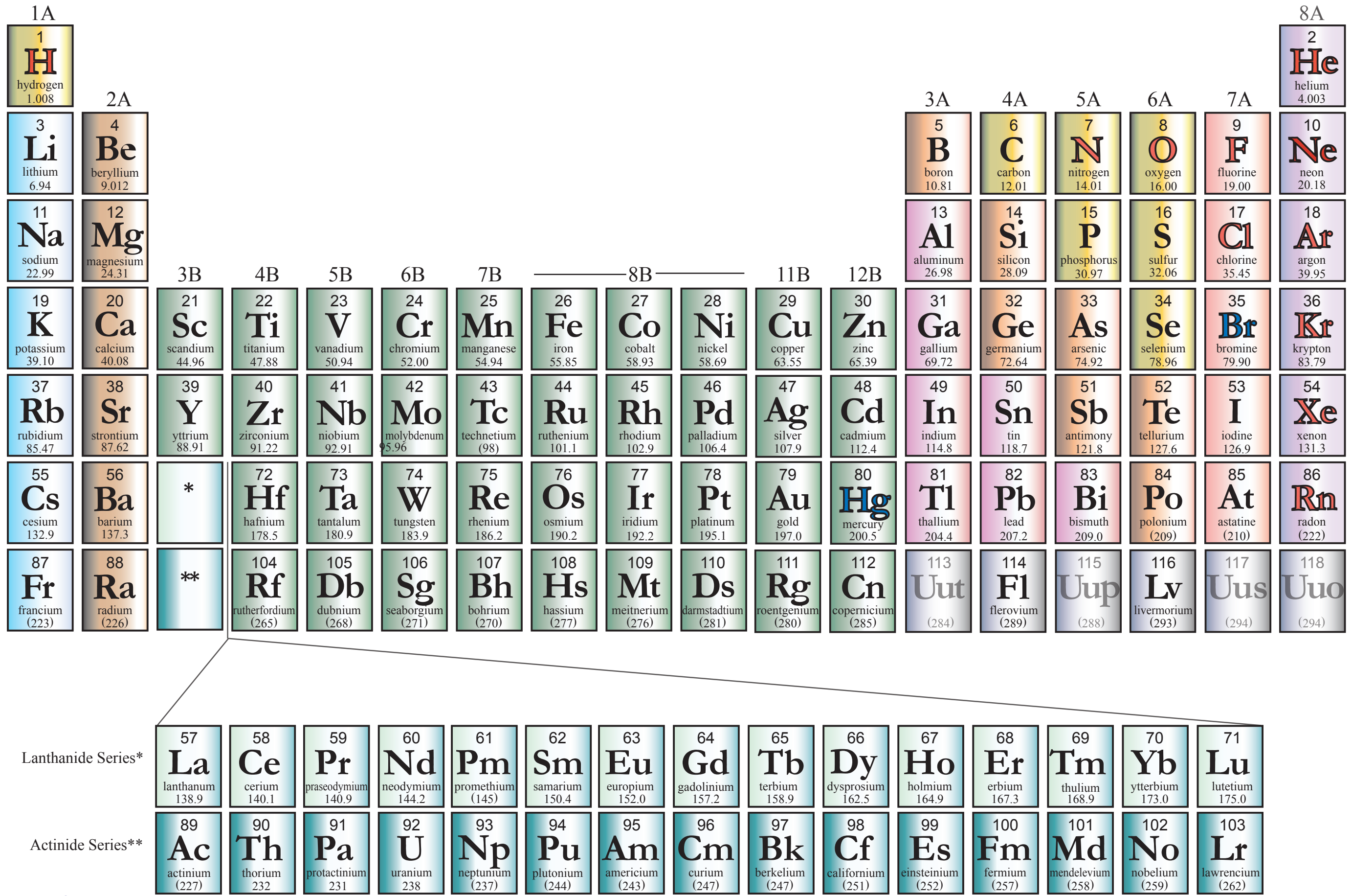
Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply



Professional Paper 1802–G

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. A fluorite specimen from the Number 1 (Minerva) Mine, Cave-in-Rock subdistrict, Illinois-Kentucky fluorspar district, showing the sequence of mineral deposition. Worldwide, fluorite is the only mineral mined solely for its fluorine content. Photograph courtesy of the Mineralogical and Geological Museum at Harvard University, Bannister Collection, MGMH 124614 © Copyright 2012, President and Fellows of Harvard College. All rights reserved.

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By Timothy S. Hayes, M. Michael Miller, Greta J. Orris, and Nadine M. Piatak

Chapter G of

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–G

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

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

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

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

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Conversion Factors

International System of Units to Inch/Pound

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

International System of Units to Inch/Pound—Continued

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

Inch/Pound to International System of Units

Multiply	By	To obtain
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
µm	micrometer
Å	angstrom
AMT	audio magnetotelluric
g/cm^3	gram per cubic centimeter
HDC	Hicks Dome Corp.
HF	hydrofluoric acid
JORC	Joint Ore Reserves Committee (Australia)
km	kilometer
km^2	square kilometer
m	meter
M	molarity
m^3	cubic meter
Ma	mega-annum
mg/L	milligram per liter
mm	millimeter
MVT	Mississippi Valley-type
NI	National Instrument
ppm	part per million
REE	rare-earth element
SAMREC	South African Code for Reporting Exploration Results
VLF	very low frequency

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By Timothy S. Hayes, M. Michael Miller, Greta J. Orris, and Nadine M. Piatak

Abstract

Fluorine compounds are essential in numerous chemical and manufacturing processes. Fluorspar is the commercial name for fluorite (isometric CaF_2), which is the only fluorine mineral that is mined on a large scale. Fluorspar is used directly as a fluxing material and as an additive in different manufacturing processes. It is the source of fluorine in the production of hydrogen fluoride or hydrofluoric acid, which is used as the feedstock for numerous organic and inorganic chemical compounds.

The United States was the world's leading producer of fluorspar until the mid-1950s. In the mid-1970s, the U.S. fluorspar mining industry began to decline because of foreign competition. By 1982, there was essentially only a single U.S. producer left, and that company ceased mining in 1996. Consumption of fluorspar in the United States peaked in the early 1970s, which was also the peak period of U.S. steel production. Since then, U.S. fluorspar consumption has decreased substantially; the United States has nonetheless increased its imports of downstream fluorine compounds, such as, in order of tonnage imported, hydrofluoric acid, aluminum fluoride, and cryolite. This combination of no U.S. production (until recently) and high levels of consumption has made the United States the world's leading fluorspar-importing country, in all its various forms.

The number of fluorspar-exporting countries has decreased substantially in recent decades, and, as a result, the United States has become dependent on just a few countries to supply its needs. In 2013, the United States imported the majority of its fluorspar from three countries, which were, in descending order of the amount imported, Mexico, China, and South Africa.

Geologically, in igneous systems, fluorine is one of a number of elements that are "incompatible." These incompatible elements become concentrated in the residual magma while the common silicates crystallize upon magma ascent and cooling, leading to relatively high fluorine concentrations in the more evolved or differentiated igneous rocks and in hydrothermal deposits associated with those evolved igneous rocks. In sedimentary rocks, fluorine's highest concentrations are found in phosphorites because fluorine substitutes for hydroxyl ions in apatite, which leads to fluorine concentrations of, typically, from 2 to 4 weight percent in phosphorites. Because of the presence of fluorine, phosphate fertilizer manufacturers can produce a fluorosilicic acid byproduct. Most deposits mined for fluorine are hydrothermal, however, and consist of fluorine minerals that precipitated from hot water. Magmatic brines and brines from deep within sedimentary basins that have high concentrations of dissolved fluoride are the mineralizing fluids for various types of hydrothermal fluorspar deposits. Relatively dilute hydrothermal fluids that formed in some volcanic rocks can also transport sufficient fluoride to form a high-grade fluorspar deposit. Fluorite has low solubility in a common range of hydrothermal temperatures, particularly from about 160 degrees Celsius (°C) down to 60 °C. The increasing fluorite solubility below 60 °C partly explains why some water with exceptionally high levels of dissolved fluorine are found even at ambient temperatures in evaporitic lake basins in some East African Rift valleys in Kenya and Tanzania. The geologic conditions that led to the high concentrations there are known to exist in a number of other places in the world as well, including, perhaps, places in the Basin and Range province of the United States.

Eight minerals or mineral groups have sufficient fluorine in their structures to be considered as possible ores of the element; they are bastnaesite (also spelled bastnäsite) and other fluorocarbonates, cryolite, sellaite, villiaumite, fluorite, fluorapatite (in phosphorites), various phyllosilicates, and topaz. Fluorite is currently the only mineral that is mined for fluorine, and no mineral except fluorite is likely to become a source of commercially produced fluorine as a primary product as long as supplies from relatively thick and high-grade fluorite deposits continue to be available.

At least seven classes (which include one subclass) of hydrothermal fluorite deposits are recognized; they are classified according to their tectonic and (or) magmatic settings, as follows: (1) carbonatite-related fluorspar deposits; (2) alkaline-intrusion-related fluorspar deposits; (3) alkaline-volcanic-related epithermal fluorspar deposits; (4) Mississippi Valley-type fluorspar deposits (and a subclass of salt-related carbonate-hosted fluorspar deposits); (5) fluorspar deposits related to strongly differentiated granites;

(6) subalkaline-volcanic-related epithermal fluorspar deposits; and (7) fluorspar deposits that appear to be conformable within tuffaceous limy lacustrine sediments. An eighth class (not hydrothermal) is that of fluorspar deposits concentrated in soils and weathered zones; that is, residual fluorspar deposits. Generally, fluorspar deposits related to strongly differentiated granites have larger tonnages and lower grades than carbonatite-related fluorspar deposits, which, in turn, have larger tonnages and lower grades than fluorspar vein deposits from various other classes.

The United States has a few identified resources of fluorspar, most notably the Klondike II property in the Illinois-Kentucky fluorspar district located about 8 kilometers southwest of Salem, Kentucky, which has a large vein that contains at least 1.6 million metric tons at a grade of 60 percent CaF_2 (Feytis, 2009). Additional fluorspar resources of lower grade but larger tonnage have been identified at Hicks Dome in the Illinois-Kentucky fluorspar district and at Lost River near the western tip of the Seward Peninsula in Alaska, along with a couple of dozen smaller, higher grade resources.

Internationally, new mines that either opened before the beginning of 2013 or were scheduled to open soon after that time include the Nui Phao tungsten-fluorspar-bismuth-copper-gold deposit in northern Vietnam; the St. Lawrence project in Newfoundland, Canada, which is located in a well-known fluorspar district; the Bamianshan deposit, which is related to a strongly differentiated granite in northwestern Zhejiang Province, China, near some of that Province's large, subalkaline-volcanic-related epithermal veins; and the Nokeng project in South Africa, which is also related to a strongly differentiated granite. Other deposits in northwestern Australia, Nevada (United States), Norway, South Africa, and Sweden have been identified and could be put into production within just a few years.

Among undiscovered resources, an interesting possibility might be to produce a fluorine product from evaporitic, high-fluorine, high-pH sodium-carbonate brines like Lake Magadi (Kenya) and Lake Natron (Tanzania) in Africa's Eastern Rift Valley. In addition, apparently conformable fluorspar deposits in tuffaceous limy lacustrine sediments, such as those in Italy, are likely to occur in similar young alkalic volcanic settings elsewhere in the world.

Modern geophysical and geochemical exploration techniques have typically not been brought to bear in exploration for new fluorspar deposits, although such techniques are likely to be used in future exploration. The tendency for fluorine to dissolve in significant concentrations in water at low temperature allows both surface water and groundwater to be used as sampling media in geochemical exploration. Evolved-granite-related fluorspar deposits may be particularly susceptible to geophysical exploration methods because crystalline rocks that form a basement to sedimentary sections can be approximately defined with gravity and magnetic methods, and magnetite-bearing skarns can be directly detected with magnetic surveys.

Environmental considerations of fluorine mining focus especially on drinking water, where high fluorine concentrations can lead to tooth decay; dental and skeletal fluorosis; and bone and cartilage conditions, including genu valgum, which is the crippling bone deformity more commonly known as knock knee. Trace amounts of other elements in fluorspar ores are a concern at some deposits; for example, high beryllium concentrations in alkaline-volcanic-related epithermal deposits or high cadmium concentrations associated with Mississippi Valley-type and salt-related carbonate-hosted fluorspar deposits.

Future research might include testing whether fluorine can be extracted economically from high-pH, sodium-carbonate brines and exploring for new occurrences of apparently conformable fluorspar deposits in tuffaceous limy lacustrine sediments outside of the Latium Region of Italy. Other promising new areas of research could be studies of fluorspar deposit fluid inclusion compositions by quadrupole mass spectrometry, by noble gas mass spectrometry on irradiated fluid inclusions, or by chlorine isotopes, while also measuring the chemistry of the same fluid inclusions either by bulk crush-and-leach methods or by laser ablation-inductively coupled plasma mass spectrometry. Advanced studies of fluid inclusion chemistry could be applied beneficially to some of the enigmatic large epithermal fluorspar veins at various places in the world, where they might determine those deposits' possible relationships to igneous intrusions, or to dissolved salt, or to heated meteoric water in volcanic sections, or perhaps to all three. This knowledge could help focus new exploration.

Introduction

Fluorine is an essential element for a number of industries, including aluminum production, steelmaking, gasoline refining, glass manufacturing, and the production of enamels, insulating foams, refrigerants, and uranium for nuclear power. The United States, which is the world's second-ranked consumer of fluorine products (Miller, 2012), obtains most of its supply through imports from Mexico. China is the world's leading fluorspar producer. It produced more than 60 percent of the world's output in 2012 (Miller, 2013). Fluorspar, which is the commercial name for fluorite (isometric CaF_2) (fig. G1), is the only mineral that is mined at large scale for fluorine. The importance of fluorine in numerous civilian and military uses and the dependence of the United States on a limited number of foreign suppliers are reasons why fluorine is considered to be a critical element for the United States. Beginning in World War II, or just after, and ending in 2009, fluorspar was judged to be of such importance that it was one of the strategic and critical minerals that were stockpiled by the U.S. Government. Starting in 2001, substantial decreases in exports of fluorspar from China have led to decreases in the world supply.

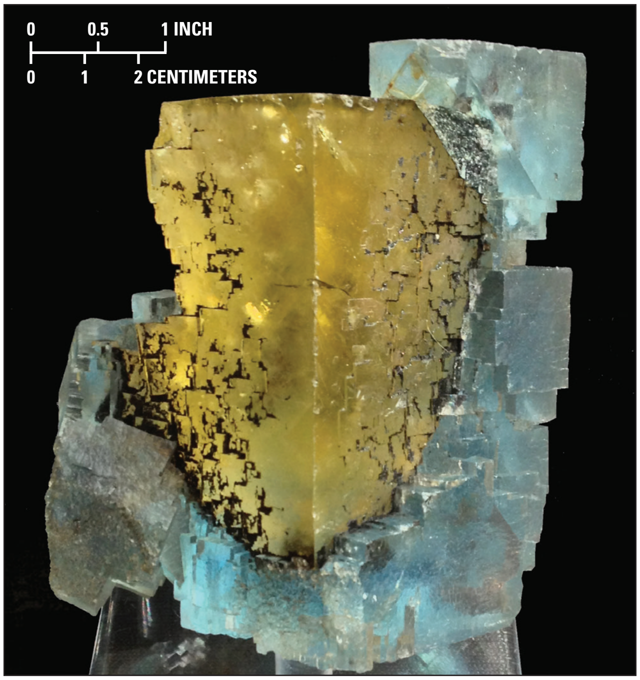

Figure G1. Photograph of a fluorite specimen from the Number 1 (Minerva) Mine, Cave-in-Rock subdistrict, Illinois-Kentucky fluorspar district, showing the paragenesis (sequence of mineral deposition), including (1) yellow fluorite number 2, (2) a redissolution surface visible particularly at the upper right beneath the blue fluorite, (3) pyrobitumens (black coating), and (4) blue fluorite (which is paragenetically equivalent to purple fluorite number 2 over most of the district). Worldwide, fluorite is the only mineral mined on a large scale solely for its fluorine content. Photograph courtesy of the Mineralogical and Geological Museum at Harvard University, Bannister Collection, MGMH 124614, © Copyright 2012, President and Fellows of Harvard College. All rights reserved.

Uses, Applications, and Consumption

Fluorspar is used directly as a fluxing material in ceramics, glassmaking, and steelmaking; as an additive in welding rod coatings; and for other, minor, uses. Fluorspar is the feedstock for fluorine chemicals, most of which are manufactured after fluorspar is converted to hydrogen fluoride; that is, hydrofluoric acid (HF). The major uses for HF are the manufacture of aluminum fluoride, synthetic cryolite, and fluorocarbons, but it is also used in the production of high-octane gasoline and in concentrating uranium; in glass etching, metal pickling, and oil and gas well treatment; and in the electronics industry. HF is used in the manufacture of a host of fluorine chemicals used in agrichemicals, dielectrics, metallurgy, mouth washes and toothpastes, pharmaceuticals, and wood preservatives.

There are three principal market grades of fluorspar—acid, ceramic, and metallurgical. Specifications for the acid grade and metallurgical grade are generally well defined, but the requirements set by individual consumers may vary in detail.

Acid-grade fluorspar (sometimes called "acidspar") is defined as containing more than 97 percent CaF_2, although material with a lower CaF_2 content can be used by manufacturers of HF (for example, those in Russia) if the remaining impurities are acceptable. Major impurities include calcium carbonate and silica content, which commonly have maximum allowable contents of 1.0 percent each. Limits are normally placed on other minor but relevant impurities, such as arsenic, phosphates, sodium chloride (NaCl), and sulfide sulfur or total sulfur. Arsenic and phosphate impurities are the most problematic because they are difficult to remove during ore beneficiation and because they have detrimental effects on HF production. If purchased as a wet flotation concentrate, the maximum allowable moisture content of the fluorspar is 10 percent water (H_2O); if purchased as a dried concentrate, the specification for acid and ceramic grades is usually a maximum of 0.10 percent H_2O. Particle size requirements for fluorspar may vary by customer, but generally the specification calls for the bulk (85 to 95 percent) to be able to pass through a 150-micrometer (µm; or 0.15-millimeter [mm]) screen.

In the United States, the use of ceramic-grade fluorspar has declined, and some former consumers of ceramic-grade fluorspar now use acid-grade fluorspar. The two ceramic grades for fluorspar are no. 1 (90 to 95 percent CaF_2) and no. 2 (85 to 90 percent CaF_2). Some domestic and foreign fluorspar suppliers still offer ceramic-grade fluorspar, but because practically every ceramic-grade user has its own specifications, suppliers tend to tailor their products to specific consumers or to offer several product grades that fall between metallurgical grade and acid grade. Customers may specify limits on the amounts of calcium carbonate, ferric oxide, lead sulfide, zinc sulfide, and silica present in the fluorspar.

In the United States, metallurgical-grade fluorspar ("metspar") generally contains a minimum of 80 percent CaF_2 and can range as high as 93 percent CaF_2. Steel mills are the major users of metspar, and their purchase specifications limit the content of silica to between 4 and 10 percent, and that of calcium carbonate, to between 4 and 9 percent. The standard size specifications for metallurgical-grade fluorspar gravel are that 100 percent of the gravel must be able to pass through a 63-mm screen and that a maximum of 15 percent must be able to pass through a 9.5-mm screen. In markets outside of the United States, the acceptable level of CaF_2 content may be lower (depending on the country), and the acceptable level of silica content may be higher than in the U.S. specification.

Geology

Geochemistry

Fluorine is one of the five halogen elements, along with chlorine (the most common), bromine, iodine, and astatine (which is the rarest). Fluorine has only one known chemical valence: –1. It has an ionic radius of 1.36 angstroms (Å), which allows it to substitute readily for the hydroxyl ion (which has an ionic radius of 1.40 Å) in mineral structures (Fleischer and Robinson, 1963). Fluorine substitutes less commonly for chloride and oxygen ions.

Fluorine in Rocks

In igneous systems, fluorine is one of a number of elements that are largely incompatible, in that they do not readily go into the common silicate minerals that crystallize from the melt. As a result, they become concentrated in the residual magma during differentiation. Early in differentiation, as mafic silicates and calcium-feldspars crystallize from the melt, the fluorine and silica (and typically As, B, Be, Cs, Dy, K, Li, Lu, Mn, Mo, Nb, Sb, Sc, Sn, Ta, Tb, Th, Tl, U, W, Y, Yb, and Zr) increase in concentration in the residual magma (Hildreth, 1981). This happens in both subalkaline and alkaline magmas, although the alkaline magmas may achieve higher fluorine concentrations (table G1; Shawe, 1976, p. 5). Fluorine's incompatibility broadly leads fluorite to be found in economic concentrations close to and within differentiation end-product rock types throughout the world, such as granites, syenites, and carbonatites, and their shallowly intrusive and extrusive equivalents. Shawe (1976) described and discussed several additional trends of fluorine in igneous rocks, some of which are not wholly predictable from the element's general incompatibility. Typical igneous-rock fluorine concentrations are given in table G1.

Because of fluorine's incompatibility, it may also occur in high concentrations in volcanic gases as well as in sublimates formed from the gases (White and Waring, 1963, table 1). Rocks altered by such gases similarly contain substantial amounts of fluorine; the fluorine is substituted mainly into hydroxyl sites in alteration micas and clay minerals, but in some places, the abundant fluorine occurs as fluorite.

In sedimentary rocks, fluorine's highest syngenetic concentrations (concentrations formed at the time of sedimentation) are found in phosphorites because of the element's substitution for hydroxyl ions in apatite, which is the principal phosphorous-bearing mineral in phosphorites; this process yields fluorapatite. Phosphorites typically have greater than 2 weight percent fluorine and may (rarely) have more than 4 weight percent (Gulbrandsen, 1966, table 1; Cheney and others, 1979, tables 3 and 6). Concentrations of fluorine in typical sedimentary rocks are given in table G1.

Fluorine geochemistry in metamorphic rocks is not well known. Fluorine is present primarily in biotite and muscovite in metamorphic rocks, and it tends to be concentrated in micas as water is lost during prograde metamorphism. Pyroxene-plagioclase granulites may contain fluorine-rich micas (up to 3.3 weight percent fluorine in biotite) (Bose and others, 2005). A few concentrations of fluorine in typical metamorphic rocks are given in table G1.

Fluorine in Water

Most deposits mined for fluorine are hydrothermal (that is, the fluorine minerals have precipitated from hot water), so understanding the geochemistry of fluorine in water is important for understanding how fluorine deposits are formed. Table G2 is a listing of some typical concentrations of fluorine in various types of water. Surprisingly, fluorine can dissolve in high concentrations (concentrations of more than 1,000 parts per million [ppm]) in low-temperature water with high pH and a low calcium concentration (Kilham and Hecky, 1973; Jones and others, 1977). This is especially true for waters in contact with rocks that have high fluorine contents, especially young volcanic rocks. In such rocks, the glassy components commonly have the highest fluorine concentrations and are inherently unstable at surface conditions, releasing fluorine as they are altered. As with the other halogens at low temperature, fluorine occurs commonly as a free ion in water, whereas there is a tendency for greater complexing at higher temperatures.

Fluoride, like many other dissolved components, is found at high concentrations in brines of various origins. Magmatic brines and brines from deep within sedimentary basins are potential mineralizing fluids for various types of hydrothermal fluorspar deposits. Another important feature of fluorine geochemistry in water is that fluorite has minimum solubility in a common range of hydrothermal temperatures, particularly from about 160 degrees Celsius (°C) down to about 60 °C (fig. G2). Its solubility increases with increasing temperature, as is the case for many dissolved components. Experiments by Richardson and Holland (1979), however, show that, unlike most minerals, the solubility of fluorite increases as temperature drops below 60 °C down to 0 °C (fig. G2). Over this temperature range, the tendency of the mineral to precipitate from solution decreases as the temperature decreases. Fluorine's high solubility in cool, calcium-poor, high-pH water from young volcanic rocks is related to this retrograde solubility. The high fluorine concentrations are found specifically in waters poor in calcium and high in carbonate, where fluorite does not control fluorine's solubility.

Table G1. Fluorine concentrations in various types of rocks.

[Without extremes** means that statistical outliers have not been included in calculating the mean. They are shown as part of the range. no., number; ppm, part per million; b.d.l., below method detection limit; —, no data]

Rock type (location)	No. of samples	Fluorine concentration (ppm)		Source(s)[1]
		Range	Mean	
Igneous rocks—Intrusive				
Alkalic ultramafic	7	200 to 2,700	1,100	3, 10
Gabbro, diabase	26	50 to 1,100	420	6
Granodiorite and granite, without extremes**	93	20 to 2,700	810	6
Tertiary intrusives, diorite to granite (central Colorado), without extremes**	592	90 to 33,900	1,170	15
Alkalic intrusives	65	200 to 2,250	1,000	6
Alkalic intrusives	100	—	2,640	13
Granite (mostly Silver Plume, central Colorado), without extremes**	459	70 to 260,000	1,100	15
Granite, (mostly Pikes Peak, central Colorado), without extremes**	284	60 to 170,000	1,116	15
Igneous rocks—Extrusive				
Picrite basalts, (Eastern Rift, Kenya and Tanzania)	5	480 to 1,400	904	11
Olivine basalts (Eastern Rift, Kenya and Tanzania)	18	290 to 1,300	900	11
Basalt	130	20 to 1,060	360	6
Andesite	77	b.d.l. to 780	210	6
Andesite	85	—	630	13
Phonolite	14	860 to 1,490	930	6
Phonolite (Eastern Rift, Kenya and Tanzania)	2	2,100 to 2,200	2,150	11
Trachyandesite (Eastern Rift, Tanzania)	1	—	1,400	11
Nephelinites (Eastern Rift, Kenya and Tanzania)	20	1,000 to 4,900	2,480	11
Peralkaline trachyte (Eastern Rift, Kenya and Tanzania)	4	1,700 to 3,600	3,070	12
Melilite, leucitite, and carbonatite (Western Rift, Uganda)	4	1,400 to 3,000	2,500	1, 4
Alkali rhyolite (Eastern Rift, Kenya)	4	1,700 to 6,800	3,870	2
Metamorphic rocks				
General metamorphic	69	60 to 1,500	380	6
Schists and gneisses (central Colorado, mostly Idaho Springs Formation), without extremes**	816	50 to 81,000	1,180	15
Sedimentary rocks				
Sandstones, without extremes**	49	10 to 880	180	6
Graywacke	17	—	40	8
Carbonaceous or dark sandstones	11	—	400	8
Varicolored sandstones	23	—	320	8
Pale, nearly white, sandstones	12	—	280	8
Shales, without extremes	79	10 to 7,600	800	6
Pierre Shale	22	560 to 880	682	5
Limestones, without extremes**	98	b.d.l. to 1,210	220	6
Dolostones	14	110 to 400	260	6
Anhydrite rock	3	b.d.l. to 350	121	7
Halite rock	7	b.d.l. to 130	31	7
Phosphorite (Phosphoria Formation, United States)	60	—	31,000	9
Phosphorite (8 mining areas worldwide)	8	30,500 to 41,000	36,560	14

[1] Sources of analyses: 1, Holmes and Harwood (1932); 2, Bowen (1937); 3, Higazy (1954); 4, von Knorring and DuBois (1961); 5, Tourtelot (1962); 6, Fleischer and Robinson (1963); 7, Stewart (1963); 8, Pettijohn (1963, p. S16); 9, Gulbrandsen (1966); 10, Bell and Powell (1969); 11, Gerasimovskiy and Savinova (1969); 12, MacDonald and others (1970); 13, Shawe (1976); 14, Cheney and others (1979); and 15, Wallace (2010).

Table G2. Concentrations of fluorine and other elements in waters.

[Deposit types: 1. carbonatite-related, 2. alkaline-intrusion-related, 3. alkaline-volcanic-related epithermal, 4a. Mississippi Valley-type (MVT), and 4b. salt-related carbonate-hosted. Chemical abbreviations: F, fluorine; CO_3, carbonate; HCO_3, bicarbonate; HF, hydrogen fluoride; SO_4, sulfate; Cl, chlorine; SiO_2, silica; Ca, calcium; Fe, iron; Mg, magnesium; Na, sodium; K, potassium; Cu, copper; Pb, lead; Zn, zinc; $CaCO_3$, calcium carbonate (calcite). calc'd, value was calculated using SOLVEQ software (Reed, 1982) and assuming charge balance and saturation with quartz, muscovite, dolomite, fluorite, pyrite, and galena or sphalerite. Units of measure: °C, degree Celsius; ppm, part per million; equiv. wt. %, equivalent weight percent; g/kg, gram per kilogram; µS/cm, microsiemens per centimeter. n.a., not applicable; —, not determined or not reported; i.d., identification; no. or n, number]

Sample type and area	Number of samples	Associated deposit type or rock type(s)	pH	Conductivity (µS/cm at 25 °C)	F (ppm)	CO_3, aqueous, dissolved (ppm)	CO_3 (ppm)	HCO_3 (ppm)	SO_4 (ppm)
Natural waters									
River water	—	n.a.	—	—	0.05 to 2.7	—	—	—	—
Seawater	—	n.a.	—	—	0.03 to 1.4	—	—	—	—
Mountain region runoff—Rhoads Fork of Rapid Creek, Black Hills, South Dakota, United States	1	Limestone and alluvium	7.9	466	<0.10	—	—	—	2.2
Near-recharge groundwater in limestone—Site i.d. 440612103152001, Well No. 10 in Madison aquifer, Rapid City, South Dakota, United States	1	Limestone	7.53	343	0.2	—	—	—	11
Basinal groundwater in limestone—Site i.d. 440415101093002, well in Madison aquifer, Midland, South Dakota, United States	1	Limestone	6.69	—	2.8	—	—	150	800
Basinal groundwater in sandstone—Well P17 in Lance/Fox Hills sandstone, Gillette, Wyoming, United States	1	Sandstone	8.18	1,810	3.2	—	2	982	1.6
Groundwater evaporite brine—Well in Paradox sandstone ("post-halite" water), Paradox Basin, Grand County, Utah, United States	1	Sandstone and anhydrite	4.6	95,000	25	—	—	1,010	4
Mineralizing water for MVT fluorspar deposits—From fluid inclusion measured data, and estimates calculated at 120 °C, Illinois-Kentucky fluorspar district, United States	n.a.	Granitic basement, sandstone, and dolostone	4.55 calc'd	—	26 calc'd	(CO_2) 17,589	—		2,558
Measured fluid inclusions in fluorite—"Complex" sedimentary brine at about 140 °C, Berbes subdistrict, Asturias Province, Spain. equiv. wt. % NaCl: 83; cations: 34	1	4b; metamorphic rocks and limestone	—	—	—	—	—	—	—
Surface water—Lake Tulusia of the Momela Lakes, Eastern Rift Valley, Tanzania	1	Alkalic volcanic rocks	—	14,390	437	—	(HCO_3+CO_3) 189		422
Water interstitial to newly precipitated, evaporitic trona and villiaumite—Borehole H4, Lake Magadi, Kenya	1	Trachyte and alluvial sediments	10.4	—	1,610	—	85,400	2,560	973
Hypothetical hydrothermal mineralizing water									
Calculated mineralizing water for MVT fluorspar deposits after adding hypothetical magmatic gas with 0.5 g/kg CO_2 and 0.5 g/kg HF and heating to 300 °C, Illinois-Kentucky fluorspar district, United States	n.a.	4a	3.7 calc'd	—	2,030 calc'd	(CO_2) 20,100 calc'd	—		105 calc'd

Table G2. Concentrations of fluorine and other elements in waters.—Continued

[Deposit types: 1. carbonatite-related, 2. alkaline-intrusion-related, 3. alkaline-volcanic-related epithermal, 4a. Mississippi Valley-type (MVT), and 4b. salt-related carbonate-hosted. Chemical abbreviations: F, fluorine; CO_3, carbonate; HCO_3, bicarbonate; HF, hydrogen fluoride; SO_4, sulfate; Cl, chlorine; SiO_2, silica; Ca, calcium; Fe, iron; Mg, magnesium; Na, sodium; K, potassium; Cu, copper; Pb, lead; Zn, zinc; $CaCO_3$, calcium carbonate (calcite). calc'd, value was calculated using SOLVEQ software (Reed, 1982) and assuming charge balance and saturation with quartz, muscovite, dolomite, fluorite, pyrite, and galena or sphalerite. Units of measure: °C, degree Celsius; ppm, part per million; equiv. wt. %, equivalent weight percent; g/kg, gram per kilogram; µS/cm, microsiemens per centimeter. n.a., not applicable; —, not determined or not reported; i.d., identification; no. or n, number]

Cl (ppm)	SiO_2 (ppm)	Ca (ppm)	Fe (ppm)	Mg (ppm)	Na (ppm)	K (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)	Alkalinity (ppm as $CaCO_3$)	Source(s)[1]
Natural waters—Continued											
—	—	—	—	—	—	—	—	—	—	—	15
—	—	—	—	—	—	—	—	—	—	—	15
3.1	9	66	0.005	23	1	0.6	<0.001	<0.001	<0.003	219	20
1	—	38	—	19	2.6	1.6	0.002	—	0.01	171	20
28	35	270	—	66	25	9.7	—	—	—	—	8
30	17	2.7	17	0.4	370	4	<0.001	0.001	<0.003	—	6
241,000	—	52,700	750	39,200	5,990	18,800	6	6	60	—	1
92,200 calc'd	59	4,994	.00094 calc'd	6,099	42,016	3,310 calc'd	—	0.14 calc'd	0.68 calc'd	—	11
~130,000	—	12,541	—	2,131	48, 987	6,424	—	92	404	—	18
646	5	3.2	—	6.1	4,600	726	—	—	—	—	4
68,400	513	—	—	—	115,000	1,430	—	—	—	—	5
Hypothetical hydrothermal mineralizing water—Continued											
92,200 calc'd	58.5 calc'd	3,930 calc'd	.00094 calc'd	6,020 calc'd	42,016	3,310 calc'd	—	0.14 calc'd	0.68 calc'd	—	11

Table G2. Concentrations of fluorine and other elements in waters.—Continued

[Deposit types: 1, carbonatite-related; 2, alkaline-intrusion-related; 3, alkaline-volcanic-related epithermal; 4a, Mississippi Valley-type (MVT); and 4b, salt-related carbonate-hosted. Chemical abbreviations: F, fluorine; CO_3, carbonate; HCO_3, bicarbonate; HF, hydrogen fluoride; SO_4, sulfate; Cl, chlorine; SiO_2, silica; Ca, calcium; Fe, iron; Mg, magnesium; Na, sodium; K, potassium; Cu, copper; Pb, lead; Zn, zinc; $CaCO_3$, calcium carbonate (calcite). calc'd, value was calculated using SOLVEQ software (Reed, 1982) and assuming charge balance and saturation with quartz, muscovite, dolomite, fluorite, pyrite, and galena or sphalerite. Units of measure: °C, degree Celsius; ppm, part per million; equiv. wt. %, equivalent weight percent; g/kg, gram per kilogram; µS/cm, microsiemens per centimeter. n.a., not applicable; —, not determined or not reported; i.d., identification; no. or n, number]

Sample type and area	Number of samples	Associated deposit type or rock type(s)	pH	Conductivity (µS/cm at 25 °C)	F (ppm)	CO_3, aqueous, dissolved (ppm)	CO_3 (ppm)	HCO_3 (ppm)	SO_4 (ppm)
Fluorspar mining area waters									
Surface runoff, Northern Pennine Orefield, United Kingdom	5	4	—	—	0.05 to 0.17	—	—	—	—
Surface runoff draining mine waste area (with fluorite), Northern Pennine Orefield, United Kingdom	25	4	—	—	0.05 to 2.3	—	—	—	—
Domestic water supplies, Northern Pennine Orefield, United Kingdom	4	4	—	—	0.12 to 0.52	—	—	—	—
Mine waters from the Frazer's Grove fluorite mine and surrounding area, Northern Pennine Orefield, United Kingdom	31 (3 sites)	4	3.8 to 7.6	335 to 3,188	—	—	—	up to 186	34 to 2,501
Surface water upstream of the Frazer's Grove Mine area, United Kingdom	2 (1 site)	4	6.7 to 7.9	89 to 91	—	—	—	16 to 18	9.9 to 17.9
Mine waters from the Moscona Mine, Spain	8	4b	7.6 to 8.2	413 to 1,779	0.5 to 3.5	—	—	—	—
Surface spring from the Moscona Mine area, Spain	1	4b	7.8	451	0.5	—	—	—	—
Surface water upstream of the Moscona Mine, Spain	1	4b	7.9	405	0.5	—	—	—	—
Waste waters from the Moscona Mine, Spain	29	4b	7.3 to 8.9	—	0.27 to 4.8	—	—	—	—
Groundwaters in Coimbatore district, Tamil Nadu, India	5	Granite and granodiorite	—	—	0.8 to 5.9	—	—	—	—
Mine pit water, Chandidongri fluorite mine, Madhya Pradesh, India	1	2	9.0	—	0.3	—	4.0	33.6	15.0
Groundwater near Chandidongri fluorite mine, Madhya Pradesh, India	4	2	7.0 to 9.0	140 to 242	0.04 to 0.4	—	6.0	13 to 88	up to 15
Groundwater in Andhra Pradesh, India	60	Granites	7.5 to 8.7	423 to 1,640	0.78 to 6.1	—	104 to 199	533 to 1,415	22 to 96
Surface water, groundwater, and mine waters, Kerio Valley, Kenya	28 (14 sites)	1, 2, or 3	6.0 to 9.5	42 to 812	0.8 to 306	—	—	—	23 to 66
Mine waters from the Lovozero niobium mine, Russia	10	2	9.6 to 12.0	—	750 to 15,000	—	(HCO_3+CO_3) 1,425 to 2,666 (n=8)		up to 200

[1] Sources: 1, White (1965); 2, Hall and Friedman (1963); 3, Kraynov and others (1969); 4, Kilham and Hecky (1973); 5, Jones and others (1977); 6, Henderson (1985); 7, Fuge and Andrews (1988); 8, Busby and others (1991); 9, Leach and others (1991); 10, Davies (1994); 11, Plumlee and others (1995); 12, Chatterjee and Mohabey (1998); 13, Narayana and others (2000); 14, Johnson and Younger (2002); 15, Kabata-Pendias and Mukherjee (2007); and references therein; 16, Jacks and others (2005); 17, Roqueñí and others (2005); 18, Sánchez and others (2009); and 19, Arveti and others (2011); 20, U.S. Geological Survey (2016).

Table G2. Concentrations of fluorine and other elements in waters.—Continued

[Deposit types: 1. carbonatite-related, 2. alkaline-intrusion-related, 3. alkaline-volcanic-related epithermal, 4a. Mississippi Valley-type (MVT), and 4b. salt-related carbonate-hosted. Chemical abbreviations: F, fluorine; CO_3, carbonate; HCO_3, bicarbonate; HF, hydrogen fluoride; SO_4, sulfate; Cl, chlorine; SiO_2, silica; Ca, calcium; Fe, iron; Mg, magnesium; Na, sodium; K, potassium; Cu, copper; Pb, lead; Zn, zinc; $CaCO_3$, calcium carbonate (calcite). calc'd, value was calculated using SOLVEQ software (Reed, 1982) and assuming charge balance and saturation with quartz, muscovite, dolomite, fluorite, pyrite, and galena or sphalerite. Units of measure: °C, degree Celsius; ppm, part per million; equiv. wt. %, equivalent weight percent; g/kg, gram per kilogram; µS/cm, microsiemens per centimeter. n.a., not applicable; —, not determined or not reported; i.d., identification; no. or n, number]

Cl (ppm)	SiO_2 (ppm)	Ca (ppm)	Fe (ppm)	Mg (ppm)	Na (ppm)	K (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)	Alkalinity (ppm as $CaCO_3$)	Source(s)[1]
Fluorspar mining area waters—Continued											
—	—	—	—	—	—	—	—	—	—	—	7
—	—	—	—	—	—	—	—	—	—	—	7
—	—	—	—	—	—	—	—	—	—	—	7
up to 258	—	52 to 673	<0.1 to 68	9.4 to 215	9.1 to 38	4.9 to 33.7	—	—	<0.1 to 111	—	14
13 to 24	—	6.1 to 8.1	0.5 to 0.6	1.8 to 3.0	5.0 to 6.3	1.1 to 1.6	—	—	0.2	—	14
—	—	—	<0.1	—	—	—	—	—	<0.05 to 2.7	—	17
—	—	—	<0.1	—	—	—	—	—	<0.05	—	17
—	—	—	<0.1	—	—	—	—	—	<0.05	—	17
—	—	—	—	—	—	—	—	—	—	—	17
—	—	—	—	—	—	—	—	—	—	—	16
30.0	—	8.8	—	—	—	—	—	—	—	—	12, 13
10 to 30	36	8.0 to 18	3.6	4 to 5	25.5	1.5	—	—	—	—	12
10 to 96		22 to 90		26 to 99	25 to 234	5 to 16	—	—	—	832 to 1,920	19
11 to 48	16 to 67	—	0.1 to 0.8	—	—	—	0.01 to 0.08	—	—	26 to 414	10
8 to 85	140 to 13,000	up to 1	—	0.6 to 140	3,680 to 26,000	35 to 250	0.3 to 0.9 (n=3)	0.02 to 0.03 (n=3)	0.4 (n=1)	—	3

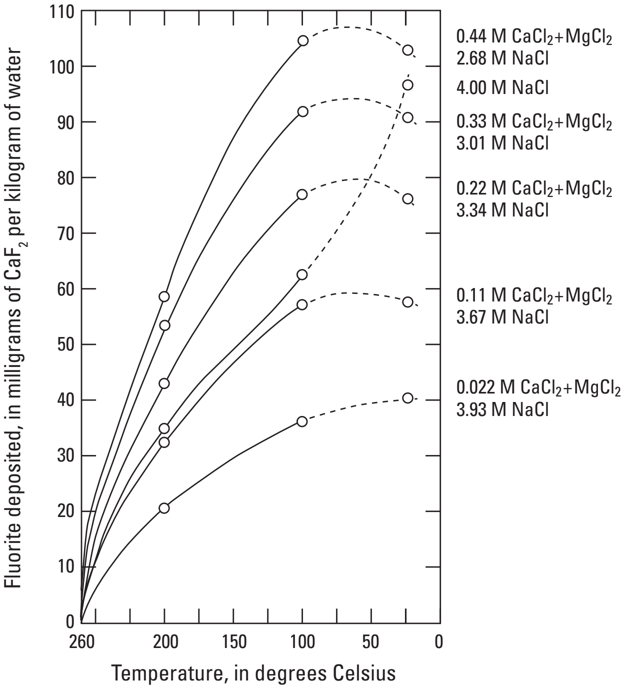

Figure G2. Graph showing the solubility of fluorite (CaF_2) as a function of temperature for complex Na-Ca-Mg-Cl (sodium-calcium-magnesium-chloride) brines from ambient temperatures (25 degrees Celsius [°C]) to 260 °C. Total ionic strength for each combination of salts was 4 moles per liter. At each molarity (M) of $CaCl_2$ + $MgCl_2$, the ratio of calcium to magnesium was 9 to 1. Curvatures in the dashed parts of the curves are inferred. Except for pure sodium chloride (NaCl) brine compositions, the solubility curves at different complex chloride salt molarities all have a maximum temperature of fluorite deposition below which the solubility (the opposite of deposition) of fluorite increases with decreasing temperature. At those temperatures (those below the maximum temperature of fluorite deposition), fluorite is said to have retrograde solubility; that is, fluorite solubility increases as temperature decreases. First, temperatures near the laboratory maxima of fluorite deposition have commonly been measured in fluid inclusion microthermometry studies of actual fluorspar deposits (for example, Richardson and Pinckney, 1984). Second, the retrograde solubility at low temperatures is explanation for relatively high concentrations of fluorine in water measured in several surface water or shallow groundwater environments (for example, Lake Magadi, Kenya; Jones and others, 1977). Graph is from Richardson and Holland (1979, fig. 5). $CaCl_2$, calcium chloride; $MgCl_2$, magnesium chloride

Mineralogy

Figure G3*A* shows the eight possible ore minerals or mineral groups that are fluorine-rich and either are, were, or might someday become fluorine ore minerals. Although all eight are possible ore minerals of fluorine, at present only deposits of fluorite are mined specifically for their fluorine content.

Bastnaesite (hexagonal (Ca,La,Nd)(CO_3)F) is representative of several fluoro-carbonate minerals that occur in or are associated with carbonatites and alkaline ultramafic igneous complexes. Bastnaesite is the major mineral from which rare-earth elements (REEs) are recovered at a number of carbonatites around the world, including at the Mountain Pass Mine in California. The Mountain Pass Mine was the world's leading producer of REEs from the 1960s to the 1980s and the sole mine that commercially produced REEs in the United States in the latter half of the 20th century. The mine was closed in 2002 but opened again in 2010; it was then placed on care-and-maintenance status in 2015 (Molycorp, Inc., 2015a, b). Mountain Pass does not recover fluorine from the bastnaesite.

Cryolite (monoclinic $Na_3(AlF_6)$) is a mineral that is seldom found outside of pegmatites. It was produced as a fluorine source from the Ivigtut pegmatite in Sermersooq municipality, Greenland, until 1987, when mining there ceased (Singleton, 1989, p. 273).

Sellaite (tetragonal MgF_2) is mined at the Suran 1 deposit in the southern Ural Mountains in Russia, and fluorine is recovered from it. The same deposit contains much larger tonnages of fluorite, and the sellaite occurs only where the fluorine-bearing hydrothermal solutions encountered magnesium-rich diabase (that is, shallowly intrusive basaltic rock) in the fault or vein walls (Ellmies and others, 1999). Apparently, the magnesium in the basaltic wall rock was used in precipitating sellaite, rather than fluorite. The situation is not geologically unique; sellaite is found in several different fluorite-bearing deposits in dolomite host rocks—for example, at Mount Bischoff, Tasmania, Australia (Kwak and Askins, 1981); at the Shepherd and Murphy Mine in the Moina district, Tasmania, Australia (Bottrill and Baker, 2008); at the Xianghuapu Mine in Linwu County, Hunan Province, China (Yuzhou, 1990); and at the Yaroslavskoye tin deposit in Primorskiy Kray, Russia (Bailey, 1980). In all these cases, magnesium from the dolomite was probably used in precipitating sellaite in preference to fluorite. In a few other occurrences, sellaite is found in rocks where calcium had earlier been removed by hydrothermal alteration, thus favoring the sellaite over fluorite (Imai and others, 1985; Pfaff and others, 2012).

Villiaumite (isometric NaF) occurs within trona (monoclinic $Na_3(HCO_3)(CO_3)\bullet 2H_2O$,) in eastern Africa. Trona is the raw material for sodium carbonate (that is, washing soda or soda ash). In some valleys of the East African Rift system, trona is precipitating because of evaporation of the closed basin lakes. With high enough concentrations of villiaumite in the trona ore, it could become a feasible byproduct and might be recovered as a source of fluorine. The trona deposits of eastern Africa are located close to peralkaline to alkaline volcanic rocks. An analysis of water pumped from within newly precipitated Lake Magadi trona is given in table G2.

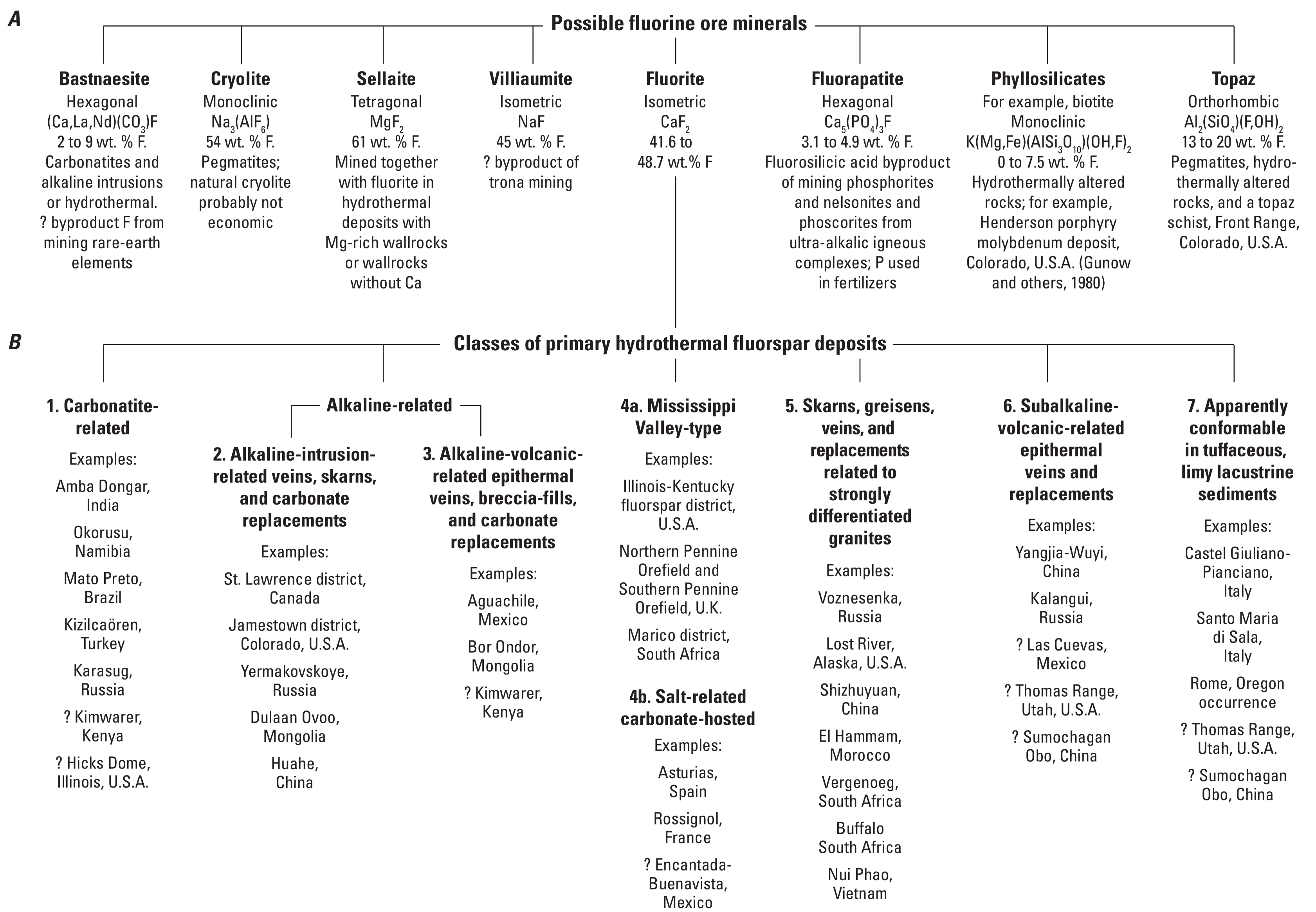

Figure G3. Chart showing *A*, eight minerals or mineral groups from which fluorine has been produced or may be produced in the future, and *B*, a preliminary classification of hydrothermal fluorspar deposits by tectonic and magmatic association. Ca, calcium; F, fluorine; Mg, magnesium; P, phosphorus; U.S.A., United States of America; wt. %, weight percent; ?, possible

Fluorite is the most common mineral that contains high concentrations of fluorine (fig. G3). Fluorite is typically almost transparent, and it has perfect octahedral cleavage. It is softer than quartz, harder than calcite, and unreactive in weak acids, so it is typically readily distinguishable from calcite and quartz, with which it is commonly associated. Fluorite occurs as a minor gangue mineral in many types of hydrothermal ore deposits; for example, epithermal gold, silver, and uranium deposits; porphyry molybdenum (± tungsten) deposits; pegmatites; iron oxide-copper-gold deposits; and typically zinc-dominated Mississippi Valley-type (MVT) deposits. In the deposit types shown in figure G3*B*, fluorite is the major economic mineral, although coproduct or byproducts Au, barite, Be, Bi, Cu, Li, Mo, Nb, Pb, REEs, Sb, Sn, W, and Zn, can be found in the various types of fluorspar deposits.

In many fluorspar deposits, it is clear that fluorine in a hydrothermal solution reacted with calcium from the wall rocks to form fluorite. In limestone wall rocks, the reaction for fluorite precipitation can be modeled as follows:

$$2\,HF + CaCO_3 \rightarrow CaF_2 + H_2O + O_2$$

Where the above reaction occurs and calcium is conserved (because the density of calcite is 2.71 grams per cubic centimeter [g/cm^3] and the density of fluorite is 3.18 g/cm^3), new open space (or porosity) results. In fact, at standard temperature and pressure, about 15 percent of the original limestone (calcium carbonate [$CaCO_3$]) volume becomes new porosity. New crystals of fluorite grow into the open space as terminated crystals, and the result is that, in most carbonate replacement deposits, fluorite occurs as well-formed cubic or cube-octahedral crystals (fig. G1) of many different colors; blue, green, purple, white, yellow, and clear are typical. Reactions similar to (1) can be written for other calcium sources, such as dolomite or plagioclase, most with the effect that new porosity is created if calcium is conserved.

Fluorapatite (hexagonal $Ca_5(PO_4)_3F$) currently accounts for only minor amounts of fluorine production, but it constitutes a very large potential supply if needed in the future. Fluorapatite is the major mineral in sedimentary phosphorite deposits, which typically have a fluorine grade of 2 to 4 weight percent fluorine. Phosphorite is a sedimentary rock composed principally of phosphate minerals. Phosphorite deposits can exceed 1 billion metric tons of ore. Phosphorites are mined in many places in the world as a source of fertilizer. Byproduct fluorine is already captured at some of the operations and is either converted to synthetic cryolite (a form in which it can be used readily in aluminum refining) or to fluorosilicic acid for use in drinking water fluoridation. Currently, the supply of fluorine obtained from phosphorites is determined by the demand for fertilizer—once the fertilizer demand is met, no additional byproduct fluorine is produced.

Fluorine is found in a number of silicate minerals, but, apparently, no feasible process to recover fluorine from any silicate structure has been developed. Topaz (orthorhombic $Al_2(SiO_4)(F,OH)_2$) is a fluorine-bearing mineral found in pegmatites, some hydrothermally altered rocks, and an apparently unique topaz-rich schist in Colorado's Front Range (Sheridan and others, 1968).

Fluorine occurs in at least trace concentrations in most mica and clay (phyllosilicate) minerals; biotite (monoclinic $K(Mg,Fe)_3(AlSi_3O_{10})(OH,F)_2$) (fig. G3*A*) is one example of fluorine in phyllosilicates. In the phyllosilicates, fluorine substitutes for the OH^- ion in interlayer sites between the sheets of linked alumina octahedrons and silica tetrahedra. Theoretically, it should be easier to recover fluorine from such mineralogic sites than from topaz, in which the fluorine and hydroxyl ions link together adjacent alumina octahedrons; however, the relatively small amount of fluorine available in the phyllosilicates (fig. G3*A*) discourages any attempts to recover fluorine from them. The maximum amount of fluorine measured in phyllosilicates to date is 7.5 weight percent from biotite from a hydrothermal vein from the Henderson porphyry molybdenum deposit in Clear Creek County, Colorado (Gunow and others, 1980).

Deposit Types

Fluorspar deposits occur in a wide variety of geologic environments. The lower part of figure G3 (fig. G3*B*) is a preliminary classification of hydrothermal fluorspar deposits by their tectonic and (or) magmatic environments. All seven of the classes are hydrothermal, but there is a great variation of fluid temperatures and compositions among them, and they clearly represent various tectonic and magmatic settings, although there is some ambiguity in classification of certain deposits. The seven classes of primary hydrothermal fluorspar deposits shown in figure G3*B* are discussed below.

Worldwide, many fluorspar deposits are found closely associated in space with igneous rocks of several different types. Understanding distinctions between several types of igneous rocks is needed in order to recognize the various magmatic and tectonic environments that are represented. Following are explanations for the terms subalkaline, peralkaline, alkaline, and carbonatitic, with generalities about the tectonic environments represented by each of these compositional types of igneous rocks.

Peralkaline igneous rocks are igneous rocks in which the molecular proportions of sodium and potassium exceed the proportions of aluminum (molar $Na_2O + K_2O > Al_2O_3$). In such rocks, the amounts of sodium and potassium are greater than can be accommodated in sodium and potassium feldspars and must be taken up in other crystallizing minerals; for example, aegerine (monoclinic $NaFeSi_2O_6$, a pyroxene mineral) or riebeckite (monoclinic $Na_2(Fe^{2+}, Mg)_3Fe_2^{3+}Si_8O_{22}(OH)_2$, an amphibole mineral). Subalkaline rocks are those that have more than enough aluminum to make the sodium and potassium feldspars, with the excess combining with calcium and silica to crystallize calcium-bearing plagioclase. In most alkaline rocks, however, the molecular proportions of sodium and potassium are so great that not even the minerals with anomalously high levels of sodium and potassium—that is, sodic and potassic pyroxenes and amphiboles, such as aegerine and riebeckite, respectively—can take up the excess of alkali molecules; consequently, minerals called feldspathoids, such as nepheline (hexagonal $(Na,K)AlSiO_4$), sodalite (isometric $Na_4(Si_3Al_3)O_{12}Cl$), leucite (tetragonal $K(AlSi_2)O_6$), and melilite (tetragonal $(Ca,Na)_2(Al,Mg)(Si,Al)_2O_7$), which have more alkalies and aluminum than do feldspars, crystallize instead of the alkali feldspars. Alkaline melts also commonly have concentrations of silica (SiO_2) that are too small to make any quartz after the crystallization of feldspars or feldspathoids; these melts are thus termed “undersaturated.” The end member of the alkaline rocks has very little silica at all. These are carbonatites—rare igneous rocks that are composed of more than 50 volume percent carbonate minerals that crystallized from a magma. Carbonatites occur together with syenites and other nepheline-rich intrusive rocks in complexes within which the carbonatite is typically the last rock type intruded.

As a gross generality, subalkaline igneous rocks are the dominant types intruded or erupted in both continental and island arcs along convergent plate boundaries, most peralkaline rocks are instead unrelated to active compressional orogenies at convergent plate margins (they are “anorogenic”), and alkaline igneous rocks and carbonatites are found intruded through mostly thick continental crust remote from convergent margins. Both the anorogenic peralkaline intrusives and the alkaline complexes may relate broadly or directly to rifts through continental crust.

For each different type of magmatic association—subalkaline, peralkaline, alkaline, or carbonatitic—the associated fluorspar deposits are, almost without exception, related to the most differentiated (latest intruded and crystallized, least iron and magnesium-rich, and most silica rich for other than the carbonatites) igneous rocks of the igneous province. So, for subalkaline magmatic provinces, the fluorspar deposits are found almost exclusively with granites that have high contents of incompatible elements. The granites associated with the fluorspar deposits typically have only biotite as a ferromagnesian mineral. For the peralkaline anorogenic igneous provinces, the fluorspar deposits are also associated with granites, particularly aegerine granites and riebeckite granites. For the alkaline complexes, the fluorspar deposits are most closely related to syenites, and only rarely to trachytes, or pyroxene-nepheline rocks. And for the carbonatite complexes, the fluorspar deposits are found most closely associated with the carbonatites themselves.

For association with volcanic rocks rather than intrusive rocks, the situation is parallel. The fluorspar deposits are nearly ubiquitously associated with rhyolites. They are nearly nowhere associated with the basalts.

Carbonatite-Related Fluorspar Deposits

Fluorite deposits associated with carbonatites and other ultra-alkaline rocks occur on every continent (fig. G4). In such deposits, it is common that the carbonate (commonly calcite) that makes up the carbonatite is partially replaced or veined by fluorite or is cut by a stockwork of fluorite veinlets. The country rock in contact with carbonatite may be altered (fenitized) by hydrothermal fluids and also mineralized with fluorite. At the Fission (Richardson) deposit in Ontario, Canada, and the Speewah deposit in Kimberley, Western Australia, Australia, the deposits have the general form of a vein or dike, although the carbonate minerals appear to be igneous and to contain minerals that are distinctive to igneous carbonatites, such as bastnaesite, parisite (rhombohedral $Ca(Ce,Nd,La)_2(CO_3)_2$), or pyrochlore (isometric $(Na,Ca)_2Nb_2O_6(OH,F)$). Two examples of carbonatite-associated fluorspar deposits that have been well studied are the Okorusu deposit located in the Otjozondjupa Region of Namibia (Kogut and others, 1997; Shivdasan-Gebhardt and Hagni, 2008) and the Amba Dongar deposit located in Gujarat State, India (Deans and others, 1972; Gwalani and others, 1993; Simonetti and Bell, 1995; Simonetti and others, 1995; Palmer and Williams–Jones, 1996; Doroshkevich and others, 2009). At the Amba Dongar deposit, studies of the fluid compositions (Palmer and Williams-Jones, 1996) and the radiogenic isotopes (Simonetti and Bell, 1995) suggest that, despite temperatures of fluorite mineralization of 160 °C and less, there was a small component of igneous-derived magmatic water mixed with dominant meteoric water (that is, groundwater derived ultimately from rain and recharged from the surface) in the mineralizing fluids.

Alkaline-Intrusion-Related Fluorspar Deposits

Alkaline-intrusion-related fluorspar deposits are fluorite-bearing deposits that are in close spatial association with granites that contain aegerine and (or) riebeckite, or are in association with syenites, any of those igneous rocks commonly being porphyritic (Teng and Strong, 1976; Lykhin and others, 2010). A distinction is arbitrarily drawn between these types of deposits and a large number of other fluorspar deposits that are associated with extrusive alkali rhyolites or trachytes (that is, volcanic equivalents of syenites) where intrusive rocks are not found nearby. It is somewhat common for deposits of both classes to contain either bertrandite or phenakite and, at some places, lithium minerals, such as lithium-rich white mica (Lykhin and others, 2010; Obolenskiy and others, 2010). Some also contain economic concentrations of niobium, REEs, tantalum, and zirconium (Kovalenko and Yarmolyuk, 1995). The Yermakovskoye deposit in Buryatiya Republic, Russia, which was the first of the Russian alkaline- intrusion-related deposits to be mined, has small skarns—that is, bodies of calcium-silicate minerals with additional valuable minerals that have replaced limestone adjacent to intrusive rocks—and bodies with veinlet stockworks of fluorite-phenakite or of fluorite-bertrandite, and in which the fluorite commonly totals 20 volume percent (Kislov and others, 2010; Lykhin and others, 2010). Phenakite is rhombohedral Be_2SiO_4, and bertrandite is orthorhombic $Be_4Si_2O_7(OH)_2$, so these deposits are commonly also deposits

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

Figure G4. World map showing locations of selected fluorspar deposits according to their tectonic and magmatic class as listed in figure G3*B*.

of beryllium. Other alkaline-intrusion-related deposits are located in the St. Lawrence district in Newfoundland, Canada, where large, discrete fluorspar veins cut across peralkaline granite (Van Alstine, 1944). Other districts, such as the Jamestown district in Boulder County, Colo., have ore contained mainly in breccia bodies that may grade laterally to veins (Goddard, 1946). Studies suggest that the fluids that formed these deposits had temperatures that ranged from 500 °C down to about 100 °C (Nash and Cunningham, 1973; Strong and others, 1984). The fluids also had a great range of salinities. Those results and oxygen isotope studies suggest that the mineralizing fluids were mixtures of magmatic and meteoric waters, and the relatively high contents of REEs in the fluorite supports that conclusion (Strong and others, 1984). At Yermakovskoye, magmatic fluids have been well documented (Reyf, 2004, 2008) and include (a) a magmatic brine highly enriched in beryllium, manganese, and molybdenum, with additional cerium, lanthanum, lead, and zinc concentrations, and (b) a carbon dioxide (CO_2)-rich fluid enriched only in beryllium with a homogenization temperature of between 335 and 355 °C and relatively low salinity of 2.4 to 8.2 equivalent weight percent NaCl. These two fluids seem likely to be the products of the boiling of a common ancestor hydrothermal fluid.

Alkaline-Volcanic-Related Epithermal Fluorspar Deposits

Northern Mexico and Kenya have fluorspar deposits and occurrences that are related to alkaline volcanic rocks. Examples of such deposits are located at Aguachile, Coahuila de Zaragoza, Mexico (McAnulty and others, 1963), and at Kimwarer, Elgeyo/Marakwet County, Kenya (Nyambok and Gaciri, 1975). These deposits are also in contact with or are hosted by carbonates (limestone or calcite marble). The igneous rock type that is most closely associated in time with ore at Aguachile is rhyolite porphyry, which occurs in a ring dike around a central plug of quartz-microsyenite porphyry. The microsyenite contains 7 volume percent riebeckite and another 8 volume percent chlorite that is an alteration product of former riebeckite (Levinson, 1962). Several other small districts are related to similar rocks in Coahuila de Zaragoza, Mexico, as, perhaps, are the deposits of the very large Encantada-Buenavista district of Mexico (Temple and Grogan, 1963; Kesler, 1977; González-Partida and others, 2003). Fluorspar deposits in the Eagle Mountains of Hudspeth County, Texas, are related to igneous rocks of the same igneous province (Gillerman, 1948). The Hidalgo del Parral district in Chihuahua, Mexico, is also related to alkali rhyolites (Pickard, 1974).

The Kimwarer deposits in Kenya, though hosted in Precambrian calcite marbles and other gneissic rocks, are most closely related in time to Tertiary phonolites of the East African Rift volcanic rocks (Nyambok and Gaciri, 1975). Phonolite is a volcanic rock that consists essentially of alkali feldspar and a feldspathoid mineral (the feldspathoid mineral is nepheline for the rocks near Kimwarer). Because the phonolites are not in contact with fluorspar ore anywhere at Kimwarer, it is possible that these deposits are instead related to unexposed (still buried) carbonatitic rocks. Carbonatites are found in several places in or near the East African Rift valleys. In these volcanic-related deposits, low temperatures and generally low salinities suggest that the mineralizing fluids were dominated by meteoric waters. Fluid inclusion homogenization temperatures are generally no greater than 175 °C, and salinities are commonly less than 10 equivalent weight percent NaCl (Kesler, 1977; González-Partida and others, 2003). Although intrusive rocks may be present, they may have served only as heat sources to cause convection of the groundwaters through fluorine-rich alkali rhyolite source rocks. Alternatively, and more likely, the magmas that contributed to the volcanic rocks also evolved a late-stage water-rich phase, which contributed to the mineralizing waters and thus at least small amounts of magmatic components to the deposits. Although the conditions and chemistry of the hydrothermal fluids were generally similar throughout this class, the geometry of mineralized bodies varies greatly. Some are discrete, large veins (Kimwarer). Others are carbonate-hosted breccia pipes or breccias along contacts with intrusions (Aguachile). Yet others are peneconformable replacement bodies in carbonates, which are known in the United States as bedding-replacement deposits (Weller and others, 1952; Gillerman, 1948) and in Spanish-speaking countries as mantos (for example, the Encantada-Buenavista district in Mexico; Temple and Grogan, 1963). A peneconformable configuration means that the replacement bodies lie within and parallel to the bedding of the sedimentary host rocks, yet have lateral boundaries that cut across those host rocks.

Some have suggested that other fluorspar deposits of the Western United States and Mongolia are related to alkaline volcanic rocks (Lindsey, 1982; Lkhamsuren and Hamasaki, 1998), but there is some doubt that the associated volcanic rocks should truly be called alkaline in the sense that the word is used above. Lindsey (1982) describes the deposits of the Thomas Range, Utah, as being related to rhyolites of the latest magmatic stage in the area—those rocks typically have a peralkaline composition. The rhyolites of the Thomas Range (the Topaz Mountain rhyolites) have phenocrysts of sanidine, biotite, and plagioclase, and lack any aegerine or riebeckite. They are alkali feldspar rhyolites, but the rocks are probably not truly of the alkaline series as that term is used above in defining the distinction between subalkaline, peralkaline, and alkaline.

The deposits of the Thomas Range are probably better assigned to the class of epithermal deposits related to subalkaline volcanic rocks (see below in the section titled Subalkaline-Volcanic-Related Epithermal Fluorspar Deposits). The rhyolite associated with fluorspar deposits in the Thomas Range contains topaz phenocrysts; it is very fluorine-rich. Some well-known fluorspar deposits in Colorado—in the Browns Canyon district of Chaffee County (Van Alstine, 1969) and in the Northgate district of Jackson County (Steven, 1960)—are also most closely associated in time with topaz rhyolites, which are not rocks in the alkaline series (Burt and others, 1982); hence, those deposits are also probably best assigned to the class of epithermal deposits related to subalkaline volcanic rocks. The topaz rhyolites of western North America do not, however, date from times of the major andesitic volcanic fields and granodiorite batholiths like those of the Sierra Nevada Range. Rather, they post date such rocks in each area where they occur, and they belong to groups of rocks believed to have formed by partial melting of continental crust. Numerous deposits in Mongolia are described as being related to “trachytic rhyolite” and “rhyolite differentiated from trachy-basalts” (Lkhamsuren and Hamasaki, 1998). Whereas true trachytes (volcanic rocks containing alkali feldspar, minor iron-magnesium-silicate minerals, minor plagioclase, and no quartz) typically are alkaline, the term “trachytic” describes a texture of lath-shaped phenocrysts of alkali feldspar that are subparallel to one another in a volcanic rock; the texture does not require the rocks to be truly alkaline. The Late Mesozoic Mongolian volcanic rocks are not described as riebeckite- or aegerine-bearing, and those volcanic rocks again include some topaz rhyolites (Kovalenko and others, 1971). The very fluorine-rich topaz rhyolites are seemingly the rocks that are the most closely associated with fluorspar deposits. Bulnayev and Kaperskaya (1995) demonstrated that fluorspar deposits in Mongolia are most frequently associated with rhyolites among the volcanic rocks there.

Mississippi Valley-Type Fluorspar Deposits

Mississippi Valley-type (MVT) deposits of lead-zinc(-fluorspar-barite) are among the best understood of all hydrothermal ore deposits. These deposits formed in carbonate aquifer rocks where there was interaquifer groundwater mixing of the following two brines: (a) a metalliferous and (or) fluorine-rich brine that escaped upward from a confined lower aquifer under artesian pressure, and (b) a second brine, probably more sulfide-rich (Wenz and others, 2012), that migrated laterally, also under artesian pressure, and was confined above, typically by a shale bed (Plumlee and others, 1994, 1995; Bouch and others, 2006; Stoffel and others, 2008; Ingebritsen and Appold, 2012; Wenz and others, 2012). Both brines likely had their origins as deep basinal groundwaters. A variety of geohydrologic situations allow the brine of the lower aquifer to escape confinement and rise to mix with the second brine in the upper aquifer. The simplest situation that leads to mixing may be where fracturing connects the two aquifers, as in a vein deposit or a breccia body, regardless how the breccia originated. A second and very important mixing situation is where a confining bed pinches out laterally between the two aquifer units (a “shale edge”). Upward escape of lower-aquifer fluids will be focused adjacent to the pinched-out confining bed. This can result in very large deposits arrayed along and above the pinchout, stratigraphically at the level of the upper aquifer; this is the situation with most of the ores of the Southeast Missouri lead district, the Tri-State (Missouri-Kansas-Oklahoma) district, and the Pine Point district in the Northwest Territories, Canada (Brockie and others, 1968; Rhodes and others, 1984; Palmer and Hayes, 1989). A number of other geohydrologic situations allow the fluids of the lower aquifer to escape and mix with the groundwater of upper aquifers, but these situations are less common. The studied brine mixtures (represented by fluid inclusions) from MVT deposits originated by evaporation of seawater, but the mixed fluids also show effects from dolomitization and sulfate reduction along the travel paths and generally show only small amounts of salt redissolution (Viets and others, 1997).

The type of deposits that occur in the Mississippi Valley in the United States resulted from water in gravity-driven regional groundwater flow systems that affected many tens of thousands of cubic kilometers of rock, with recharge in or near collisional orogenic mountain belts like the Ouachita Mountains (Leach and Rowan, 1986). Fluids traveled down through deep basins, then up, driven by artesian pressure from the elevated recharge area, across the cratonic margins towards the craton centers. The regional nature of the mineralizing systems is demonstrated in places where the sequence of mineral precipitation (that is, the paragenesis) of hydrothermal minerals that have partially filled many different kinds of rock porosity can be correlated from MVT district to district, and through all of the former aquifer rocks in between, across hundreds of kilometers (Hayes and others, 1990; Hayes and Anderson, 1992).

Districts of the MVT class that contain significant amounts of fluorite account for 3 of the 10 largest sources of fluorspar in the world (appendix G1). These are the Illinois-Kentucky fluorspar district in the United States, the Northern Pennine Orefield and the Southern Pennine Orefield in the United Kingdom, and the Marico district of North West Province, South Africa.

Richardson and Pinckney (1984) established that oscillatory growth layering in fluorite crystals within the Cave-in-Rock subdistrict (Hardin County, Illinois) of the Illinois-Kentucky fluorspar district could be correlated from mine to mine throughout an area of about 8.5 by 2.5 kilometers (km). By correlating generations of hydrothermal carbonates, Hayes and Anderson (1992) extended the correlation of hydrothermal minerals throughout the Illinois-Kentucky fluorspar district, then correlated that paragenesis with that of the Central Tennessee (Elmwood-Gordonsville) zinc district, and with the paragenesis of the Central Kentucky district. The total area with correlatable paragenesis of hydrothermal minerals partially filling the former porosity in carbonates from Early Ordovician through Mississippian age is 600 km east-west by 300 km north-south and averages slightly more than 2 km thick, thus yielding about 350,000 cubic kilometers of rock affected by this single MVT system (Hayes and Anderson, 1992). The correlations may extend even farther—perhaps to the Upper Mississippi Valley district in southern Wisconsin (Heyl and West, 1982) and to the Findlay arch in northwestern Ohio (Carlson, 1983). The Illinois-Kentucky-Central Tennessee MVT system differs markedly from that of the Ozark Region of southern Missouri, northern Arkansas, southeastern Kansas, and northeastern Oklahoma, however, where no fluorite is found. Furthermore, in the Illinois-Kentucky fluorspar district, thin dikes and sills of mafic igneous rock are fairly numerous and a few small plugs of intrusive breccia occur. Hicks Dome in the northwestern portion of the district is thought to be underlain by a larger related igneous body, but that remains unproven.

In the Illinois-Kentucky fluorspar district, the dikes and sills are likely near-surface indicators of larger igneous masses at depth, and the igneous rocks related to these dikes are likely the cause of the district's unique richness in fluorine among the MVT deposits. This district hosts 62 known dikes and sills that are 1 to 12 meters (m) thick and intruded along faults or bedding planes. It also hosts eight known "diatremes" (brecciated volcanic pipes) that are approximately upright and cylindrical with diameters from a few tens of meters to nearly 200 m (Denny and others, 2008; Anderson and Sparks, 2012).

Almost all the district's igneous rocks studied to date were originally ultramafic and alkalic. Where fresh, the dike and sill rocks are dark green and porphyritic to inequigranular. Their major primary minerals are olivine, phlogopite, melilite, garnet, apatite, perovskite, and magnetite with secondary serpentine, chlorite, and iron-rich calcite. Differentiates from the magmas that produced these dikes would be expected to be syenites and perhaps could include carbonatite. The xenoliths in the diatremes include aegerine syenite (Bradbury and Baxter, 1992, p. 15), and the rocks in places are nepheline-bearing (Lewis and Mitchell, 1987). The neodymium-samarium isochron age of MVT fluorite mineralization from five mines in the Cave-in-Rock subdistrict is 277.0±15.6 mega-annum (Ma), or million years before present (Early Permian) (Chesley and others, 1994), which overlaps entirely the four best-dated igneous rocks in the district that would together give an age range of 266.5 to 273.4 Ma (Early Permian), inclusive of all uncertainties (Reynolds and others, 1997; Fifarek and others, 2001). Where the igneous rocks are in contact with MVT mineralization, the phlogopite of the igneous rocks is hydrothermally altered to illite.

Hicks Dome appears to be the thermal center for hydrothermal mineralization in the Illinois-Kentucky fluorspar district. Deep drilling at Hicks Dome has encountered mineralization with elemental and mineralogical signatures that suggest alkalic igneous rock and possibly carbonatite, which agrees with the widespread but small occurrences of alkaline ultramafic rock in the greater district. The dome is underlain at depths of from 450 m to perhaps 1,000 m by fluorite-barite-cemented breccias that contain anomalous concentrations of Be, Nb, Th, Ti, Y, and REEs (Brown and others, 1954; Kirkemo, 1978). Across the district, fluid inclusion homogenization temperatures in fluorite from growth zones late within the sequence of banding described by Richardson and Pinckney (1984) decline regularly from the center of Hicks Dome (175 °C), to the flanks of the dome (150 °C), to the Cave-in-Rock subdistrict (150 to 132 °C), to mines central to the district in Kentucky (130 to 120 °C), to the southern margin of the district (128 to 117 °C), to the most distant outliers of the district (<50 °C?) (Taylor and others, 1992). This concentric zonation of homogenization temperatures around Hicks Dome has the same generally concentric form as contours of lead isotopes from galena (Heyl and others, 1966) and contours of silver and antimony content of galena (Hall and Heyl, 1968). Thus, the Illinois-Kentucky fluorspar district records a single large mineralizing system that was likely influenced in some way by magmatism at or near Hicks Dome. It is not inferred that magmatic fluids migrated outward from Hicks Dome; only that it was the highest temperature area of the district and probably has intrusive rocks at depth.

Plumlee and others (1995) used reaction path modeling to try to better understand the Illinois-Kentucky fluorspar district. They modeled a mineralizing fluid that had the measured compositions for major elements from fluid inclusions in fluorite (Hall and Friedman, 1963; Richardson and others, 1988) and assumed saturation with respect to dolomite, quartz, muscovite, pyrite, sphalerite, galena, and fluorite at 120 °C and a pH of 4.55. They could not reproduce the district's MVT ores in terms of phase abundance or paragenesis until they modeled the addition of 0.5 gram of HF and 0.5 gram of CO_2 to each kilogram of the initial fluid. In the HF- and CO_2-modified models, they found that any or all of the following resulted in copious amounts of fluorite precipitation: (a) cooling the fluid from 150 to 142 °C, (b) replacement of limestone, and (c) mixing of the fluid with another fluid with different concentrations of calcium and fluorine. Plumlee and others (1995) concluded that HF from alkaline igneous sources, particularly at Hicks Dome, was added to regional MVT metals-transporting fluids to produce the district's fluorite-rich MVT ores. The fluorite-rich ores formed where alkaline igneous rocks and their evolved magmatic fluids intruded into an ongoing regional MVT mineralizing system that extended to at least the Central Tennessee and Central Kentucky districts.

Exposed or geophysically indicated alkalic magmatic source rocks have not been identified at either of the Pennine orefields nor in the Marico district, which are the other identified fluorite-rich MVT districts. Dunham (1948) speculated that the Weardale Granite, which forms the basement to the sedimentary host rocks of the Northern Pennine Orefield, was a heat source simply from decay of elevated concentrations of radioactive elements within it, and that convection of mineralizing meteoric groundwaters through the fracturing systems was set up around the Weardale Granite because of the anomalous heat. Bau and others (2003) suggested that sources of REEs and yttrium in the fluorite of the Southern Pennine Orefield were relatively pure marine sedimentary carbonates, and that, in contrast, the sources for the Northern Pennine Orefield were aluminosilicate rocks, which is consistent with the Weardale Granite being a source for REEs in the Northern Pennine Orefield fluorite.

The Bushveld Complex is located relatively near the Marico MVT district in South Africa. The large Buffalo fluorspar deposit (Limpopo Province) and the very large Vergenoeg fluorspar deposit (Gauteng Province) are located near the center of the Bushveld Complex and at its highest structural level (appendix G1). Buffalo and Vergenoeg appear to be related to strongly differentiated Bushveld Complex granites (deposit type 5 of fig. G3*B*). In a contact zone that surrounds the Bushveld intrusives, the Marico fluorspar ores have been metamorphosed by the heat from the intrusions (Martini, 1976), so it was not possible for Bushveld-age hydrothermal fluids from those granites to provide fluorine for the preexisting MVT fluorspar deposits.

Salt-Related Carbonate-Hosted Fluorspar Deposits

Leach and others (2005, appendix A, table A1) consider salt-related carbonate-hosted deposits to be part of their classification of MVT deposits and have given them an alternate subclass name (“salt dome related”). According to the authors, only 5 of their 247 example MVT deposits worldwide are said to be salt dome related. Indeed, these deposits have the same simple mineralogy, the same kinds of orebody geometries, similar parageneses, and probably the same types of local geohydrologic controls (various scenarios that produce interaquifer groundwater mixing) as the MVT deposits within the Mississippi Valley itself. In figure G3, salt-related carbonate-hosted deposits are shown to be a subclass of MVT deposits. What MVT and salt-related carbonate-hosted deposits do not share, however, is their regional and temporal geologic settings, along with other details that result from the differences in their settings.

Salt deposits themselves are commonly found on passive continental margins that formed in the arid tropics or in failed arms of the rifts extending inland from passive continental margins (aulacogens). Thus, in contrast with the MVT deposits of the Mississippi Valley, which are associated in time and distantly in space with collisional orogenic belts, the salt-related carbonate-hosted deposits are in many places clearly associated with continental rifting, with passive margins, or with aulacogens. The salt-related classification originated with French scientists who studied deposits in Algeria and Tunisia where the salt is Triassic (Charef and Sheppard, 1987; Orgeval, 1994; Perthuisot and Rouvier, 1995; Sheppard and others, 1997); however, the best example of these types of deposits are from the Miocene to recent Red Sea margins (El Aref and Amstutz, 1983; Hayes and others, 2002). The U.S. Gulf of Mexico margin, where the Middle to Upper Jurassic Louann Salt is located, also has deposits of this type (Price and others, 1983; Kyle and Saunders, 1997; Saunders and Swann, 1994), but none has been proven economic to mine.

Differences between MVT deposits and salt-related carbonate-hosted zinc-lead-fluorite-barite deposits are important considerations for exploration. The sedimentary sections that host salt-related carbonate-hosted deposits contain evaporites, which typically form major parts of the local sedimentary section and, at places, exceed one-half of the total sedimentary thickness. Although evaporites are present in traces in the sedimentary sections of the MVT deposits of the Mississippi Valley, none appear to be as much as 5 percent of the thickness of the involved section anywhere within 100 km of a deposit (although adjacent basins have considerably more; for example, the Michigan Basin). Salt-related carbonate-hosted zinc-lead-fluorite-barite deposits differ from the MVT deposits by having paragenetic sequences of hydrothermal minerals that cannot be correlated for even as much as tens of kilometers. Connected secondary porosity needed for long-distance transport of hydrothermal brines does not generally exist in strongly fault-segmented continental rifts and early passive margins.

Although many of the salt-related zinc-lead-fluorite-barite deposits are located close to salt deposits, with some actually within the cap rocks of salt domes, the critical role of the salt is probably not in creating sites for mineralization, such as caprock hosts, nor in creating structural paths for the required interaquifer groundwater mixing. Rather, the critical role of salt in these deposits is probably that it dissolves in mineralizing brines to supply chloride and thus provides high solubilities of zinc, lead, iron, and barium as chloride complexes in those mineralizing brines (Hayes and others, 2001, 2002). Spatial association with salt and the presence of fluid inclusions in ore minerals that demonstrate the process of dissolving preexisting salt to create an ore solution are true indicators of this class. Spatial association is not necessary if the fluid inclusions contain redissolved salt—as demonstrated from the Cl^-:Br^- and Na^+:Br^- ratios (Carpenter, 1978; Hanor, 1987; Kesler and others, 1995)—as a major component in the ore fluids.

Fluorspar deposits in the Asturias region of Spain are the best known examples of fluorine-rich deposits of this class as a result of some recent work on the composition of the deposits’ fluids (Sánchez and others, 2009). The geographic association of the deposits with Late Triassic salt in diapirs is shown in figure G5, which shows as well the locations of zinc-lead-(fluorspar-barite-copper-iron) deposits and siderite iron deposits of the enclosing and larger Cantabrian region (Velasco and others, 1994). The zinc-lead-(fluorspar-barite-copper-iron) deposits and the siderite iron deposits probably all originated from the same general mineralizing events; all these deposits are probably salt-related carbonate-hosted deposits (Grandia and others, 2003). In studies of the microthermometry and composition of fluid inclusions in the Asturias deposits, Sánchez and others (2009) identified two discrete fluids that mixed to precipitate fluorspar ore: a simple sodium-chloride-dominated groundwater with salinities of 0 to 8.2 equivalent weight percent, and a complex sodium chloride–calcium chloride brine with salinity of 9 to 25 equivalent weight percent sodium chloride. They found that the complex higher-salinity brine had Cl^-:Br^- and Na^+:Br^- ratios that demonstrated a large proportion of halite dissolution. A comparable degree of halite dissolution was

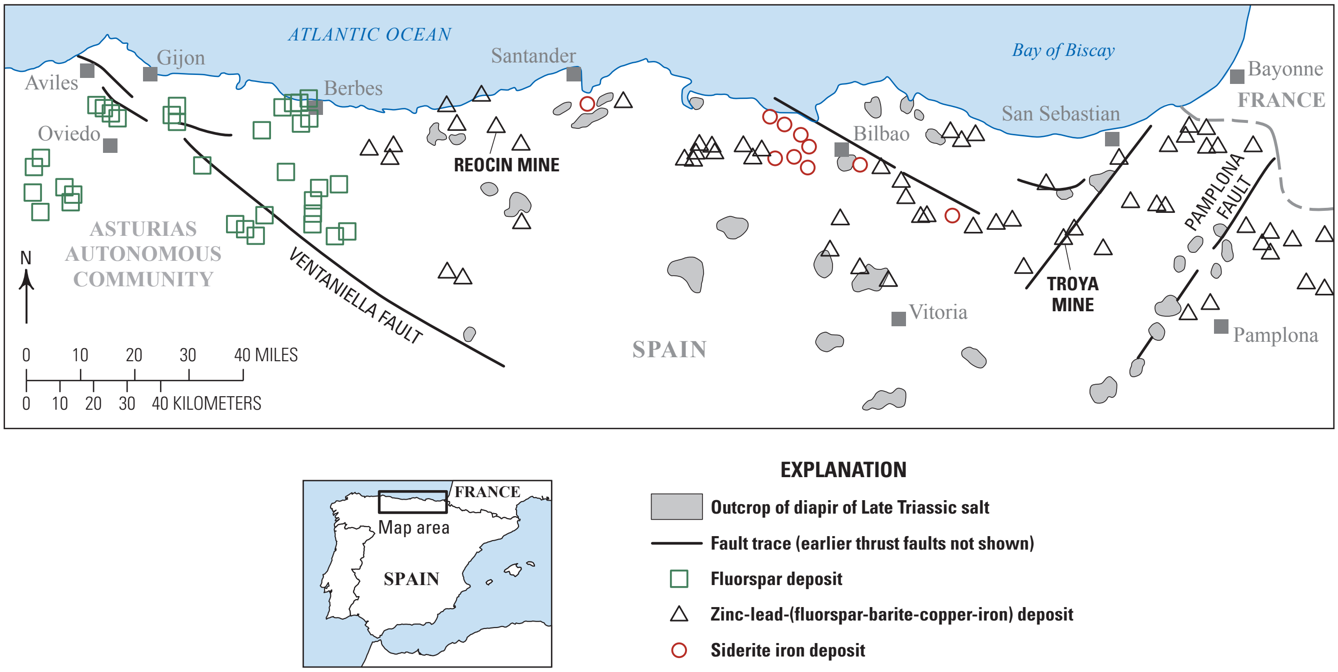

Figure G5. Map showing the locations of deposits in the Cantabrian salt-related carbonate-hosted mineral district in north-central Spain. The locations of the fluorspar mines and occurrences and the base map of the Asturias Autonomous Community on the west are modified from Garcia-Iglesías and Loredo (1994), and the locations of siderite iron deposits, zinc-lead-(fluorspar-barite-copper-iron) deposits, and outcrops of Late Triassic salt diapirs, as well as the base map of the eastern two-thirds of the area, are modified from Velasco and others (1994).

nowhere measured among sphalerite fluid inclusions from 12 different MVT districts, including all of the districts of the Mississippi Valley itself (Viets and others, 1997). Sánchez and others (2009) found that the Asturias complex halite dissolution brine also had very high metal contents; that is, up to 500 ppm zinc, 170 ppm lead, and 480 ppm barium—or about one order of magnitude greater than those found in most other metalliferous basinal brines (Land, 1995; Hanor, 1997). The Asturias fluorspar deposits were also samarium-neodymium isotopically dated, yielding an age of 185±29 Ma (Early Jurassic) (Sánchez and others, 2006). This date demonstrates the association with rifting instead of collisional tectonics, because in the Early Jurassic Period, the Asturias region of Spain and the rest of Western Europe were in the process of renewed rifting along the middle Atlantic rift following upon the initial rifting that took place during the Permian Period (Yilmaz and others, 1996).

Many other fluorspar deposits of the western part of Europe appear to share many of the characteristics of the deposits of Asturias. Similar hypersaline brines at temperatures of from 81 to 165 °C and salinities of from 17 to as much as 26 equivalent weight percent NaCl were found in northeastern (Catalonia) Spain's Berta, Osor, and Rigros veins (Cardellach and others, 2003; Piqué and others, 2008); in the Muscadroxiu-Genna-Tres Montis-S'Acqua Frida veins (Silius Mine) (Boni and others, 2009) and other veins in southern Sardinia, Italy (Belkin and others, 1984); in the Le Burc vein in the Massif Central (Midi-Pyrénées Region, France; Deloule, 1982); and in the Rossignol vein (Centre Region, France) and exhalative sediment (Sizaret and others, 2004). Four of these locations are shown in fig. G4. Each of these fluorite deposits has been isotopically or geologically constrained to have formed between the Early Jurassic Period and Early Cretaceous Period and is related to the renewed rifting of the middle Atlantic (Sizaret and others, 2004; Munoz and others, 2005; Piqué and others, 2008).

The above deposits are all probably examples of the general salt-related carbonate-hosted class and related to rifting, even where the wall rocks are Hercynian basement rocks. A characteristic magmatic rock of some continental rifts or rifted margins is peralkaline, however, and, consequently, each of the deposits could instead be of the alkaline-intrusion-related type, with the intrusive rocks buried and providing mainly just the heat to produce hydrothermal circulations. The deposits at Hansonburg in Socorro County, New Mexico, have been called MVT (Putnam and others, 1983; Norman and others, 1985), despite their setting adjacent to the Rio Grande Rift, which hosts a number of epithermal, alkaline-volcanic-related fluorspar deposits (Van Alstine, 1976). Recent results demonstrate that the Hansonburg hydrothermal fluids had from 13 to 49 percent asthenospheric magmatic chlorine (Partey and others, 2009), so the deposits are also alkaline-intrusion-related. Deposits of the Encantada-Buenavista district in Coahuila de Zaragoza, Mexico (fig. G4) have been shown to have fluid inclusions with homogenization temperatures of from 75 to 170 °C and salinities of from 7.8 to 15.4 equivalent weight percent NaCl; that is, complex brines of probably sedimentary origin (González-Partida and others, 2003). On that basis, the Encantada-Buenavista deposits are labeled salt-related carbonate-hosted in figure G4. They are probably related to the salt-bearing Jurassic basin adjacent to the west. Kesler (1977), however, had earlier concluded that these and other deposits in the same Cretaceous limestone host rocks in Coahuila de Zaragoza, Mexico, were deposited from boiling, probably partly magmatic, fluids. Many of the deposits are at contacts with rhyolitic or trachytic high-level intrusive rocks (Temple and Grogan, 1963; Pickard, 1974; Kesler, 1977). As with Hansonburg, the Encantada-Buenavista district is likely to prove to have some magmatic component, thus validating its classification as both salt-related carbonate-hosted and related to peralkaline igneous rocks.

Fluorspar Deposits Related to Strongly Differentiated Granites

Fluorspar deposits are known to be present in association with strongly differentiated granites with a considerable range of compositions of the granite, from rather ordinary monzogranites, to two-mica granites, to tin granites. Generally, the greater the differentiation, the more common the occurrence of associated fluorspar deposits. Although the general behavior during differentiation is similar to that in alkaline granites, the associated metals and deposit types are distinct from the metals and deposit types associated with alkaline intrusive rocks. Deposits with the subalkaline granites include fluorite-rich tin and tungsten skarns, fluorite-rich veins with tin and (or) tungsten, some with antimony, and fluorite-rich greisen deposits, and, fewer in number, disseminated or stockwork fluorspar deposits. Molybdenum and bismuth are additional elements that are commonly anomalous in these deposits. Greisens are rocks composed principally of muscovite (or lithium-rich white mica) and quartz with lesser abundances of one or more of the following: bertrandite, beryl, cassiterite, columbite-tantalite, fluorite, phenakite, topaz, tourmaline, and wolframite. Minor sulfides are found in greisens, principally pyrite, but locally others as well, including molybdenite. Although greisens appear to form by hydrothermal alteration of intrusive igneous rocks, a distinguishing feature is that feldspars are absent and have presumably been altered to the white mica.

Among the end-member granites that are included in the broad class of strongly differentiated granites, two-mica granites are those with both muscovite and biotite, which, given those two aluminous micas and the presence of both plagioclase and alkali feldspars, are invariably strongly peraluminous. (In peraluminous igneous rocks, molar $Al_2O_3 > (Na_2O + K_2O)$.) Tin granite is also a very specific type of granite (Tischendorf, 1978; Hudson and Arth, 1983). Tin granite can be porphyritic, seriate, or equigranular in texture, but all are light-colored peraluminous biotite granites, and all are small offshoots of large granodiorite-to-granite batholiths from which the tin granite evolved by fractional crystallization. The tin granites are found in stable cratonal regions and not in continental or oceanic arcs (Hudson and Arth, 1983). Fluorspar deposits associated with tin granites have a variety of geometries (veins; replacements; skarns at intrusive contacts; greisens in small, upward projections on the granite body's roof [that is, endogreisens in granitic cupolas]; and greisens in wall rocks of the granite [that is, exogreisens]). Lithium-rich annite is an important characteristic mineral in tin granites. It was earlier termed "zinnwaldite." Annite is the iron-rich end member of the biotite solid solution—that is, monoclinic $K_2Fe_6\,(Si_6Al_2O_{20})(OH)_4$. In lithium-rich annites, the lithium substitutes for aluminum and iron in this mineral and produces micas of the zinnwaldite series.

To date, fluorspar deposits related to strongly differentiated granites have been identified on every continent except South America and Antarctica (fig. G4 and appendix G1). They probably also occur on those two continents as well but simply have not yet been discovered. Tin-granite end members have not been found in the Andean magmatic belts, however, because those belts appear to be composed entirely of intrusive rocks of oceanic and continental arcs (Steve Ludington, U.S. Geological Survey, retired, written commun., December 6, 2013).

At places, assignment of a deposit to the class associated with strongly differentiated granites is very obvious, but at others, it is not as clear. For example, the very large Vergenoeg deposit in South Africa is near to but not in contact with granites that host tin deposits. The granites are part of the Bushveld Complex and are related to the platinoid-metal-, chromium-, vanadium-, and copper-nickel-bearing rocks of the layered mafic to ultramafic rocks of the lower part of the Bushveld Complex (Hatton and Sharpe, 1989). The Vergenoeg deposit is an approximately carrot-shaped, root-downward mass of very iron-rich igneous (or metasomatic?—that is, formed by replacement from hydrothermal fluids) rocks that cuts intermediate to felsic Rooiberg volcanic rocks. Those Rooiberg volcanic rocks are thought to have been derived by partial melting of upper crustal rocks that lay above the intrusion of the enormous, lobate, sill-like body of the Bushveld Complex and are considered to be the eruptive products of the magmas that became Bushveld granites and granophyres (Kleemann and Twist, 1989; Schweitzer and others, 1997). Vergenoeg ore consists of very coarse-grained (pegmatitic-textured) fayalite-magnetite-siderite-fluorite rock that contains an average of 28 percent CaF_2 and less than 30 percent SiO_2. Flat-lying deposits of fluorite-hematite are located nearby in three directions from the pipe; these deposits are interpreted by Crocker (1985) as tuffs of unusual composition that erupted from the pipe. The average REE pattern of Vergenoeg fluorite precisely parallels that of average Bushveld granite but the fluorite has slightly less than one-tenth the concentrations found in the granites (Goff and others (2004). The origin of the Vergenoeg deposit remains uncertain, but its classification as related to strongly differentiated granite is indicated by the parallel REE patterns.

Definitely within the class of deposits associated with strongly differentiated granites are the Voznesenka and the Pogranichny deposits in Russia's Far East Region (Ryazantseva, 1998; Sato and others, 2003) and the Lost River prospect in Nome Borough, Alaska (Dobson, 1982). These are fluorite deposits in which tin granites and related greisens are exposed literally within the map limits of the fluorspar deposits, although the tin granites themselves are not fluorspar ore. These deposits contain related cassiterite-bearing tin skarn that is very distinctive because the skarn (known as "wrigglite") is rich in magnetite and vesuvianite and has a tortuously sinuous mineralized structure formed by layers that are a millimeter or less in thickness (Kwak and Askins, 1981). Cassiterite, which is the major ore mineral of tin, is tetragonal SnO_2 and vesuvianite, which is the calc-silicate mineral of the skarn, is tetragonal $Ca_{19}Fe(Mg,Al)_8Al_4(SiO_4)_{10}(OH)_{10}$. Magnetite is isometric Fe_3O_4. The fluorspar ores, which are replacements of former carbonate sedimentary rocks by minerals deposited from hydrothermal solutions, contain micas that are very lithium- and fluorine-rich, so the ores may also be termed fluorspar greisens. Most of the same features are found at Moina in Tasmania, Australia (Kwak and Askins, 1981) and, apparently, at Bamianshan in Zhejiang Province, China (Han and others, 2012).

The El Hammam deposit in the Meknès-Tafilalet Region of Morocco; the Yinkuangchong deposit in Hengyang Prefecture, Hunan Province, China; and the Taskaynar deposit in Kazakhstan have spatial association to granitic rocks, but the description of the granites is not detailed enough to determine if they are strongly differentiated, much less whether they are tin granites or two-mica granites. The fluorspar ores at these places contain tin, tungsten, bismuth, or molybdenum minerals, and that association of elements leads to the deposits' tentative classification as related to strongly differentiated granites. The veins at El Hammam contain minor amounts of stannite (tetragonal Cu_2FeSnS_4) and bismuthinite (orthorhombic Bi_2S_3; Cheilletz and others, 2010). At Yinkuangchong, two types of mineralized bodies are recognized. The lesser type consists of quartz veins that contain some amount of cassiterite. The larger polymetallic-fluorspar bodies are silicified breccias that contain minor amounts of scheelite (tetragonal $CaWO_4$) (Chen and others, 1996). The carbonate replacement body at Taskaynar contains cassiterite in a pre-fluorite stage of the paragenetic sequence, and there is a halo of rocks that are high in molybdenum surrounding the deposit (Koplus and others, 1977).

Subalkaline-Volcanic-Related Epithermal Fluorspar Deposits

Many fluorspar deposits worldwide occur in association with subalkaline volcanic rocks. Subalkaline volcanic rocks, in contrast to alkaline and peralkaline volcanic rocks, do not have an excess of potassium and sodium over what is needed for feldspars. They commonly contain both plagioclase and an alkali feldspar. They are typically saturated with silica, and thus quartz crystallized as a late mineral from the differentiating melt. Subalkaline volcanic rocks are the most common rocks of continental arcs, and andesites are the most common rocks among the subalkaline volcanic rocks.

Fluorspar deposits associated with subalkaline volcanic rocks are the most plentiful in China, and many are found in Zhejiang Province along the county's southeastern coast (fig. G4). Chen and others (1996) and Zhang and others (1997) describe the geology of fluorspar deposits in Zhejiang Province. Most of the deposits are described as simple large veins that have no close spatial association and no obvious genetic association with plutonic or shallowly intrusive igneous rocks. Some veins of the Yangjia-Wuyi district are continuous for more than 15 km along strike with thicknesses of 2.3 to 5.8 m. The ore is not continuous along strike, but ore shoots are typically separated by just 15- to 46-m intervals of quartz-rich and fluorite-poor parts of the veins. The Yangjia-Wuyi veins cut a section of Jurassic-aged intermediate to dominantly felsic volcanic rocks that are intercalated with sedimentary rocks. The section is dominated by rhyolitic tuff but is interlayered with limestone, quartzite, tuffaceous siltstone, and, locally, with shale and mudstone (Chen and others, 1996; Zhang and others, 1997). The veins include gangue minerals of quartz, chalcedony, opal, calcite, and barite, and small amounts of pyrite (isometric FeS_2), apatite (hexagonal $Ca_5(PO_4)_3(F,OH,Cl)$), and kaolinite (triclinic $Al_2Si_2O_4(OH)_2$). Wall rocks are altered with the addition of quartz, a lesser amount of kaolinite, and local pyrophyllite (monoclinic $AlSi_2O_5(OH)_2$), carbonates, chlorite (monoclinic $(Mg,Al,Fe,Li,Mn,Ni)_{4-6}(Si,Al,B,Fe)_4O_{10}(OH,O)_8$), and pyrite. The ore and gangue mineralogy as well as the fluid temperatures and salinities are consistent with epithermal conditions (Chen and others, 1996). Isotopic studies are insufficient to address the origins of the fluids, but meteoric water was probably dominant. The fluorspar deposits in Zhejiang Province have been dated at 70 to 90 Ma by a samarium-neodymium isochron on fluorite and calcite (Li and others, 1998). Studies of neodymium and strontium isotopes are interpreted to indicate that most of the neodymium and strontium was derived from the Precambrian metamorphic rocks lying below the host rock, and that the remainder was derived from the Mesozoic volcanic and sedimentary wall rocks themselves (Li and others, 1998). Although the deposits contain a record of multiple igneous events dating from 135 through 97 Ma with various chemical signatures, the intrusive rocks from 97 Ma are those that, in time, could have contributed in small proportions to the mineralizing fluids. Those rocks, which belong to a high-potassium subalkaline suite of volcanic rocks (Lapierre and others, 1997), are peraluminous granites of an apparently ordinary continental arc. In these epithermal systems, the role of the high-potassium subalkaline volcanic rocks as sources for fluorine may have been more important than that of the granites, which may have merely been heat sources needed to cause groundwater convection. In other countries, also, the deposits associated with subalkaline volcanic rocks tend to be simple epithermal veins with crystals that grow symmetrically inward from both vein walls.

Other deposits that may tentatively be included in the class of epithermal fluorite deposits associated with subalkaline volcanic rocks are the Las Cuevas deposit in the State of San Luis Potosi, Mexico, and the nearby mines at El Realito and El Refugio in Guanajuato State, Mexico. Each of these three deposits is at the faulted and brecciated contact of limestone and rhyolite breccia (Ruiz and others, 1980). The rhyolites are part of a province of high-potassium subalkaline rocks (Ruiz, 1983) that lies east of the main subalkaline Sierra Madre Occidental volcanic complex. Although the rhyolite lying along one wall of the Las Cuevas orebody is relatively fluorine-rich, and although Ruiz (1983) showed that the composition of the Las Cuevas deposit fluorite reflects the composition of its local wall rocks (including that rhyolite), the Las Cuevas rhyolite is not one of the "topaz rhyolites" that were erupted at approximately the same time as the Las Cuevas rhyolite, that have the highest fluorine of any volcanic rocks in the region, and that have associated tin mineralization in the Mexican tin belt (Huspeni and others, 1984). Clark and others (1982) included these deposits together with those in a belt to the north, including Aguachile in Pico Etereo district, and El Tule district in Coahuila de Zaragoza, Mexico, which are associated with peralkaline rhyolites, as well as deposits of the Eagle Mountains in Hudspeth County, Tex., which are associated with a quartz syenite intrusion. That inclusion appears questionable based on the contrast in chemistry of the volcanic rocks near Las Cuevas, El Realito, and El Refugio compared with the chemistry of volcanic rocks associated with the deposits in Coahuila. The rhyolites at those three deposits are part of a high-potassium subalkaline province; they are not peralkaline like the rhyolites in Coahuila.

The Sumochagan Obo deposit in China's Inner Mongolia Autonomous Region may also belong in the class of epithermal fluorspar deposits associated with subalkaline volcanic rocks. It is a large, rich deposit approximately conformable with the layering of calcareous tuffs and tuffaceous limestones (Nie and others, 2008) within a high-potassium subalkaline volcanic and sedimentary pile (Xu, 2009) of Early Permian age (appendix G1). At its closest point, the deposit is about 1,200 m distant from a peraluminous granite intrusion (Xu and others, 2008) into that volcanic pile. It thus resembles the other deposits listed in this section in its tectonic and magmatic setting; however, its tuffaceous limy host rock and its approximately conformable geometry would perhaps allow it to be alternatively placed in the class of apparently conformable deposits within tuffaceous limy lacustrine sediments.

Fluorspar Deposits Apparently Conformable Within Tuffaceous Limy Lacustrine Sediments

A number of deposits in the Latium Region of west-central Italy make up the class of apparently conformable deposits within tuffaceous limy lacustrine sediments, together with a single fluorite occurrence in southeastern Oregon, and, as noted above, possibly the Sumochagan Obo deposit in China. The deposits in Latium, Italy, are fine grained with more than 85 weight percent of the fluorite less than 40 µm (that is, silt and clay size), and, in fact, the proportion of fluorite in the Latium Region resource increases as the grain size decreases (Mastrangelo, 1976, p. 31). In an apparently conformable occurrence near Rome, Oregon, the fluorite grain size is predominantly less than 1 µm (Sheppard and Gude, 1969). The occurrence at Rome, Oreg., is in Pliocene rock (1.8 to 5.3 Ma). If Sumochagan Obo belongs within this class, then it must have been considerably modified from its original form because fluorite in the deposit has grain sizes of from 110 to 6,370 µm; that is, it has the grain sizes of very fine sand to fine conglomerate using standard grain sizes for sand. The texture of the "primary industrial ore" of Sumochagan Obo is "sugar-granular" (Yong and others, 2011, p. 14); thus, it ranges from coarse to very coarse sand. That the grain size of the Sumochagan Obo ore would have coarsened since the time of its deposition is reasonable. The deposit is in Early Permian age rocks (about 270 Ma), whereas the Italian deposits are in Pleistocene to Pliocene age rocks (0.9 to 3.7 Ma).

The deposits of the Latium Region appear to be conformable with layering in a mixed volcanic and sedimentary section, and they appear to constitute a hydrothermal sediment interlayered within lake-deposited tuffaceous limy mudstone and siltstone. The volcanic rocks of this region are alkaline, varying from trachytic tuffs to leucitites to phonolites to tephrites (the series of names of alkalic volcanic rocks just listed is from richest to poorest in alkali feldspar; all are undersaturated with silica). Most of the volcanic rocks contain leucite, analcime (isometric or monoclinic $Na(AlSi_2)O_6 \bullet H_2O$), or nepheline. Flat-lying volcanic rocks dominate the section, but lake-deposited and lesser amounts of stream-deposited sedimentary rocks occur in multiple places in the section. The Latium Region is pockmarked by maar lakes (that is, lakes formed in shallow volcanic craters), which occur in the same 40-by-110-km zone as the fluorspar deposits. Maar lakes are nearly circular, have no volcanic cone, and have very steep walls. They are produced by single volcanic explosions caused by magma intruding into groundwater-rich rocks, which changes the groundwater explosively to steam, which then throws the overlying rocks upward and outward. Although a number of Latium Region fluorspar deposits were mined in the past, most notably the Castel Giuliano-Pianciano deposit, little of the fluorite was recovered, probably because of the very fine grain sizes of the minerals, and no deposit there is currently being mined despite the presence of identified resources.

The Latium Region deposits consist of various proportions of fluorite, barite, apatite, calcite, and quartz (or chalcedony), and the overall grades are from 37 to 83 weight percent CaF_2. The content of barite varies inversely with that of fluorite. The deposits are from 1 m thick to as much as 15 m thick over areas of up to tens of square kilometers. The host lacustrine rocks include beds of diatomite, but diatoms (fossils consisting of silica that are each the size of a sand grain or less) are not typically found in the fluorspar resource. From a 1976 symposium about the deposits, the majority opinion was that the fluorspar deposits had formed from fumarolic or hydrothermal solutions that discharged onto the floors of maar lakes (Matteucci, 1976). A strong support of that hypothesis was that, at places, a tawny, plastic earthy facies of fluorite-rich rock is slump-folded but overlain by an undeformed white-to-yellowish gray gritty facies of fluorite-rich rock.

The occurrence near Rome, Oreg., underlies an area of about 18 square kilometers (km^2) with an average thickness of about 2.3 m and an average grade of about 2.65 weight percent CaF_2. Using semiquantitative X-ray diffraction, Sheppard and Gude (1969) found a regular set of changes in fluorite content and in other authigenic minerals through the section of basaltic tuffs and lacustrine tuffaceous mudstone. An overlying yellow tuff section appears to have lost fluorine, perhaps during a weathering period that produced alkaline, sodium bicarbonate ($NaHCO_3$)-type soil waters. The climate and local rock compositions would probably have led to developing the same kind of $NaHCO_3$-rich water of high pH as was found in the Eastern Rift Valley of eastern Africa that had anomalously high concentrations of fluorine (table G2) (Kilham and Hecky, 1973), although probably at considerably lesser concentrations in Oregon. Probably the once glassy components of that yellow tuff altered to the zeolite minerals clinoptilolite (monoclinic $(Na,K)_6(Al_6Si_{30)})0_{72}\bullet 20H_2O$), phillipsite (monoclinic $K(Ca_{0.5},Na)_2(Al_3Si_5)O_{16}\bullet 6H_2O$), and erionite (hexagonal $K_2NaCa_{1.5}Mg(Al_8Si_{28})O_{72}\bullet 28H_2O$). Beneath it, the fluorite-bearing tuffaceous mudstone became enriched in calcite, fluorite, quartz (or chalcedony), and mordenite, a potassium-rich zeolite (orthorhombic $K_{2.8}Na_{1.5}Ca_2(Al_9Si_{39})O_{96}\bullet 29H_2O$). Although some parts of their geologic settings are shared, there is no observed or predicted evidence that the same mechanism might have created the conformable fluorite deposits of the Latium Region, Italy, and the occurrence at Rome, Oreg. At just 2.65 percent CaF_2, the Rome, Oreg., occurrence is unlikely ever to be considered economic for mining.

Residual Fluorspar Deposits

Many fluorspar deposits of the world were first discovered in residuum, and many constituted ore at the surface, particularly where costs allowed the ore to be hand sorted. Residual fluorspar deposits were well known in the Illinois-Kentucky fluorspar district in the United States, where the carbonate gangue of the veins, predominantly calcite, and the limestone wall rocks were dissolved away during weathering (Weller and others, 1952, p. 29). Residual ore extended to depths locally as great as 30 m. A large volume of the ore in the Marico district in North West Province, South Africa, is residual, where it is termed “kokkoman.” Large bodies of kokkoman can exceed 50 percent CaF_2 (Martini, 1986; Ryan, 1986). The ore is residually enriched by the dissolving away of dolomite from the host rocks during weathering. Residual fluorite deposits were also widespread in the northern area of fluorspar production in Thailand near the Ban Hong deposit (fig. G4; Fulton and Montgomery, 1983).

Fluorine Recovery From Brines

Fluorine products are not currently recovered from brines anywhere in the world. As pointed out by Shawe (1976, p. 22), however, production of a fluorine product from a brine is a distinct possibility, perhaps in the near future. A number of other mineral commodities are produced from brines, for example, lithium (Kunasz, 1974; Ericksen and others, 1978). If a fluorine product is produced from a brine, it would not be a brine similar to those that produce lithium, however. Fluorine-rich brines are very alkaline (pH commonly about 10), are dominated by sodium (Na) and bicarbonate (HCO_3^-), and are brines from which trona is precipitating. The brine from Lake Magadi, Kenya (table G2), is an example of such a fluorine-rich brine from within the trona sediment that makes up the floor of the lake. This is the area from which villiaumite has been identified in the trona (Nielsen, 1999). The surface water of Lake Magadi averages about 1,360 ppm fluorine, and intrastratal brines from boreholes in bottom sediments average about 1,200 ppm (Jones and others, 1977). At present, there is no process by which fluorine can be recovered from the water even with such high concentrations; however, because fluorite has been observed in calcareous rocks where they are in contact with this high-fluorine water, and where the fluorite has replaced calcite (Surdam and Eugster, 1976), it is likely that addition of calcium by almost any means is a possible way to extract the fluorine from the water (for example, see Aldaco and others, 2007). The water could be run across a bed of ground limestone (the area has caliche developed in several levels of the Tertiary and Quaternary stratigraphy—Eugster, 1980); however, production of an aluminum-fluoride (AlF_3) product might be preferable. Possibly, bauxite could be reacted with fluorine-rich brine to make an AlF_3 product directly.

Fluorspar Deposit Grades and Tonnages by Deposit Class

From the previous discussions, it could be expected that the deposit classes have different typical grades and tonnages. The only published previous attempt to examine fluorspar deposit grades and tonnages systematically was Orris (1992), who restricted her study to fluorspar veins. The advent of measures such as Canadian Government National Instrument (NI) 43–101 reports and the South African Code for Reporting Exploration Results (SAMREC)-compliant resource and reserve estimates has made information on the grades and tonnages of many more fluorspar deposits publicly available since the 1992 study.

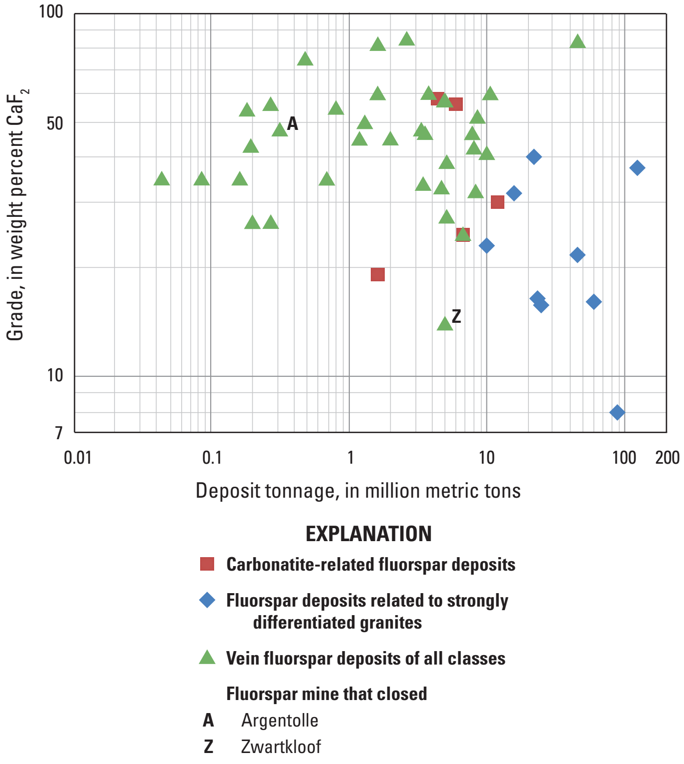

Figure G6. Plot of fluorite (CaF_2) grade versus tonnage for fluorspar deposits related to strongly differentiated granites, for carbonatite-related fluorspar deposits, and for veins from all classes of fluorspar deposits. Two vein fluorspar mines that failed because of either insufficient grade (Zwartkloof; Z) or insufficient tonnage (Argentolle; A) are identified on the plot. Data are from table G1–1; deposits whose grade and tonnage are plotted are listed in the footnote.

Figure G6 is a plot of fluorspar deposit grades and tonnages made from the data in appendix G1. The plotted grades and tonnages have not been exhaustively vetted to assure their validity. A number of pitfalls are possible in the reporting of deposit grades and tonnages by private interests. The data in appendix G1 have come from many different sources, so the resulting plot presents data collected using a wide variety of reporting criteria. If the majority of the data used are valid, then the overall trends shown on the plot are probably real.

In figure G6, deposits with vein geometry have been treated as a single category regardless of their class in figure G3*B*, but deposits without vein- or dike-like geometry (that is deposits associated with carbonatites, and deposits associated with strongly differentiated granites) are each treated separately. The plot in figure G6 probably includes a few small occurrences in which only the resources considered to be sufficient to assure the next planned advance of mining were reported, although in cases where this could be confirmed, the deposit was not plotted. A number of other occurrences that were mined, but then closed, or that were mined intermittently only when prices were high have been included. Examples are the Huckleberry (Carlton County), the White Eagle (Sierra and Grant Counties), and the Great Eagle (Grant County) occurrences in New Mexico; the Canxixe (Sofala Province), the Mount Muambe (Tete Province), and the Macossa (Manica Province) occurrences in Mozambique; and the Jebel Sumayh occurrence in North Kordofan State, Sudan. Consequently, not all the plotted deposit grades and tonnages are for reserves (resources that were profitable to mine). The reasons why unprofitable resources were included is explained below.

Although individual classes on the plot appear to show very little tendency for tonnage and grade to systematically covary or to vary inversely, the three deposit classes together appear to show that, of reported deposits, high-grade fluorspar deposits tend to be smaller in tonnage, and lower grade deposits tend to be larger in tonnage. That overall inverse relation is common to deposits of many different kinds of mineral commodities. The lack of reporting for low-grade, low-tonnage deposits also is a contributing factor to the inverse relation observed with the reported data. The plot shows that economic fluorspar veins are generally smaller and higher grade than economic carbonatite-related fluorspar deposits which are, in turn, generally smaller and of higher grade than economic fluorspar deposits associated with strongly differentiated granite. These results may be overly simplistic, however, because some veins have barite, lead, and zinc byproducts or coproducts; some carbonatite-related deposits have niobium and barite byproducts; and some granite-related deposits have tin, tungsten, and possibly antimony, bismuth, and (or) molybdenum byproducts or coproducts.

On the plot in figure G6, the Zwartkloof deposit in the Warmbaths district of Limpopo Province, South Africa, which is a deposit related to strongly differentiated granite, is labeled Z, and the Argentolle deposit, Bourgogne Region, France, which is a vein deposit probably of the salt-related carbonate-hosted type, is labeled A. The Zwartkloof Mine operated only from 1971 to 1973 and was closed when the operating company concluded that the grade of the deposit (13.7 percent CaF_2) was insufficient (Brian Hodge, consultant on world fluorspar deposits, written commun., April 29, 2013). The deposit at Argentolle was mined from 1971 to 1982, and was also abandoned as uneconomic. Zwartkloof and Argentolle are important because an imaginary line connecting the two on the grade vs. tonnage plot (fig. G6) divides the plot into two parts, one to the right and up from the line; the other to the left and down from the line. That line approximately marks a boundary between deposits that, as of late 2015, were viably economic (right and up) and those that were uneconomic (left and down, including Zwartkloof and Argentolle, themselves).

The approximate boundary formed by the line between A and Z should not be considered a permanent and rigid divider between economically favorable and unfavorable grades and tonnages of fluorspar deposits. For example, that line certainly expresses some aspects of mining history, showing, on that boundary, at least two deposits that were historically considered minable but that have become uneconomic in the modern fluorspar world market. Also, a deposit that is being explored may likely pass from lower left to upper right—from uneconomic to economic—by crossing the line horizontally (that is, becoming larger with the knowledge gained by additional drilling), although a deposit might cross the line vertically (that is, become higher grade as high-grade drilling results are achieved once the best part of the deposit is reached through exploration).

In any case, the plot provides a measure with which to compare the resources of new deposits or deposits still in exploration with typical fluorspar deposit grades and tonnages; the farther to the right and up, the better. The deposits in Las Cuevas, Mexico, and Vergenoeg, South Africa, are the two deposits that are farthest up and to the right of that imaginary line between A and Z.

Resources and Production

Identified Resources in the United States

The United States has numerous moderate-tonnage (that is, tens of thousands of metric tons to up to a few hundred thousand metric tons) but high-grade fluorspar deposits scattered across seven States (Idaho, Illinois, Kentucky, Montana, Nevada, New Mexico, and Utah). Some larger tonnage but lower grade deposits have also been identified in Alaska, Illinois, Nevada, and Tennessee.

Some moderate-tonnage high-grade fluorspar deposits and one large-tonnage low-grade deposit have been identified in the Illinois-Kentucky fluorspar district. The Anabelle Lee, the Denton, and the Minerva Number 1 Mines (Hardin County, Ill.) in the Illinois-Kentucky fluorspar district closed in 1996 with ore still in the faces of each mine and some limited tonnages of drilled resources identified at each (Richard Yancy, former Ozark-Mahoning Co. mine geologist at the three mines, oral commun., March 11, 2013). Since that time, exploration and development in the Illinois-Kentucky fluorspar district has taken place at the Klondike II project, which is located about 8 km southwest of Salem, Ky., in Livingston County. Production began in 2012 (W.H. Anderson, Kentucky Geological Survey, oral commun., October 22, 2014). The Klondike II deposit is located on the Pittsburgh Fault and constitutes a vein resource of at least 1.6 million metric tons of ore grading 60 percent CaF_2 (Feytis, 2009). A decline has been driven from the surface to allow rubber-tire mechanized underground mining. Plans are in place to ramp up production to 200,000 metric tons per year during a period of several years. Other exploration is ongoing nearby and to the northeast in southern Crittenden County. Farther north, Hicks Dome Corp. (HDC) has continued to hold and explore the company property since obtaining its first leases in 1970.

Since the HDC property was first leased, several different partners have worked together in joint ventures with HDC, although each left the partnership within a few years. The last public announcement of tonnage and grade at Hicks Dome was reported by Kirkemo (1978) and totaled just 11.3 Mt at a grade of 11.5 percent CaF_2. This estimate was made when only 12 exploration core holes had been completed, however. Since that time, tens of additional holes have been drilled, many of these encountering similar mineralization. Still, this is a relatively low-grade fluorspar deposit, although its tonnage as now known is doubtlessly significantly larger than that previous estimate of 11.3 Mt. With the known geology of Hicks Dome, production of fluorspar as a byproduct or coproduct of REE mining could possibly take place if the property comes into production (Kirkemo, 1978). Fluorite mineralization at Hicks Dome is found in breccias that also contain substantial concentrations of beryllium, niobium, REEs, thorium, and yttrium, as well as local concentrations of zinc, lead, and barite.

Lost River, Alaska, mentioned earlier, is the largest identified resource of fluorspar in the United States outside of the Illinois-Kentucky fluorspar district. Tin and fluorspar could possibly be produced as coproducts, along with tungsten and possibly beryllium as byproducts if a mine can operate profitably in that remote location and extreme climate. Additional resources in the Western United States have been identified in southwestern Utah, along the flanks of the Rio Grande Rift in New Mexico and Texas, in two small districts in Idaho, in one place in Montana, and in at least two places in Nevada. Among identified resources in the Western United States, the McCullough Butte deposit, which is located 19 km southwest of Eureka, Nevada, appeared to be in an advanced stage of exploration at the end of 2013. Several exploration programs had been conducted at the property in the past; the latest one was by Tertiary Minerals plc, which also owns the Storuman deposit in Lappland Province, Sweden, and the Lassedalen fluorspar deposit in Buskerud County, Norway. McCullough Butte is a skarn deposit in limestone along its contact with a quartzite adjacent to and extending away from dikes of Late Cretaceous two-mica granite porphyry (Barton, 1982). Tertiary Minerals has announced a Joint Ore Reserves Committee-compliant estimate of 6.1 million metric tons of indicated resources at a grade of 10.8 percent CaF_2, and 80.3 million metric tons of inferred resources at a grade of 10.7 percent CaF_2 at a cutoff grade of 8 percent CaF_2 (Tertiary Minerals plc, 2015). The geology and topography of the McCullough Butte deposit would allow for open pit mining.

In the Eastern United States, low-grade resources have been identified in the Sweetwater (MVT) district in Tennessee. With the exception of the deposits in the Illinois-Kentucky fluorspar district described above and possibly the McCullough Butte deposit, none of the resources in the United States would appear to be economic at this time, given competition with Mexican and South African imported HF and fluorspar.

The success of the project at the recently discovered Klondike II deposit in Kentucky demonstrates that there probably are still additional deposits to discover in old districts. The Klondike II deposit has been described as being 18 m thick, 91 m vertically from the surface to the bottom of the ore, and about 1,200 m along the strike of the vein, and as containing 3.6 million metric tons of proven ore (reported as 60 feet wide, 300 feet deep, more than 4,000 feet long, and containing about 4 million short tons) (Anderson and Moodie, 2010). That an orebody of such size would have escaped discovery for some 140 years since the district was recognized as a major source of fluorspar is perhaps surprising, but it is not remarkable. The district has several tens of known veins and areas of bedding replacement ores. The aggregated total strike length of faults with known fluorspar mineralization along them is conservatively estimated to be 350 km. A scientist from the Kentucky Geological Survey (W.H. Anderson, Kentucky Geological Survey, oral commun., January 24, 2014) who has worked in the Illinois-Kentucky fluorspar district now and again since 1989 says that exploration along those faults is generally thorough enough to preclude additional orebodies, but points to the following two areas that are thought to have remaining potential: (1) the area of the Rock Creek graben southwest of the Ohio River in Kentucky for new discoveries of bedding replacement deposits, and (2) the extension of the Tabb faults southeastward beyond the Senator, Eddie Crowder, and Williamson Mines that form the current-day southeastern limit of the district for new discoveries of vein ores.

Identified Resources in Other Countries

The Nui Phao fluorspar-tungsten-bismuth-copper-gold deposit in Thai Nguyen Province, Vietnam, about 80 km north-northwest of Hanoi, began operations at the end of April 2013 after an extended period of permitting, land acquisition, and other preparations. The deposit is being mined by open pit, and it is projected to provide nearly 214,000 metric tons per year of CaF_2 for 20 years, as well as about 5,620 metric tons per year of tungsten, 2,675 metric tons per year of bismuth, and 588,000 grams per year of gold. Paragenetically, early mineralization at Nui Phao is a tungsten skarn thought to be related to the intrusion of a Triassic biotite granite. Later hydrothermal overprint thought to be related to the intrusion of a Cretaceous two-mica granite is of pyrrhotite-fluorite-albite greisen (Richards and others, 2003; Masan Group, 2013).

In South Africa, the Nokeng fluorspar project, which is located on a property that borders the Vergenoeg Mine in northern Gauteng Province, was scheduled to start mine construction in late 2012, with production targeted for the second quarter of 2014. As of February 2014, construction had apparently not yet started, and no further information that explains the reason for the delay was available. The project planned to mine two orebodies—the Plattekop deposit and the Outwash Fan deposit. Together, the deposits contain SAMREC-compliant reserves of about 12.2 million metric tons of 27.2 percent CaF_2 (Clay and de Wit, 2009). The Plattekop deposit is a conformable layer within the local Vergenoeg Suite stratigraphy that overlies the Vergenoeg fluorite-magnetite-fayalite-sulfide breccia pipe. The Plattekop deposit is a 6- to 27-m-thick layer of hematite-fluorite within a sequence of ferruginous agglomerates, tuffs, felsites, and ironstones. Its outcrop, which forms a hilltop, extends from a sharp contact with the pipe southeastward for about 1,200 m. The Outwash Fan deposit occurs 7.6 km south-southeast from Plattekop Hill and extends for another 3.5 km from there. The Outwash Fan ore is in a 1- to 9-m-thick layer of fluorite-bearing conglomerate or sedimentary breccia intercalated among laminated fine grits, quartzites, bedded ironstones, cherts, and conglomerates. The orebodies are planned to be mined by separate open pits. Fluorspar is to be recovered by flotation to make acid-grade concentrates, and a production rate of 180,000 metric tons per year of CaF_2 is expected (Clay and de Wit, 2009).

Also in South Africa, the Doornhoek deposit in North West Province is simply the eastward extension of the Witkop MVT dolomite-hosted fluorspar deposit in the Marico district. The Doornhoek owners “planned to initiate underground development, feasibility studies and design” (Roberts, 2012, p. 38.). No additional information from the company was available.

The Speewah fluorspar deposit in Western Australia, Australia (which contains 6.7 million metric tons grading 24.6 percent CaF_2), was purchased by a Chinese company, Jiangxi Yunfeng. The project was undergoing a preproduction feasibility study (Mining Atlas, 2016).

The Lassedalen fluorspar mine (which contains 4 million metric tons grading 24.6 percent CaF_2) in Buskerud County, southwestern Norway, was scheduled by Tertiary Minerals to be reopened in 2012, but the latest available company releases suggest that prefeasibility study drilling would be conducted with the purpose of completing a Joint Ore Reserves Committee (JORC)-compliant estimate of reserves (Tertiary Minerals plc, 2014). The deposit is adjacent to one of the Permian peralkaline granites of the Oslo graben (Ineson and others, 1975). Tertiary Minerals’ Storuman deposit in Sweden was somewhat nearer to being ready to mine; the deposit is a replacement deposit along bedding in Cambrian sandstones. This has been called an MVT deposit, based on nearby sphalerite-galena-fluorite-calcite-bearing ores occurring in fractures within the Precambrian basement with strongly saline fluid inclusions that homogenize mostly from 80 to 200 °C and also, in the fluorite, contain hydrocarbon inclusions (Billström and others, 2012). The class assignment is also based on analogy with the zinc-lead deposit at Laisval, located nearby, that formed in the same host rocks in the mid-Silurian Period, a time when thrust-belt compressional mountains were thrown up just tens of kilometers to the west (Sherlock and others, 2005). The JORC-compliant resource estimate for Storuman is 25.0 million metric tons of indicated resources grading 10.28 percent CaF_2 and 2.7 million metric tons of inferred resources grading 9.57 percent CaF_2. Tertiary Minerals planned to submit its mining lease application in the first quarter of 2014 and its environmental permit application sometime in 2014. The company planned to begin development of the Storuman Mine in 2016 and to start production in 2017. The mine had a planned mine life of at least 18 years at a production rate of roughly 160,000 metric tons per year of CaF_2. The deposit appears to be open in at least two directions, however, and additional drill holes indicate mineralization in both directions.

In China, a probably relatively large tungsten-tin-bismuth-molybdenum-fluorite deposit was found in western Zhejiang Province within the past several years. It is called Bamianshan, and although there is considerable geologic literature on the deposit already, its exact location and grade and tonnage have apparently not been reported. The deposit is geologically interesting because it is clearly related to a strongly differentiated granite (Liu and others, 2012), and it is located close to several large epithermal deposits related to subalkaline volcanic rocks, including (in decreasing order of size) Yangjia-Wuyi, Houshu, Hushan, and Badu.

In Newfoundland, Canada, the St. Lawrence fluorspar project, which has had exploration ongoing for nearly a decade by Canada Fluorspar, Inc., appears to be becoming active again, after a period of pause and review. Arkema, Inc. of France became a joint-venture partner with Canada Fluorspar in May 2012, stimulating a review of the project's costs that began in about September 2012. The project issued an updated preliminary feasibility study in 2013 (Lecuyer and others, 2013). No new startup date had then been announced. The project planned to mine two large veins, the Blue Beach North and the Tarefare veins, which cut Late Devonian or Early Mississippian peralkaline granite (Van Alstine, 1944; Teng and Strong, 1976; Strong and others, 1984). This mining district was last active in 1978, but mining had been documented there for up to 45 years before that time, and some records indicate that it had been mined as early as 1870 by early French settlers. Total indicated and inferred resources on the Blue Beach North and Tarefare veins combined are 10.05 million metric tons grading 41 percent CaF_2 (Lecuyer and others, 2013). Plans were in place to produce about 131,000 metric tons per year of acidspar.

In the United Kingdom, British Fluorspar was formed as a successor of Minmet UK, Ltd., and the company has reopened the Milldam Mine on Hucklow Edge Rake in the Southern Pennine Orefield (Hodge, 2012). British Fluorspar restarted mining in March 2013 and sent its first shipments in May 2013 (Lismore-Scott, 2013). Milldam Mine was part of the holdings of the former Glebe Mines, last a subsidiary of INEOS Flúor, and Glebe had been separated from an acquisition of INEOS Flúor's fluorochemical business by Mexichem Flúor on April 1, 2010. That had led to an end, for a time, to fluorspar mining in the United Kingdom, as of the end of 2010, although Mexichem had continued to operate the fluorochemical production facilities of the former ICI/INEOS using acidspar imported from Mexico.

Summarizing the above, there are multiple new fluorspar mines being started up or reopened around the world, including a mine in China as well as at least one mine each in five other countries. Four of those five mines (excluding the Milldam Mine) planned cumulative production of about 770,000 metric tons per year of fluorspar within a few years. Additional resources have been identified in Australia, South Africa, Tunisia, the United States, and probably a few other countries. Hodge (2012) was clearly correct in his conclusion that ". . . there should be no serious supply shortages providing a pragmatically sensible and ongoing rapport is established . . . between consumers and producers."

Miller (2013) estimated the reserves of fluorspar of various countries for which information was available at that time. In units of 100 percent CaF_2 and rounded to the nearest million metric tons, they are as follows, from most to least reserves among the top eight countries: South Africa, 41 million metric tons; Mexico, 32 million metric tons; China, 24 million metric tons; Mongolia, 22 million metric tons; Spain, 6 million metric tons; Namibia, 3 million metric tons; Kenya, 2 million metric tons; and Brazil, 1 million metric tons. Reserve data were not available for Kazakhstan, Morocco, Russia, and the United States. As discussed above, reserves from Vietnam and Canada and additional reserves from the United States can be expected to enter this list soon. Reserves in the remainder of the world were estimated to be 110 million metric tons totaling, together with the eight countries for which reserves were reported, about 240 million metric tons. The world's total identified resources were estimated to be 500 million metric tons of contained fluorspar (Miller, 2013).

Undiscovered Resources in the United States

A preliminary model for large, high-grade fluorspar deposits has been developed based on deposits in Mexico. Such deposits as Las Cuevas (San Luis Potosi State), Realito (Guanajuato State), and El Refugio (Guanajuato State) are localized along faulted and brecciated contacts between Cretaceous limestone and Tertiary rhyolite, east of the main volcanic arc that is slightly older than the rhyolite. The fluorspar-related rhyolites are post-convergent and extension-related and are not derived from the same arc (or any arc) (Steve Ludington, U.S. Geological Survey, retired, written commun., 2013). Deposits in Texas in a belt parallel to the Rio Grande from El Paso to Big Bend National Park share most if not all of these characteristics, but the deposits are too small to mine profitably (McAnulty, 1974). Modern exploration has not taken place in these areas. Elsewhere along the Rio Grande Rift are numerous fluorspar occurrences and deposits (Van Alstine, 1976), some of which are fairly large (Hansonburg district, New Mexico, for example). Modern exploration techniques have not been applied in those areas either.

Iron Mountain, N.M., is a fluorine-, beryllium-, and tungsten-bearing skarn related to a strongly differentiated granite (Jahns and Glass, 1944), and this type of mineralizing system has formed many large deposits around the world (fig. G4).

The presence of additional strongly differentiated granites in southwestern New Mexico is predictable, perhaps, by the numerous occurrences of wood tin related to rhyolite flows and domes in that region (Maxwell and others, 1986). A one-to-one relation between rhyolites with wood tin and strongly differentiated granites has not been demonstrated, however.

The province of Late Cretaceous two-mica granites described by Barton and Trim (1991), including the granite porphyry related to the McCullough Butte deposit in Eureka County, Nev., could be examined closely to determine if others of those granites have related fluorite-bearing skarns. Likewise, the province of tin granites on the Seward Peninsula in Alaska (Hudson and Arth, 1983) might contain additional fluorspar skarn-and-greisen deposits similar to the Lost River deposits. Other areas of Alaska with tin greisen mineralization have been explored but with little attention paid to the associated fluorspar (Hudson and Reed, 1997).

The Basin and Range province of the United States in Nevada and parts of Arizona, California, Oregon, and Utah may contain lacustrine brines that have extractable fluorine. Taking Lake Magadi (Kenya) and Lake Natron (Tanzania) discussed earlier in this chapter as examples, the water in and beneath Alkali Lake in Lake County, Oreg., could be an analogous evaporitic brine from which fluorine might be recoverable. That playa lake has magadiite (monoclinic $NaSi_7O_{13}(OH)_3 \bullet 3H_2O$) and trona precipitated as evaporites in the lake's recent sediments (Rooney and others, 1969), which are the same two minerals that characterize the evaporite minerals of Lake Magadi and Lake Natron. Chemical data for water from several sites around the Alkali Lake basin from 1969 and 1970, however, show a maximum fluoride concentration of only 12.75 milligrams per liter (mg/L), which is about 100 times less than the largest concentrations at Lake Magadi (Newton and Baggs, 1971, p. 18–30). The highest fluorine value comes from a water sample with a pH of 10 and total dissolved solids of 74,850 mg/L, both also highest among the 13 water-sample analyses from the Alkali Lake area. Together, these water chemical values appear to indicate that some of the same evaporation-dominated processes are operating at Alkali Lake as operate at Lake Magadi and Lake Natron. Other basin and range lakes with recent evaporitic precipitates of trona include Big Soda Lake located northwest of Fallon, Nev. (Vanderburg, 1940); Searles Lake, California (Smith, 1979); and Deep Springs Lake, Calif. (Jones, 1965). Water analyzed by Jones (1965, p. A30) from near Deep Springs Lake had concentrations up to 171 ppm fluorine. Although this sample was anomalous, the fluorine concentration is still roughly 10 times smaller than in Lake Magadi. Most of the water analyses reported in Smith (1979) at Searles Lake did not include fluorine among the analytes, but eight did. The highest fluorine concentration among those eight samples was 35 ppm, which is approximately 10 times the typical fluorine concentration in low-temperature surface water or groundwater, but it is still far below a concentration that would be economically interesting for its fluorine content.

Undiscovered Resources in Other Countries

Conclusions from the analysis in the Identified Resources in Other Countries section are extensible to the subject of worldwide undiscovered fluorine resources; in short, the world likely has no shortage of deposits yet to be discovered. Many deposits probably remain to be discovered on every continent. Deposits of every type (fig. G3) almost certainly remain to be discovered, though some general additional guidelines for exploration can be helpful to supplement deposit-type models.

In the category of undiscovered resources, perhaps the most interesting is the possibility of producing a fluorine product from the high-fluorine, high-pH, sodium-carbonate brines of Lake Magadi (Kenya) and Lake Natron (Tanzania) in the East African Rift system. Also, apparently conformable fluorspar deposits in tuffaceous limy lacustrine sediments, such as those in Italy, are likely to occur in similar young alkalic volcanic settings elsewhere in the world.

Production and Consumption

Fluorspar mining began in the United States at various locations between 1820 and 1840. The first commercial production appears to have been in 1837 from a vein in Trumbull, Fairfield County, Connecticut. The existence of fluorspar in Illinois and Kentucky was known from the early 19th century, but it was not until 1871 that the first commercial shipments from Kentucky to a glassworks in Baltimore were recorded (Ladoo, 1927, p. 2–3). Production was limited by demand to at most a few thousand metric tons per year until the late 1880s when demand for its use as a flux in steelmaking was bolstered by the introduction of the open-hearth-furnace steelmaking process. The United States was the world's leading producer of fluorspar until it was surpassed by Mexico in the mid-1950s (McDougal and Roberts, 1958).

U.S. domestic fluorspar production peaked during World War II at 375,000 metric tons in 1944 (Miller, 2002). In the post-World War II period, a booming economy and increasing consumer demand for products containing aluminum, fluorochemicals (especially chlorofluorocarbons), and steel continued to push U.S. consumption of fluorspar upward. Domestic production, however, was unable to keep up with rising demand and in the mid-1970s, the domestic fluorspar mining industry began to decline because of foreign competition. In 1996, primary fluorspar mining in the United States ceased, although small amounts continued to be recovered as a byproduct of quarrying activities in southern Illinois (fig. G7). Consumption of fluorspar peaked in the early 1970s, which was, not coincidentally, also the peak period of U.S. steel production. Thereafter, decreasing steel production, a change in consumption practices by the steel industry, and the ban on chlorofluorocarbons when it was found that they were responsible for the "ozone hole" above Antarctica resulted in a general decrease in U.S. fluorspar consumption. From that time, consumption stabilized and then began to

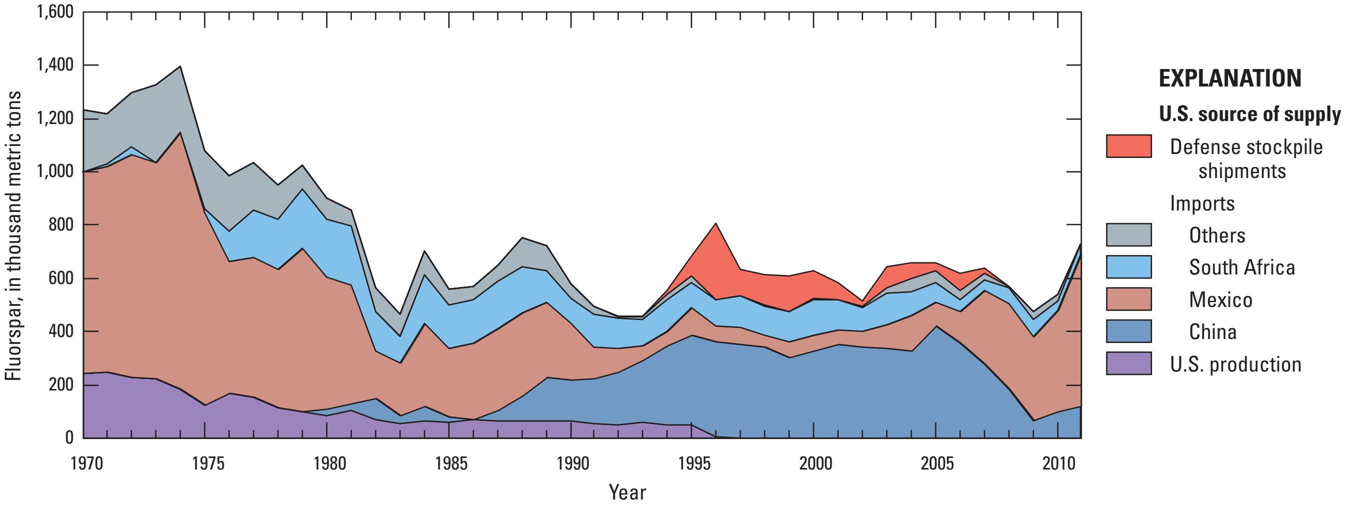

Figure G7. Graph showing sources of U.S. fluorspar supply from 1970 to 2011. The layers of the graph are placed one above the other, forming a cumulative total. Data are from U.S. Bureau of Mines (1972–96) and U.S. Geological Survey (1997–2016).

increase slowly as replacement fluorocarbon compounds, such as hydrochlorofluorocarbons and hydrofluorocarbons, were introduced into the market (U.S. Bureau of Mines, 1972–96; U.S. Geological Survey, 1997–2016).

Despite substantial domestic production for much of the 20th century, the United States has been a net importer of fluorspar since the early 20th century. Sources of supply for the United States have changed over the years. Beginning during the period of peak U.S. consumption, the United States sources of supply have been dominated by a few countries—China, Mexico, and South Africa (fig. G7). In addition, between 1993 and 2006, the U.S. fluorspar supply was augmented by sales from the National Defense Stockpile. In 2012, annual world production and consumption was about 7 million metric tons. The leading fluorspar producing countries were, in descending order, China, Mexico, Mongolia, and South Africa, which together accounted for 89 percent of estimated world production (Miller, 2016).

The global supply of fluorspar available for export decreased between 2001 and 2012 because of the substantial decreases in exports from China. China began exporting significant amounts of fluorspar in the 1960s, and the first exports to the United States took place in 1980 (fig. G7). China was the world's leading fluorspar exporter from the early 1990s to 2008 or 2009. Beginning in the early 2000s, China's fluorspar exports started to decrease as its domestic consumption increased. Producers outside of China were unable to increase production capacity to make up for the reduction in global supply. At the same time, global industrial activity increased, resulting in increased demand for fluorspar and higher prices (U.S. Bureau of Mines, 1972–96; U.S. Geological Survey, 1997–2016).

In recent decades, the United States annual fluorspar consumption has ranged from 500,000 to 700,000 metric tons per year, although "fluorine" consumption is higher because the United States imports significant amounts of HF as well as aluminum fluoride and synthetic cryolite. In 2012, the United States imported 133,000 metric tons of HF (equivalent to 293,000 metric tons of acid-grade fluorspar) and 58,100 metric tons of aluminum fluoride and synthetic cryolite (equivalent to an additional 85,000 metric tons of acid-grade fluorspar; Miller, 2016).

Fluorine, mostly in the form of fluorspar, is expected to continue to be important to the United States owing to its use in the manufacture of diverse materials and products necessary to the U.S. economy. The United States will continue to be import-reliant for most of its fluorspar needs, although in 2012, mine production began at the Klondike II fluorspar mine in the Illinois-Kentucky fluorspar district, mentioned earlier (Feytis, 2009). An additional fluorine resource exists in the form of fluorosilicic acid, which is produced as a byproduct of phosphoric acid production in the phosphate fertilizer industry. In 2012, U.S. phosphate reserves were estimated to contain about 100 million metric tons of 100 percent CaF_2-equivalent, and world reserves were estimated to contain 4.7 billion metric tons of 100 percent CaF_2-equivalent. In 2012, about 70,000 metric tons per year of 100 percent basis fluorosilicic acid was produced and used in the United States mostly for water fluoridation, although fluorosilicic acid can be used to produce aluminum fluoride, and the technology exists to convert it to HF (Miller, 2013).

The United States does have some remaining resources of fluorspar, and those were discussed in the previous section on Identified Resources in the United States. Internationally, several new mines either have been opened recently or are expected to open in the next few years, as discussed in the previous section on Identified Resources in Other Countries.

Exploration for New Deposits

None of the deposit types listed in figure G3 has been found in any oceanic geologic terrane, so apparently only continental rock terrains are favorable. Fluorite is commonly associated with end-member igneous differentiates, so exploration will profit from focusing on granites (all types, but particularly those not related to arc magmatism; that is, anorogenic granites), syenites, and carbonatites, and their volcanic equivalents. Fluorite is commonly found replacing limestone or dolostone. Thus, the optimal areas to explore are carbonates intruded by anorogenic granites, syenites, or carbonatites and carbonates in contact with anorogenic rhyolite or trachyte. The continental rifting association of salt-related carbonate-hosted fluorspar deposits could also be used to guide exploration; continental rifts have associated fluorspar deposits owing to their associated salt deposits and (or) their associated peralkaline to alkaline intrusive and volcanic rocks.

More specifically, provinces with strongly differentiated granites could be targeted for fluorspar skarn-and-greisen deposits. Although most of the belts of tin granites of the world have been identified, most of these belts have not been thoroughly explored for either tin or fluorspar. Some of the belts are located in places that are difficult to explore owing either to climate (for example, the Seward Peninsula tin granite province in Alaska and the Southeast Asian tin granite province) or other factors (for example, political risk in the Nigerian province). Taylor (1979, p. 6) has mapped 42 tin provinces worldwide, and provided consistently structured packages of information on 23 of these provinces (Taylor, 1979, p. 491–511). Not all of the provinces that have tin deposits have tin granites, however.

No fluorspar deposits analogous to those of the Latium Region, Italy, have been discovered to date, but that they would be unique in the world seems unlikely. The broadest scale indicator for these types of deposits would appear to be young alkalic volcanic rocks with interlayered lacustrine sedimentary rocks, and such volcanic rocks are widespread across the globe. As an initial test, a keyword search of geologic literature conducted on the combination of terms “phonolite” and “maar,” and a second search conducted on “trachyte” and “maar” yielded 15 areas of the world (in addition to central Italy). They are (1) the Czech Republic, (2) southern Italy, (3) northern South Africa, (4) western Germany, (5) east-central Germany, (6) southern Germany, (7) Hungary, (8) central France, (9) the Canary Islands, Spain, (10) Slovakia, (11) Shandong Province, eastern China, (12) Hawaii, (13) Big Bend National Park, Tex., (14) Pinacate volcanic field, northwestern Mexico, and (15) western Cameroon (including maar Lake Nyos in North-West Region, where a catastrophic lake-water overturn released CO_2 from depth in the lake and killed 1,700 people in 1986). Among these areas, the Canary Islands and Hawaii seem unlikely possibilities because no economic fluorspar deposits are known to occur on any oceanic islands. The Big Bend area of Texas, on the other hand, is firmly within the belt of fluorspar deposits in that region. Also, the Aguachile deposit in Coahuila State, Mexico, consists of limestone replacements adjacent to rhyolite porphyry ring dikes of a caldera; these replacement deposits may have formed beneath a caldera lake.

As mentioned previously, an unconventional source of fluorine could be brines from Lake Magadi and Lake Natron along the East African Rift, as well as other places where such alkaline evaporite brines may occur.

In the past, exploration for fluorspar deposits has not used methods comparably sophisticated with those used in exploring for such minerals as gold and copper. Most deposits have been found by simply following up occurrences of outcropping fluorite. It was common for mines to drill only enough to establish a few years’ worth of reserves ahead of the mining operation. This has probably begun to change since the advent of such requirements as those of the Canadian Government NI 43–101 reports and Australia’s JORC-compliant resource and reserve estimates. The requirements of such publicly released documents has encouraged the estimation of total deposit resources to be known before financing and various government permitting approvals are granted, or it has at least encouraged the definition of resources adequate for many years of mine life. Even just a few decades ago, geophysical methods were seldom used in exploration for fluorspar. Geochemical exploration methods were slightly more common, but still not heavily used. The future probably will see the use of increasingly sophisticated geophysical and geochemical methods of exploration.

Grogan (1960, 1964) was of the opinion that geochemical prospecting was not well adapted to finding fluorspar deposits because he thought that fluorite is too effectively dispersed, being soft and extremely cleavable. Geochemical prospecting for fluorspar deposits has succeeded in some areas, however. Van Alstine (1965) demonstrated effective results from sampling and analyzing rock or soil for fluorine in various areas within the Browns Canyon district in Chaffee County, Colo. In addition, geochemical prospecting was shown to be effective in an area near the Osor vein in the eastern Pyrenees in Spain’s Catalonia Autonomous Region (Schwartz and Friedrich, 1973). Near Osor, broad-scale prospecting using measured fluoride in surface water identified target areas of 3 to 10 km^2. Dry stream-sediment samples narrowed the search to targets of less than 1 km^2 and led geologists to mineralized outcrops. Then, fluoride in soil samples was used to map small areas and guide placement of drill holes. The work resulted in discovery of an area of fluorite veinlet stockwork. In addition, surface waters proved to be an effective medium for district-scale exploration. This is likely because of the relatively high solubility of fluorine at low temperatures and because of fluorite’s increasing solubility with decreasing temperature below about 60 °C (fig. G2).

Three different studies (Graham and others, 1975; Deering and others, 1983; and Ebbott and others, 1985) have shown that groundwater sampled from wells revealed areas of high fluorine concentration broadly centered on areas of fluorite-bearing MVT mineralization. This method would not be applicable in areas of greenfield exploration because the distribution of water wells into a target aquifer would be insufficient in remote areas. The method is applicable in the agricultural areas of central North America, although only in defining an area of tens of square kilometers as anomalous.

An extensive rock geochemical study of the Taskaynar deposit related to a strongly differentiated granite in Kazakhstan demonstrated that several additional elements had primary dispersion patterns similar to that of fluorine, and, consequently, might be used as "pathfinders" in exploration, especially to guide exploration drilling. The Taskaynar deposit is hosted by sandstone that lies above limestone with nearby "porphyrite" and granodiorite. The elements Ag, As, Ba, La, Mo, Sr, Y, and Yb all had primary dispersion patterns that were as far-reaching from the ore as fluorine itself. The dispersion patterns of lead, zinc, and sodium+potassium were somewhat more restricted around the orebody, but also had abundance boundaries parallel to the fluorine boundaries, and both showed control by fracturing (Koplus and others, 1977).

In exploring for skarn-and-greisen fluorspar deposits related to strongly differentiated granites, several more sophisticated methods could be brought to bear. Gravity and magnetic geophysical studies could be used to determine the depths to crystalline rocks through sedimentary cover, with the magnetics also directly targeting magnetite-bearing skarn. For a deposit standing upright and arrayed around a granitic cupola on a larger batholith, detailed magnetic surveys could help identify magnetite-bearing skarn, probably forming a magnetic ridge in a partial ring around a magnetic low, the low produced by greisen with a nonmagnetic pyrite-muscovite(-fluorite) assemblage. Fluorspar system-related but locally developed semimassive sulfide bodies typically rich in sphalerite-pyrrhotite-arsenopyrite can be detected by a number of different methods that show anomalies in rock conductivities. An airborne electromagnetic survey using the Barringer INPUT (induced pulse transient) method detected such a sulfide-rich body at the Ar Ridaniyah fluorite-bearing tin skarn system located 200 km west of Riyadh, Saudi Arabia, in 1967 (Canadian Aero Mineral Surveys, Ltd. and Arabian Geophysical and Surveying Company, 1967).

Most vein fluorspar deposits of various types are also detectable using methods that measure conductivities. Successful exploration of fluorite veins in granitic terrain using the combination of very low frequency (VLF) electromagnetics and audio-magnetotelluric (AMT) methods was reported by Zhang and others (2010). Vein fluorspar deposits are amenable to discovery by such methods despite the low conductivity of fluorite. Anomalous amounts of saline groundwater in fractured porous rock of fault zones mineralized by fluorite and (or) metallic sulfide minerals associated in minor concentrations with the vein fluorite are detectable. In China, VLF electromagnetics provided clear resolution of veins and accurate positioning of their location near the surface, and AMT methods provided accurate location of the veins at greater depth (Zhang and others, 2010). These methods could work effectively as long as the host rocks of the veins have high resistivities (that is, low conductivities) so that the vein zones contrast sufficiently.

Environmental Considerations

Sources and Fate in the Environment

Fluorine is chemically and biologically active. It readily forms hydrogen fluoride or combines with metals to make fluoride compounds, some of which are relatively stable, such as calcium fluoride (fluorite). The weathering of rocks and soils may release dissolved fluoride into the environment, and fluoride is added to drinking water in some countries, which is then released into surface water in municipal wastewater. Clay content, pH, temperature, and the concentrations of aluminum, calcium, magnesium, phosphorus, and hydroxides all influence the dissolved fluoride content of water. Fluoride compounds generally are most soluble and thus mobile under acidic conditions. In contrast, alkaline conditions in the presence of carbonates limit the mobility of fluorine in the environment; fluorine is fixed by reaction with carbonates to form stable fluorides. In the absence of carbonates, however, alkaline evaporitic conditions yield the greatest known solubility of fluorine at ambient temperature (table G2). Also, fluorine is easily sorbed by clay minerals (Kabata-Pendias and Mukherjee, 2007). As previously mentioned, fluorite tends to dissolve as temperature decreases (that is, it has "retrograde" solubility) under most earth-surface temperatures (60 °C to freezing, depending on the composition of the water; Richardson and Holland, 1979).

Fluorine is present in most natural waters. River waters commonly contain between 0.05 to 2.7 ppm fluorine, whereas seawater generally contains between 0.03 to 1.4 ppm with a median of approximately 1.3 ppm fluorine (table G2). High concentrations of fluorine have been shown to be present in waters in regions of volcanic activity or granitic bedrock, particularly in arid areas, and where fluorite or phosphates are mined and processed. China, East Africa, and India have the most extensive areas of high-fluorine groundwaters (Jacks and others, 2005). Table G2 includes examples of both naturally occurring and mine-influenced concentrations of fluorine in waters. One extreme example of naturally occurring concentrations of fluorine in surface waters is in Africa's Eastern Rift Valley in Kenya and Tanzania where concentrations reached 437 ppm from the weathering of volcanic rocks; evaporation also concentrates the fluorine in the water, locally elevating the fluorine concentration to above 2,000 ppm in closed basin lakes in that setting (table G2; Kilham and Hecky, 1973; Jones and others, 1977). An example of anomalous mine-affected waters is that within mine workings at the now-closed Lovozero niobium mine in Russia that were highly alkaline (pH 9.6 to 12) and contained extreme concentrations of fluorine (1 to 1.5 percent) and silica (1 to 1.3 percent) (table G2; Kraynov and others, 1969).

The amount of fluorine in soils is a reflection of its content in parent rocks as influenced by soil-forming processes, soil texture, and climatic conditions. Concentrations of fluorine in most soils range between 150 to 400 ppm (Kabata-Pendias and Mukherjee, 2007). For soils in the conterminous United States, fluorine concentrations average 430 ppm and range from less than 10 to 3,700 ppm (Shacklette and Boerngen, 1984). The lowest fluorine content is found in sandy soils under humid climate conditions and the highest content is in clay soils and soil derived from mafic rocks (Kabata-Pendias and Mukherjee, 2007). High levels of fluorine (more than 1,000 ppm) have commonly been reported for uncontaminated soils derived from fluorine-rich bedrock (Fuge and Andrews, 1988; Ermakov, 2004). Contaminated soils surrounding aluminum processing plants, china clay production facilities, and phosphate-fertilizer factories have been reported to contain between 2,000 and 3,600 ppm fluorine (Kabata-Pendias and Pendias, 2001).

The major natural source of atmospheric fluorine in the environment is volcanic activity, with sea-salt spray and suspension of soil by wind as additional natural sources. Anthropogenic sources include mining and processing of phosphorites, apatites, and fluorite; production of cement, bricks, steel, aluminum and other metals; combustion of coal; and production and use of fertilizers, fluorine-bearing pesticides, and drugs, plastics, and refrigerants (Ermakov, 2004). Fluorine is removed from the atmosphere primarily by wet deposition either as particulate fluorides or by dissolving into atmospheric water. Fluorine concentrations in the atmosphere are variable. The ambient air concentration of gaseous fluoride varies from 0.01 to 2.1 parts per billion (0.01 to 2.1 micrograms per cubic meter) in the United States and Canada, with about 75 percent as hydrogen fluoride (Bourgeau and others, 1996).

The geochemical signatures in soils and waters associated with fluorspar deposits before mining are variable because fluorite is common in a wide range of geologic environments. The chemistry of soils, streams, and groundwaters near fluorspar deposits reflect the composition of the ore and host rock, the structure of the deposit, and the climatic conditions. Streamwater and groundwater near deposits may not display the same geochemical signature as soils and stream sediments because some of the enriched elements occur in relatively stable insoluble minerals. For example, soils and weathered rock associated with carbonatite deposits may be naturally enriched in Ba, Fe, Nb, P, REEs, Th, Ti, U, and Zr, and stream sediments downstream from deposits commonly contain anomalous abundances of Ba, Nb, Th, and REEs (Modreski and others, 1995). The content of such elements as Nb, REEs, Th, and U may not be anomalous in streamwaters, however, because they are present in relatively stable, insoluble minerals (Modreski and others, 1995). The pre-mining environment around alkaline- to peralkaline-related deposits may contain anomalous concentrations of some of the same elements as carbonatites, including Be, Li, Nb, REEs, and Ta. Streamwaters near the Yermakovskoye deposit in Russia contained naturally elevated concentrations of Cu, F, Fe, Hg, Mn, Mo, and Zn. In addition, native soils near the deposit contained anomalous concentrations of As, Ba, Be, and F (Kislov and others, 2010). Natural metal-rich acidic drainage could be significant from deposits associated with significant pyrite or other sulfides. Carbonates are nearly ubiquitous at fluorspar deposits and may neutralize the acid generated by sulfides by removing many trace elements from the solution. In MVT deposits, iron, lead, and zinc from the weathering of associated sulfides may occur in anomalous concentrations in soils and stream sediments; however, at most deposits, elevated concentrations of these metals are not present because carbonate rocks limit the dispersion of trace elements by precipitating them as carbonates (Leach and others, 1995).

In the United States, some fluoride compounds are recycled in industrial settings. For example, synthetic fluorite is recovered from uranium enrichment and, to a lesser extent, from petroleum alkylation and stainless-steel pickling, producing on the order of a few thousand metric tons per year. In addition, aluminum producers recycle hydrofluoric acid and fluorides from smelting operations, and hydrofluoric acid is recycled in the petroleum alkylation process (Miller, 2013). New methods are being developed to recover fluoride from industrial wastewaters. One of these methods produced a nearly pure synthetic fluorite (>97 percent) that can be used for the manufacture of hydrofluoric acid (Aldaco and others, 2007).

Mine Waste Characteristics

Mine waste is the material generated during ore extraction and processing at the mine site that has no direct economic value. The volume and characteristics of the waste material depend on the type of deposit and its size, the commodity or commodities recovered, and the mining and processing methods used. A summary of the mineralogy, chemistry, and volume, if available, of mine waste generated at several fluorspar mines is presented in table G3.

In general, overburden may need to be removed or host rock separated from the fluorite-rich ores as the first step of ore extraction; the fluorite-poor material becomes waste rock and can be backfilled into mine workings or pits, disposed of in waste piles, or, depending on the composition, used or sold for reuse (for example, as aggregate for construction purposes). The next step is to concentrate the fluorite in the ore. This is accomplished using a variety of methods, which typically include crushing and grinding followed by gravity separation and (or) flotation. The gangue minerals become the major components of waste tailings; common gangue minerals include calcite, dolomite, quartz, sulfides, and (or) barite, and, for carbonatite-related deposits, possibly apatite. Gravity separation is most often used to separate fluorite from calcite and silicates. Chemical flotation is used, however, when barite, celestite, or sulfide minerals are present, as they are denser than fluorite. Tailings generated from flotation are usually disposed of as an aqueous slurry into a tailings impoundment, where they are allowed to dry.

It is common for mine waste to contain a significant amount of fluorite as a result of inefficient or nonrecovery in years past; at some places, the fluorite content is high enough that the waste can be reprocessed using current methods (most commonly flotation) to recover most of the remaining fluorite. For example, mine waste and tailings from several locations in Kentucky (Crittenden and Livingston Counties) were reprocessed during World War II to meet the increased demand for fluorite (Fine, 1948). The tailings and waste rock contained a significant amount of fluorite (up to 59 percent), as well as calcite, chert, clay, and quartz; a minor amount of barite; and some lead and zinc sulfides (table G3). Another example of mine waste with a significant amount of fluorite (up to 17 percent total fluoride) is from fluorite and lead-zinc mines from the Northern Pennine Orefield and the Southern Pennine Orefield in the United Kingdom (table G3; Cooke and others, 1976; Fuge and Andrews, 1988). Modern recovery in fluorite operations is generally more efficient than in earlier operations.

Human Health Concerns

Fluorine is essential for some organisms but, like most substances, in excess, is highly toxic. Soluble forms of fluorine are absorbed into the body through the mouth lining, stomach, and intestines. Nearly all fluorine in the human body is in the form of fluorapatite, which is resident mostly in the bone, teeth, and cartilage (Ermakov, 2004). The primary chronic exposure route of concern for fluorine compounds is oral ingestion of drinking water, food, and fluoride-containing dental products. Inhalation and dermal exposure to HF is an acute occupational exposure that can occur (Agency for Toxic Substances and Disease Registry, 2003).

Fluorine is important for hard teeth in humans. In the United States, artificially fluoridated water commonly contains between 0.7 and 1.2 ppm fluorine (National Research Council, 2006). Fluorine deficiency in humans (less than 0.3 to 0.5 ppm in drinking water) leads to tooth decay and osteoporosis. Also, animals with diets low in fluorine have exhibited slow growth, reproduction issues, and higher mortality (Ermakov, 2004). On the other hand, consumption of water with high concentrations of fluorine may lead to dental and skeletal fluorosis (that is, mottling of the tooth enamel, and pain and damage to bones and joints, respectively) starting at concentrations of 1.5 ppm and becoming severe at greater than 6 ppm (Reimann and de Caritat, 1998). Other health effects related to a high intake of fluorine include endocrine effects and carcinogenic changes, particularly in bone (National Research Council, 2006). According to the U.S. Environmental Protection Agency (2002), the no-observable-effect level for dental fluorosis based on children is approximately 1.0 ppm fluoride, whereas crippling skeletal fluorosis, the most severe stage of skeletal fluorosis, was not observed in adults at consumption levels of up to 4 ppm fluoride. In the United States, primary and secondary drinking water standards have been established for fluorine. The primary drinking water standard (maximum limit of 4 ppm fluorine) was established to prevent adverse health effects and the secondary standard (maximum limit of 2.0 ppm fluorine) was established to reduce adverse cosmetic consequences (U.S. Environmental Protection Agency, 2009). A recent review of the U.S. drinking water guidelines by the National Research Council (2006) suggests that the maximum contaminant level of 4 ppm should be lower. For comparison, the World Health Organization reports a guideline value of 1.5 ppm (World Health Organization, 2008).

Skeletal deformations and the crippling bone deformities of genu valgum (that is, knock knee) have been reported to occur in regions in India, Kenya, and Tanzania where high levels of fluorine (3 to 8 ppm) are present in drinking water (Ermakov, 2004). Also, surface water, groundwater, and mine water from Kerio Valley, Kenya, in Africa's Eastern Rift Valley, reaches 305 ppm, with average values greater than 25 ppm fluoride (table 2; Davies, 1994); tooth decay, dental and skeletal fluorosis, and osteochondral conditions are common in this area. Regional groundwater studies in China and Mexico also link high fluorine groundwaters to high fluorine rocks and fluorspar mines with some documentation of serious human health effects (Fuhong and Shuqin, 1988; Mahlknecht and others, 2004).

Although severe human health effects from high fluoride in drinking water are not commonly reported in the United States, naturally occurring fluoride concentrations in waters do exceed U.S. drinking water standards in several areas. In 1992, approximately 10 million people had public water supplies that were naturally fluoridated. The concentration of fluoride in 14 percent of those people's drinking water supplies were between 2.0 and 3.9 ppm; about 2 percent of those people's water supplies had concentrations equal to or greater than 4.0 ppm fluoride. The highest, but not necessarily typical, concentrations were found in Colorado, Oklahoma, New Mexico, and Idaho, with maximum values of greater than 10 ppm fluoride (National Research Council, 2006). In Texas, where groundwater makes up about 60 percent of the drinking water consumed, well water from a northwest region in the state exceeded the drinking water standard of 4 ppm fluoride in more than 50 percent of the samples (Agency for Toxic Substances and Disease Registry, 2003). For those areas with fluoride greater than 4 ppm in the drinking water, the Agency for Toxic Substances and Disease Registry recommends buying bottled drinking water.

Table G3. Selected examples of the chemistry and mineralogy of mine waste generated at fluorspar mines.

[Elements: Ca, calcium; Cd, cadmium; Cu, copper; F, fluorine; Fe, iron; Ni, nickel; P, phosphorus; Pb, lead; S, sulfur; Si, silicon; Zn, zinc. Abbreviations and symbols: ppm, part per million; wt. %, weight percent; —, not determined or not reported; ?, identification uncertain]

Sample type	Location	Deposit type	Minerals/compounds/components
Tailings and mine waste (pre-World War II)	Several locations in Crittenden and Livingston Counties, Kentucky, United States	Mississippi Valley-type	Fluorite (13 to 59 wt. %), calcite (2 to 28 wt. %), quartz (8 to 65 wt. %); usually with smaller amounts of clay, barite (0 to 2 wt. %), Pb, Zn, Fe sulfides (sphalerite, galena, pyrite)
Tailings	Southern Pyrenees, France	?Salt-related, carbonate-hosted	Quartz, shale, iron hydroxides, fluorite (1 to 5 wt. %), iron carbonate, iron/copper sulfides
Mine waste[1]	Hammam Zriba Mine, Tunisia	Salt-related, carbonate-hosted	Quartz, barite, calcite > K-feldspar, sylvite > plagioclase, fluorite, limonite, zeolites, opaque minerals
Mine waste	Northern Pennine Orefield and Southern Pennine Orefield, United Kingdom	Mississippi Valley-type	Barite (16 to 23 wt. %), aluminosilicates (20 to 51 wt. %), calcium carbonate (15 to 32 wt. %), fluorite, among others

[1] Chemistry is for a partial digestion procedure (that is, silicates were not completely digested).

For soils, screening levels based on human health risk in the United States have been established based on the use of the land (residential versus industrial) to determine whether concentrations of elements or compounds at sites warrant further investigation or site cleanup. Screening levels for noncancer health effects are 3,100 ppm fluoride and 4,700 ppm fluorine (soluble fluoride) for residential land use and 41,000 ppm for fluoride and 61,000 ppm for fluorine (soluble fluoride) for industrial land use (U.S. Environmental Protection Agency, 2012). Natural soils in the United States, even those developed on fluorine-rich rocks, will almost never contain such concentrations, and if so, only in isolated small areas; however, such concentrations may be more common in soils located in industrial areas.

Other human health concerns related to fluorine are related to the mining and processing of fluorspar ores, which may expose workers to dust or, for some types of ores, radiation. Silica is associated with many types of ore, including fluorspar, and may be inhaled during mining and milling operations and can cause silicosis. In addition, inhaling high amounts of fluorspar dust during ore processing can lead to health issues that include gastric, intestinal, circulatory system, and nervous system problems, and, in the long term, anemia, weight loss, bone and teeth defects, pulmonary lesions, and bronchitis (Osinsky and Stellman, 1998). In the United States, the permissible exposure limits in air for fluorine in an 8-hour working day is 0.3 ppm (0.2 milligram per cubic meter) (Occupational Safety and Health Administration, 2013). Dust control should be carefully enforced for mining and processing of ores from any type of fluorspar deposit. In addition to dust, human health issues have been documented from exposure to radiation during the mining of deposits related to peralkaline granite in the St. Lawrence district in Newfoundland, Canada. In this district, higher incidences of lung cancer were reported for underground miners exposed to high levels of radon and its progeny during fluorspar mining; mining started in the 1930s and continued until 1978. In the early 1960s, mechanical ventilation was installed, which decreased radon to levels below the exposure limit (Morrison and others, 1998).

An additional human health concern associated with mining operations that process ores using flotation techniques, which include some fluorspar mines, is the failure of tailings impoundments. Although rare, collapse of tailings dams can destroy property and cause injuries, fatalities, and environmental damage. For example, a fluorspar mine in Italy that used flotation to process ores from 1961 to 1985 stored tailings and waste in two large tailings impoundments. In 1985, approximately 180,000 cubic meters (m^3) of tailings slurry was inadvertently released and flowed into a valley, destroying a small town and causing destruction in another small town; this event caused 268 deaths and 100 injuries. The failure was owing to construction errors and a lack of operational monitoring during tailings deposition (Luino and De Graff, 2012). In more recent times, technical and scientific investigations on tailings impoundments and new legislation and regulations for stricter control and monitoring are helping to minimize tailings dam failures.

Table G3. Selected examples of the chemistry and mineralogy of mine waste generated at fluorspar mines.—Continued

[Elements: Ca, calcium; Cd, cadmium; Cu, copper; F, fluorine; Fe, iron; Ni, nickel; P, phosphorus; Pb, lead; S, sulfur; Si, silicon; Zn, zinc. Abbreviations and symbols: ppm, part per million; wt. %, weight percent; —, not determined or not reported]

pH	Ca (wt. %)	F (wt. %)	Fe (wt. %)	P (wt. %)	S (wt. %)	Si (wt. %)	Cd (ppm)	Cu (ppm)	Ni (ppm)	Pb (ppm)	Zn (ppm)	Reference
—	—	—	—	—	0.03 to 2.2	—	—	—	—	<500 to 8,200	1,000 to 38,300	Fine (1948)
—	—	—	3.5 to 7	—	—	37 to 42	—	—	—	—	—	European Commission (2009)
—	7.8	—	0.31	0.11	0.3	—	36	34	0.5	3,420	12,100	Yoshida and others (2002)
6.2 to 7.7	—	2.3 to 17.4	—	0.001 to 0.06	—	—	8 to 28	32 to 67	30 to 65	4,360 to 30,800	2,020 to 20,360	Cooke and others (1976)

Ecological Health Concerns

Only small amounts of fluorine are taken up by plants from soils. Terrestrial plants from uncontaminated soils usually do not contain greater than 30 ppm fluorine and likely do not require fluorine (Kabata-Pendias and Mukherjee, 2007). Plants, in particular tea plants (*Camellia sinensis*), however, can accumulate up to 2,000 ppm fluorine in areas with high soil concentrations. Levels of fluorine in soils between 200 and 2,000 ppm have been shown to result in toxicity to plants (that is, phytotoxicity) (Ermakov, 2004). Food plants commonly contain between 0.1 and 11 ppm (Kabata-Pendias and Mukherjee, 2007). Fluorine on and within the plant parts can enter the food chain by animals foraging on the plants, and toxic threshold values for fluorine in fodder has been reported to be in the range of 20 to 50 ppm (Ermakov, 2004). Fluorine toxicity in dairy cattle has resulted in lower reproduction and lower milk production (Swarup and others, 1998). Studies on minks and screech owls reported effects on fertility and reproduction success when fluorine concentrations reached hundreds of ppm in food (Aulerich and others, 1987; Pattee and others, 1988). Marine aquatic organisms have been shown to accumulate fluorine, and fluorine concentrations are commonly an order of magnitude higher (for example, 500 ppm compared with 50 ppm) in sea organisms compared with freshwater fish and land organisms because of the generally higher fluorine levels in seawater compared to freshwater (Ermakov, 2004). Industrial releases of high amounts fluorine in waterways have had toxic effects on aquatic organisms (Davies, 1994; Agency for Toxic Substances and Disease Registry, 2003). Water-quality criteria and stream-sediment guidelines for the protection of aquatic life are generally lacking. Suter (1996), however, suggested an estimate of the highest concentration in surface water to which an aquatic community can be exposed briefly (that is, acute exposure) and indefinitely (that is, chronic exposure) without resulting in an unacceptable effect; these secondary acute and chronic aquatic ecosystem guidelines, established with fewer data than regulatory guidelines, are 19.2 and 1.18 ppm fluorine, respectively. These guideline concentrations are higher than those found in the vast majority of natural surface waters in the United States.

The mining and processing of ores may enrich waters and soils in potentially toxic elements and can cause ecological health concerns at some mine sites. Several examples from a few different fluorspar deposit types are discussed below. In general, ecosystem impact studies are more frequently conducted for sulfide-containing deposits, such as MVT deposits, because sulfides can generate acid and contribute to the release of some potentially toxic trace elements into the environment. Several studies have been conducted regarding the environmental impact of mining lead and fluorspar from MVT deposits in the Northern Pennine Orefield and Southern Pennine Orefield of the United Kingdom. The mine waste from the mines contains high concentrations of some trace elements as shown in table G3. Waters from one mine contained high concentrations of, in order of greatest environmental concern, zinc (up to 111 ppm), manganese (up to 138 ppm), iron (up to 68 ppm), and sulfate (up to 2,501 ppm), and, although most waters were near neutral, some were acidic, likely from sulfides in shales and mudstones (table G2; Johnson and Younger, 2002). Fluorine concentrations in soils surrounding mines in the Northern Pennine Orefield reach up to 20,000 ppm; surface waters, up to 2.3 ppm fluorine, and grasses up to about 400 ppm fluorine (table G2; Fuge and Andrews, 1988). A study of plants growing on mine waste in both the Northern Pennine Orefield and the Southern Pennine Orefield revealed fluoride concentrations of up to 4,500 ppm in leaves and up to 10,000 ppm in seeds; the plants did not shown signs of phytotoxicity (Cooke and others, 1976). Some waste piles have been revegetated to create natural ecosystems, and small mammals living on and near the revegetated piles have been shown to contain significantly higher levels of cadmium, fluorine, and lead and somewhat higher levels of zinc than do small mammals living in uncontaminated areas (Wright and others, 1978; Andrews, Johnson, and Cooke, 1984, 1989a, b: Andrews, Cooke, and Johnson, 1989). Geeson and others (1998) suggested health problems affecting young lambs living in the vicinity of old mines or smelters in the Southern Pennine Orefield may be related to the excess lead as well as fluorine in their diets.

Ecological health impacts have also been studied at a peralkaline to alkaline-intrusion-related fluorspar deposit in Russia that contains only a minor amount of sulfides. Waters from the open pit at the previously mined Yermakovskoye beryllium-fluorine deposit contained elevated concentrations of some elements, including Cu, Fe, Mg, Mn, Mo, Pb, and Zn, all of which exceeded local standards for water bodies used for fishery purposes. In addition, sediment at the bottom of the pit was contaminated with As, Be, Cd, Pb, and Zn, and the concentrations of Pb and Zn exceeded values above which effects to aquatic biota are likely. Mine waste piles contained concentrations of beryllium that were above the maximum allowable concentrations (Kislov and others, 2010). The natural background contents of some of the elements, such as Cu, F, Fe, Mn, Mo, and Zn, in local streams and melt waters are also elevated and above ecological-health guidelines, making it difficult to distinguish the contamination from mining from the pre-mining concentrations associated with the mineralized area. According to Kislov and others (2010), the pasture vegetation in the local area may contain high levels of beryllium from the deposition of contaminated dust, and the agricultural uses of the land should be limited.

The potential ecosystem health concern associated with the Moscona Mine, which is a salt-related carbonate-hosted fluorspar deposit in Asturias, Spain, is related to aqueous fluoride; acidic metal-rich mine drainage from the weathering of sulfides is not an issue because of neutralization by associated carbonates. Waters from within the underground mine and from a surface spring are saline (800 to 1,700 microsiemens per centimeter conductivity), have near neutral pH (pH 7.6 to 8.2), and contain elevated levels of fluoride (0.5 to 3.5 ppm), carbonate, and sulfate (table G2; Roqueñí and others, 2005). Also, each year approximately 200,000 m^3 of wastewater from the mine is discharged into a nearby stream, which results in fluoride concentrations of up to 4.8 ppm. The release of this water, some of which exceeds the secondary chronic surface water guideline for the protection of aquatic life as suggested by Suter (1996), may be a threat to the health of the local ecosystem: however, decant ponds were constructed to reduce the contamination of the nearby stream (Roqueñí and others, 2005).

Carbon Footprint

A new fluorine-based compound, hydrofluoroolefin, is recommended as a refrigerant for air conditioning in motor vehicles to replace an existing compound, chlorofluorocarbon, currently in use. The new compound has a lower global warming potential, which is a relative measure of the warming effects of greenhouse gases, than the fluorocarbon compound and has been approved by the U.S. Environmental Protection Agency as a replacement (U.S. Environmental Protection Agency, 2011). Another advantage of the replacement compound is that it may contribute to the reduction of ozone concentrations in the stratosphere.

Mine Closure

The post-mining landscape at mines, including fluorspar mines, depends on the deposit type and size, the character of the host rock, the mining and processing methods, the climate, and the regulations in place regarding mine closure. Open pits, shafts and adits from underground operations, processing facilities, mine and processing wastes, and drainage from the site may need to be addressed for mine closure. One example of a remediated mine site in the United States is the Burlington Mine, which was the largest fluorspar deposit in the Jamestown district in Boulder County, Colo.; this site was reclaimed through a Voluntary Clean Up action, which is a State cooperative program that encourages voluntary cleanup of contaminated industrial and commercial properties (O'Shea-Stone, 2011). The mine produced fluorspar, in addition to some silver, lead, and uranium, from 1920 to 1973; limited remediation was conducted at the time of mine closure, and a Voluntary Clean Up action was conducted within the past 10 years. Prior to the recent cleanup, the landscape included a large vegetation-free, acidic, waste pile, a mine adit and shaft openings, and subsidence features. In addition, water draining from the waste pile flowed into a nearby creek. The remediation efforts consisted of consolidating acid-generating waste rock, closing of the adit and shafts, filling subsidence pits, limiting surface water and groundwater interaction with waste materials and mine workings, adding soil amendments (including lime, soil, and compost) to waste rock piles and disturbed soils, and site-wide revegetation. In 2008, remediation efforts were considered successful by State and Federal agencies based on improved water quality, minimal erosion from the site, removal of safety hazards, and the establishment of a natural and functional self-sustaining plant community (O'Shea-Stone, 2011).

Other mines have not been reclaimed. For example, remediation efforts were not undertaken when production ceased in 1989 at the Yermakovskoye beryllium-fluorine deposit in Russia. The surface area of the open pit is 277,000 square meters with a depth of at least 70 m, and it contains a few meters of water in the bottom (Kislov and others, 2010). The impact to the ecosystem from the mined landscape was discussed in the previous section. Future plans for the site include resuming mining and construction of a processing plant; construction was expected to begin in 2013 (Jaskula, 2013). An estimated 8,500,000 m^3 of rock will be extracted from an open pit operation, including ore and waste rock (Kislov and others, 2010). The combined volume of sulfide-rich and nonsulfide-rich tailings generated will be about 830,000 m^3. Eventually, mine closure will involve stabilizing disturbed surfaces and reclaiming soils, waters, and stream sediments at and near the mine site.

Problems and Future Research

The Klondike II Mine (Livingston County, Ky.) began production in 2012, the Nui Phao Mine (Thai Nguyen Province, Vietnam) began production in 2013, and, until late 2013, the Nokeng Mine (Gauteng Province, South Africa) had been scheduled to start production in the second quarter of 2014. A number of other projects were projected to begin mining in the 2015–17 timeframe. With these new supplies, Chinese domination of the world fluorspar market is likely to lessen. Also, China's reduced exports of fluorspar in response to the need for fluorspar by their own industries may be compensated for with production from other countries.

The possible extraction of fluorine from alkaline, $NaHCO_3$-type evaporite brines is a subject deserving of additional research. Extraction of resources from brines has proven very cost effective for some mineral commodities, such as borax, lithium, potash, and soda ash. Lake Magadi (Kenya) and Lake Natron (Tanzania) within the Eastern Rift Valley contain large resources of surface and interstitial water with fluorine concentrations in excess of 1,000 ppm. Because the existing trona mining operation does not recover the villiaumite from the solid trona, it would seem a boon to remove fluorine from the brines, possibly allowing two new product streams—an evaporating pond product of fluorine-poor trona and a solid fluorine product of some type.

Exploration focused on discovery of new, apparently conformable fluorspar deposits in tuffaceous limy lacustrine sediments also could be fruitful. In the Latium Region of Italy, deposits were marginally economic because of difficulty recovering the fine-grained fluorite, but other regions may have deposits that do not have that problem. The Latium deposits are in a minimally eroded young volcanic terrane that is specifically ultrapotassic and alkaline. That set of parameters can be matched at multiple places in the world; for example, Italy's Pantelleria Island in the Mediterranean Sea between Sicily and Tunisia. The deposits in Italy could be studied further, possibly to include exploration of the nearby maar lakes to see if mineralization processes are ongoing in their bottom sediments.

Three types of research in recent years on the composition of fluid inclusions in hydrothermal ore deposits have led to greatly increased understanding of the sources of the hydrothermal fluids. These are quadrupole mass spectrometry (Landis and Hofstra, 1991), noble gas mass spectrometry on irradiated fluid inclusions (Kendrick and others, 2002), and study of chlorine isotopes in inclusion fluids (Partey and others, 2009). Each of these methods has succeeded in defining magmatic contributions to hydrothermal fluids where magmatic involvement had previously been in question. These methods are especially effective when combined with determination of cation concentrations and halogen ratios (Na^+:Br^- and Cl^-:Br^-) in the same hydrothermal fluids. The ratios can help define any component of redissolved halite within the fluids. The combined methods on elemental composition of solutes in the hydrothermal fluid can separate the fluids of salt-related carbonate-hosted systems from those of other systems with sedimentary brines as ore fluids (Sánchez and others, 2009, for example). These modern methods are likely to prove valuable when extended to additional deposits and districts. For deposits whose relation to igneous rocks is equivocal, such studies would provide critical new genetic knowledge. The fluid inclusion studies are even more effective when combined with modern isotopic age determination (Chesley and others, 1994; Sánchez and others, 2006; Munoz and others, 2005). These multifaceted methods have made clear the processes and tectonic setting that produced fluorspar and base-metal deposits in Western Europe of the class that here are called salt-related carbonate-hosted deposits. A promising place to apply this combination of methods is Las Cuevas in San Luis Potosi State, Mexico.

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References Cited

Note: All Web links listed were active as of the access date but may no longer be available.

Agency for Toxic Substances and Disease Registry, 2003, Toxicological profile for fluorides, hydrogen fluoride, and fluorine: Atlanta, Ga., U.S. Department of Health and Human Services, Public Health Service, September, 356 p. plus 4 appendixes, accessed April 30, 2013, at http://www.atsdr.cdc.gov/toxprofiles/tp.asp?id=212&tid=38.

Aldaco, R., Garea, A., and Irabien, A., 2007, Calcium fluoride recovery from fluoride wastewater in a fluidized bed reactor: Water Research, v. 41, no. 4, p. 810–818. [Also available at http://dx.doi.org/10.1016/j.watres.2006.11.040.]

Anderson, W.H., and Moodie, Boyce, III, 2010, Stop 1—Klondike II Mine, *in* Smath, R.A., comp., Selected areas within the western Kentucky fluorspar district and the Illinois fluorspar district and a tour of the Ben E. Clement Mineral Museum—Kentucky Society of Professional Geologists fall field trip guide, October 23, 2010: Lexington, Ky., Kentucky Society of Professional Geologists, Field Conference Guidebook, p. 14–15. [Also available at http://www.kspg.org/pdf/2010%20KSPG%20field%20guide%20REPLACEMENT%20PAGES.pdf.]

Anderson, W.H., and Sparks, T.N., 2012, Mines and minerals of the western Kentucky fluorspar district: Kentucky Geological Survey Series XII, Map and Chart 201, scale 1:50,000. [Also available at http://kgs.uky.edu/kgsweb/olops/pub/kgs/MC201_12.pdf.]

Andrews, S.M., Cooke, J.A., and Johnson, M.S., 1989, Distribution of trace element pollutants in a contaminated grassland ecosystem established on metalliferous fluorspar tailings. 3—Fluoride: Environmental Pollution, v. 60, nos. 1–2, p. 165–179. [Also available at http://dx.doi.org/10.1016/0269-7491(89)90225-x.]

Andrews, S.M., Johnson, M.S., and Cooke, J.A., 1984, Cadmium in small mammals from grassland established on metalliferous mine waste: Environmental Pollution, Series A, Ecological and Biological, v. 33, no. 2, p. 153–162. [Also available at http://www.sciencedirect.com/science/article/pii/0143147184901752.]

Andrews, S.M., Johnson, M.S., and Cooke, J.A., 1989a, Distribution of trace element pollutants in a contaminated grassland ecosystem established on metalliferous fluorspar tailings. 1—Lead: Environmental Pollution, v. 58, no. 1, p. 73–85. [Also available at http://dx.doi.org/10.1016/0269-7491(89)90238-8.]

Andrews, S.M., Johnson, M.S., and Cooke, J.A., 1989b, Distribution of trace element pollutants in a contaminated grassland ecosystem established on metalliferous fluorspar tailings. 2—Zinc: Environmental Pollution, v. 59, no. 3, p. 241–252. [Also available at http://dx.doi.org/10.1016/0269-7491(89)90229-7.]

Arveti, Nagaraju, Sarma, M.R.S., Aitkenhead-Peterson, J.A., and Sunil, K., 2011, Fluoride incidence in groundwater—A case study from Talupula, Andhra Pradesh, India: Environmental Monitoring and Assessment, v. 172, no. 1, p. 427–443. [Also available at http://dx.doi.org/10.1007/s10661-010-1345-3.]

Aulerich, R.J., Napolitano, A.C., Bursian, S.J., Olson, B.A., and Hochstein, J.R., 1987, Chronic toxicity of dietary fluorine to mink: Journal of Animal Science, v. 65, no. 4, p. 1759–1767. [Also available at http://dx.doi.org/10.2527/jas1987.6561759x.]

Bailey, J.C., 1980, Formation of cryolite and other aluminofluorides—A petrologic review: Bulletin of the Geological Society of Denmark, v. 29, p. 1–45. [Also available at http://2dgf.dk/xpdf/bull29-01-02-1-45.pdf.]

Barton, M.D., 1982, Some aspects of the geology and mineralogy of the fluorine-rich skarn at McCullough Butte, Eureka County, Nevada: Carnegie Institution of Washington Year Book, v. 81, p. 324–328.

Barton, M.D., and Trim, H.E., 1991, Late Cretaceous two-mica granites and lithophile-element mineralization in the Great Basin, *in* Raines, G.L., Lisle, R.E., Schafer, R.W., and Wilkinson, W.H., Jr., eds., Geology and ore deposits of the Great Basin—Symposium proceedings—Sponsored by the Geological Society of Nevada and United States Geological Survey, April 1–5, 1990: Reno, Nev., Geological Society of Nevada, v. 1, p. 529–538. [Also available at http://www.geo.arizona.edu/~mdbarton/MDB_papers_pdf/Barton[91_LEM2mica_GSN.pdf.]

Bau, Michael, Romer, R.L., Lüders, Volker, and Dulski, Peter, 2003, Tracing element sources of hydrothermal mineral deposits—REE and Y distribution and Sr-Nd-Pb isotopes in fluorite from MVT deposits in the Pennine Orefield, England: Mineralium Deposita, v. 38, no. 8, p. 992–1008. [Also available at http://dx.doi.org/10.1007/s00126-003-0376-x.]

Belkin, H.E., de Vivo, Benedetto, and Valera, Roberto, 1984, Fluid inclusion study of some Sarrabus fluorite deposits, Sardinia, Italy: Economic Geology, v. 79, p. 409–414. [Also available at http://dx.doi.org/10.2113/gsecongeo.79.2.409.]

Bell, Keith, and Powell, J.L., 1969, Strontium isotopic studies of alkalic rocks—The potassium-rich lavas of the Birunga and Toro-Ankole regions, east and central equatorial Africa: Journal of Petrology, v. 10, no. 3, p. 536–572.

Billström, Kjell, Broman, Curt, Schneider, Jens, Pratt, Warren, and Skogsmo, Göran, 2012, Zn-Pb ores of Mississippi Valley type in the Lycksele-Storuman district, northern Sweden—A possible rift-related Cambrian mineralisation event: Minerals, v. 2, no. 3, p. 169–207. [Also available at http://dx.doi.org/10.3390/min2030169.]

Boni, Maria, Balassone, Giuseppina, Fedele, Luca, and Mondillo, Nicola, 2009, Post-Variscan hydrothermal activity and ore deposits in southern Sardinia (Italy)—Selected examples from Gerrei (Silius vein system) and the Iglesiente district: Periodico di Mineralogia, v. 78, no. 3, p. 19–35. [Also available at http://dx.doi.org/10.2451/2009pM0010.]

Bose, Sankar, Das, Kaushik, and Fukuoka, Masato, 2005, Fluorine content of biotite in granulite-grade metapelitic assemblages and its implications for the Eastern Ghats granulites: European Journal of Mineralogy, v. 17, no. 5, p. 665–674. [Also available at http://dx.doi.org/10.1127/0935-1221/2005/0017-0665.]

Bottrill, R.S., and Baker, W.E., 2008, A catalogue of the minerals of Tasmania: Rosny Park, Tasmania, Australia, Mineral Resources Tasmania, Tasmanian Geological Survey Bulletin, v. 73, 254 p.

Bouch, J.E., Naden, Jonathan, Shepherd, T.J., McKervey, J.A., Young, Brian, Benham, A.J., and Sloane, H.J., 2006, Direct evidence of fluid mixing in the formation of stratabound Pb-Zn-Ba-F mineralization in the Alston Block, north Pennine orefield (England): Mineralium Deposita, v. 41, no. 8, p. 821–835. [Also available at http://dx.doi.org/10.1007/s00126-006-0093-3.]

Bourgeau, M., Clapin, D., Foster, K., Jones, R., Prior, M., Shepherd, M., and Walsh, P., 1996, National ambient air quality objectives for hydrogen fluoride (HF)—Science assessment document: Ottawa, Ontario, Canada, CEPA/FPAC Working Group on Air Quality Objectives and Guidelines, DQ3.1.1, Report No. 6211–19–018, 122 p., accessed April 17, 2013, at http://www.bape.gouv.qc.ca/sections/mandats/ap50_rio_tinto_alcan/documents/DQ3.1.1.pdf.

Bowen, N.L., 1937, Recent high-temperature research on silicates and its significance in igneous geology: American Journal of Science, ser. 5, v. 33, no. 193, p. 1–21. [Also available at http://dx.doi.org/10.2475/ajs.s5-33.193.1.]

Bradbury, J.C., and Baxter, J.W., 1992, Intrusive breccias at Hicks Dome—Hardin County, Illinois: Illinois State Geological Survey Circular 550, 23 p. [Also available at http://hdl.handle.net/2142/44637.]

Brockie, D.C., Hare, E.H., Jr., and Dingess, P.R., 1968, The geology and ore deposits of the Tri-State district of Missouri, Kansas, and Oklahoma, *in* Ridge, J.D., ed., Ore deposits of the United States, 1933–1967; the Graton-Sales Volume: New York, N.Y., American Institute of Mining, Metallurgical and Petroleum Engineers, v. 1, p. 400–430.

Brown, J.S., Emery, J.A., and Meyer, P.A., Jr., 1954, Explosion pipe in test well on Hicks Dome, Hardin County, Illinois: Economic Geology, v. 49, p. 891–902. [Also available at http://dx.doi.org/10.2113/gsecongeo.49.8.891.]

Bulnayev, K.B., and Kaperskaya, Yu.N., 1995, Genetic significance of the distribution of some REE in Transbaykalian and Mongolian Late Mesozoic volcanites and fluorites: Geochemistry International, v. 32, no. 8, p. 72–78.

Burt, D.M., Sheridan, M.F., Bikun, J.V., and Christiansen, E.H., 1982, Topaz rhyolites—Distribution, origin, and significance for exploration: Economic Geology, v. 77, p. 1818–1836. [Also available at http://dx.doi.org/10.2113/gsecongeo.77.8.1818.]

Busby, J.F., Plummer, L.N., Lee, R.W., and Hanshaw, B.B., 1991, Geochemical evolution of water in the Madison Aquifer in parts of Montana, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273–F, p. F1–F89. [Also available at http://pubs.er.usgs.gov/publication/pp1273F.]

Canadian Aero Mineral Surveys Ltd. and Arabian Geophysical and Surveying Company, 1967, Airborne EM "Input" system, vol. 2, Ad Dawadimi area: Report for Saudi Arabian Directorate General of Mineral Resources, unnumbered report, 39 p., 6 figs., 18 maps.

Cardellach, Esteve, Canals, Àngels, and Grandia, Fidel, 2003, Recurrent hydrothermal activity induced by successive extensional episodes—The case of the Berta F-(Pb-Zn) vein system (NE Spain): Ore Geology Reviews, v. 22, nos. 1–2, p. 133–141. [Also available at http://dx.doi.org/10.1016/s0169-1368(02)00112-9.]

Carlson, E.H., 1983, The occurrence of Mississippi Valley-type mineralization in northwestern Ohio, *in* Kisvarsanyi, Geza, Grant, S.K., Pratt, W.P., and Koenig, J.W., eds., International Conference on Mississippi Valley type lead-zinc deposits, 2d, Rolla, Mo., 1982, Proceedings: Rolla, Mo., University of Missouri-Rolla, p. 86–112.

Carpenter, A.B., 1978, Origin and chemical evolution of brines in sedimentary basins, *in* Johnson, K.S., and Russell, J.A., eds., Thirteenth Annual Forum on the Geology of Industrial Minerals, Norman, Okla., May 12–14, 1977, Proceedings: Oklahoma Geological Survey Circular 79, p. 60–77. [Also available at http://www.ogs.ou.edu/pubsscanned/Circulars/circular79.pdf.]

Charef, Abdelkrim, and Sheppard, S.M.F., 1987, Pb-Zn mineralization associated with diapirism—Fluid inclusion and stable isotope (H, C, O) evidence for the origin and evolution of the fluids at Fedj-el-Adoum, Tunisia: Chemical Geology, v. 61, nos. 1–4, p. 113–134. [Also available at http://dx.doi.org/10.1016/0009-2541(87)90032-5.]

Chatterjee, M.K., and Mohabey, N.K., 1998, Potential fluorosis problems around Chandidongri, Madhya Pradesh, India: Environmental Geochemistry and Health, v. 20, no. 1, p. 1–4. [Also available at http://dx.doi.org/10.1023/A:1006529925395.]

Cheilletz, Alain, Gasquet, Dominique, Filali, Fouad, Archibald, D.A., and Nespolo, Massimo, 2010, A late Triassic $^{40}Ar/^{39}Ar$ age for the El Hammam high-REE fluorite deposit (Morocco)—Mineralization related to the Central Atlantic magmatic province?: Mineralium Deposita, v. 45, no. 4, p. 323–329. [Also available at http://dx.doi.org/10.1007/s00126-010-0282-y.]

Chen Xianpei, Gao Jiyuan, and Cao Junchen, 1996, Barite and fluorite deposits of China, *in* Editorial Committee of the Mineral Deposits of China, eds. [Responsible ed., Liu Nailong], Mineral deposits of China, v. 5: Beijing, China, Geological Publishing House, p. 52–117.

Cheney, T.M., McClellan, G.H., and Montgomery, E.S., 1979, Sechura phosphate deposits, their stratigraphy, origin, and composition: Economic Geology, v. 74, p. 232–259. [Also available at http://dx.doi.org/10.2113/gsecongeo.74.2.232.]

Chesley, J.T., Halliday, A.N., Kyser, T.K., and Spry, P.G., 1994, Direct dating of Mississippi Valley-type mineralization—Use of Sm-Nd in fluorite: Economic Geology, v. 89, p. 1192–1199. [Also available at http://dx.doi.org/10.2113/gsecongeo.89.5.1192.]

Clark, K.F., Foster, C.T., and Damon, P.E., 1982, Cenozoic mineral deposits and subduction-related magmatic arcs in Mexico: Geological Society of America Bulletin, v. 93, no. 6, p. 533–544. [Also available at http://dx.doi.org/10.1130/0016-7606(1982)93%3C533:cmdasm%3E2.0.co;2.]

Clay, A.N., and de Wit, D.R., 2009, Definitive feasibility study on the Nokeng Fluorspar Mine (Pty) Limited's Nokeng fluorspar project in the form of a competent person's report and valuation, report prepared for Sephaku Holdings, Ltd.: Johannesburg, South Africa, Venmyn Rand (Pty), Ltd. , 159 p., accessed May 10, 2013, at http://www.sephakuholdings.co.za/b/files/CPR_fluorspar_dec09.pdf.]

Cooke, J.A., Johnson, M.S., Davidson, A.W., and Bradshaw, A.D., 1976, Fluoride in plants colonising fluorspar mine waste in the Peak District and Weardale: Environmental Pollution, v. 11, no. 1, p. 9–23. [Also available at http://dx.doi.org/10.1016/0013-9327(76)90003-3.]

Crocker, I.T., 1985, Volcanogenic fluorite-hematite deposits and associated pyroclastic rock suite at Vergenoeg, Bushveld Complex: Economic Geology, v. 80, p. 1181–1200. [Also available at http://dx.doi.org/10.2113/gsecongeo.80.4.1181.]

Davies, T.C., 1994, Water quality characteristics associated with fluorite mining in the Kerio Valley area of western Kenya: International Journal of Environmental Health Research, v. 4, no. 3, p. 165–175. [Also available at http://dx.doi.org/10.1080/09603129409356814.]

Deans, T., Sukheswala, R.N., Sethna, S.F., and Viladkar, S.G., 1972, Metasomatic feldspar rocks (potash fenites) associated with the fluorite deposits and carbonatites of Amba Dongar, Gujarat, India: Institution of Mining and Metallurgy Transactions, v. 81, no. 783, p. B1–B9.

Deering, M.F., Mohr, E.T., Sypniewski, B.F., and Carlson, E.H., 1983, Regional hydrogeochemical patterns in ground water of northwestern Ohio and their relation to Mississippi Valley-type mineral occurrences: Journal of Geochemical Exploration, v. 19, nos. 1–3, p. 225–241. [Also available at http://www.sciencedirect.com/science/article/pii/0375674283900195.]

Deloule, E., 1982, The genesis of fluorspar hydrothermal deposits at Montroc and Le Burc, the Tarn, as deduced from fluid inclusion analysis: Economic Geology, v. 77, p. 1867–1874. [Also available at http://dx.doi.org/10.2113/gsecongeo.77.8.1867.]

Denny, F.B., Goldstein, Alan, Devera, J.A., Williams, D.A., Lasemi, Zakaria, and Nelson, W.J., 2008, The Illinois-Kentucky fluorite district, Hicks Dome, and Garden of the Gods in southeastern Illinois and northwestern Kentucky, *in* Maria, A.H., and Counts, R.C., eds., From the Cincinnati Arch to the Illinois Basin—Geological field excursions along the Ohio River Valley: Boulder, Colo., Geological Society of America Field Guide, v. 12, p. 11–24. [Also available at http://dx.doi.org/10.1130/2008.fld012(02).]

Dobson, D.C., 1982, Geology and alteration of the Lost River tin-tungsten-fluorine deposit, Alaska: Economic Geology, v. 77, p. 1033–1052. [Also available at http://dx.doi.org/10.2113/gsecongeo.77.4.1033.]

Doroshkevich, A.G., Viladkar, S.G., Ripp, G.S., and Burtseva, M.V., 2009, Hydrothermal REE mineralization in the Amba Dongar carbonatite complex, Gujarat, India: The Canadian Mineralogist, v. 47, no. 5, p. 1105–1116. [Also available at http://dx.doi.org/10.3749/canmin.47.5.1105.]

Dunham, K.C., 1948, Geology of the Northern Pennine Orefield, v. 1, Tyne to Stainmore—Economic memoir covering the areas of 1:50,000 and one-inch geological sheets 19 and 25, and parts of 13, 24, 26, 31, 32 (England and Wales): London, United Kingdom, H.M. Stationery Office, British Geological Survey, 300 p.

Ebbott, K.A., Krothe, N.C., Shaffer, N.R., and Berg, J.H., 1985, Hydrogeochemical reconnaissance study in Washington County, Indiana [abs.], *in* Berg, J.H., ed., The Geological Society of America, North-Central Section, 19th annual meeting: Geological Society of America Abstracts With Programs, v. 17, no. 5, p. 286.

El Aref, M.M., and Amstutz, G.C., 1983, Lead-zinc deposits along the Red Sea coast of Egypt—New observations and genetic models on the occurrences of Um Gheig, Wizr, Essel and Zug El Bohar: Stuttgart, West Germany, Gebrüder Borntraeger, Monograph Series on Mineral Deposits, no. 21, 103 p., 1 pl.

Ellmies, R., Germann, K., Krupenin, M.T., Möller, P., and Echtler, H.P., 1999, The fluorite-sellaite deposits of Suran, Bashkir Meganticline, Urals, *in* Stanley, C.J. and others, eds., Mineral deposits—Processes to processing—Proceedings of the Fifth Biennial SGA Meeting and the Tenth Quadrennial IAGOD Symposium, London, United Kingdom, August 22–25, 1999: Brookfield, Vt., A.A. Balkema, p. 841–844.

Ericksen, G.E., Vine, J.D., and Ballón A.R., 1978, Chemical composition and distribution of lithium-rich brines in Salar de Uyuni and nearby salars in southwestern Bolivia: Energy, v. 3, no. 3, p. 355–363. [Also available at http://dx.doi.org/10.1016/0360-5442(78)90032-4.]

Ermakov, V.V., 2004, Fluorine, chap. 9.1 *of* Merian, E., Anke, M., Ihnat, M., and Stoeppler, M., eds., Elements and their compounds in the environment—Occurrence, analysis and biological relevance (2d ed.): Weinheim, Germany, Wiley-VCH, p. 1415–1421. [Also available at http://dx.doi.org/10.1002/9783527619634.ch60a.]

Eugster, H.P., 1980, Lake Magadi, Kenya and its precursors, chap. 15 *of* Nissenbaum, A., ed., Hypersaline brines and evaporitic environments—Proceedings of the Bat Sheva Seminar on Saline Lakes and Natural Brines: New York, N.Y., Elsevier, p. 195–232.

European Commission, 2009, Reference document on best available techniques for management of tailings and waste-rock in mining activities: Brussels, Belgium, European Commission, January, variously paged, accessed November 4, 2014, at http://eippcb.jrc.ec.europa.eu/reference/BREF/mmr_adopted_0109.pdf.

Feytis, Alex, 2009, Fluorspar supply fortified: Industrial Minerals Web page, September 21, accessed January 9, 2010, at http://www.indmin.com/Article/2299402/Fluorspar-supply-fortified.html.

Fifarek, R.H., Denny, F.B., Snee, L.W., and Miggins, D.P., 2001, Permian igneous activity in southeastern Illinois and western Kentucky—Implications for tectonism and economic resources [abs.]: Geological Society of America Abstracts with Programs, v. 33, no. 6, p. A–420. [Also available at https://gsa.confex.com/gsa/2001AM/finalprogram/abstract_14266.htm.]

Fine, M.M., 1948, Concentration of fluorite from tailings and mine waste rock in Crittenden and Livingston Counties, Ky.: U.S. Bureau of Mines Report of Investigations 4370, 21 p. [Also available at http://hdl.handle.net/2027/mdp.39015078467555.]

Fleischer, Michael, and Robinson, W.O., 1963, Some problems of the geochemistry of fluorine, *in* Shaw, D.M., ed., Studies in analytical geochemistry: Toronto, Ontario, Canada, University of Toronto Press in cooperation with the Royal Society of Canada Special Publication no. 6, p. 58–75.

Fuge, Ronald, and Andrews, M.J., 1988, Fluorine in the UK environment: Environmental Geochemistry and Health, v. 10, nos. 3–4, p. 96–104. [Also available at http://dx.doi.org/10.1007/bf01758677.]

Fuhong Ren, and Shuqin Jiao, 1988, Distribution and formation of high-fluorine groundwater in China: Environmental Geology and Water Sciences, v. 12, no. 1, p. 3–10. [Also available at http://dx.doi.org/10.1007/bf02574820.]

Fulton, R.B., and Montgomery, Gill, 1983, Fluorite and cryolite, *in* Lefond, S.J., ed., Industrial minerals and rocks—Nonmetallics other than fuels (5th ed.): New York, N.Y., American Institute of Mining, Metallurgical, and Petroleum Engineers, v. 2, p. 732–744.

Garcia-Iglesías, Jesús, and Loredo, Jorge, 1994, Geological, geochemical, and mineralogical characteristics of the Asturias fluorspar district, northern Spain: Exploration and Mining Geology, v. 3, no. 1, p. 31–37. [Also available at http://www.cim.org/en/Publications-and-Technical-Resources/Publications/Technical_Papers/1994/1/BULL-1994-01-08.aspx.]

Geeson, N.A., Abrahams, P.W., Murphy, M.P., and Thornton, I., 1998, Fluorine and metal enrichment of soils and pasture herbage in the old mining areas of Derbyshire, UK: Agriculture, Ecosystems, and Environment, v. 68, no. 3, p. 217–231. [Also available at http://dx.doi.org/10.1016/s0167-8809(97)00153-9.]

Gerasimovskiy, V.I., and Savinova, Y.N., 1969, Fluorine contents of volcanic rocks in the rift zone of East Africa: Geochemistry International, v. 6, no. 6, p. 1124–1128. [Originally published in Geokhimiya, no. 12, p. 1466–1471.]

Gillerman, Elliot, 1948, The bedding-replacement fluorspar deposits of Spar Valley, Eagle Mountains, Hudspeth County, Texas: Economic Geology, v. 43, p. 509–517. [Also available at http://dx.doi.org/10.2113/gsecongeo.43.6.509.]

Goddard, E.N., 1946, Fluorspar deposits of the Jamestown district, Boulder County, Colorado: Colorado Scientific Society, Proceedings, v. 15, no. 1, 47 p.

Goff, B.H., Weinberg, R., Groves, D.I., Vielreicher, N.M., and Fourie, P.J., 2004, The giant Vergenoeg fluorite deposit in a magnetite-fluorite-fayalite REE pipe—A hydrothermally-altered carbonatite-related pegmatoid?: Mineralogy and Petrology, v. 80, nos. 3–4, p. 173–199. [Also available at http://dx.doi.org/10.1007/s00710-003-0012-6.]

González-Partida, E., Carrillo-Chávez, A., Grimmer, J.O.W., Pironon, J., Mutterer, J., and Levresse, G., 2003, Fluorite deposits of Encantada-Buenavista, Mexico—Products of Mississippi Valley-type processes: Ore Geology Reviews, v. 23, nos. 3–4, p. 107–124. [Also available at http://dx.doi.org/10.1016/s0169-1368(03)00018-0.]

Graham, G.S., Kesler, S.E., and Van Loon, J.C., 1975, Fluorine in ground water as a guide to Pb-Zn-Ba-F mineralization: Economic Geology, v. 70, p. 396–398. [Also available at http://dx.doi.org/10.2113/gsecongeo.70.2.396.]

Grandia, Fidel, Canals, Àngels, Cardellach, Esteve, Banks, D.A., and Perona, Joaquim, 2003, Origin of ore-forming brines in sediment-hosted Zn-Pb deposits of the Basque-Cantabrian Basin, northern Spain: Economic Geology, v. 98, p. 1397–1411. [Also available at http://dx.doi.org/10.2113/gsecongeo.98.7.1397.]

Grogan, R.M., 1960, Fluorspar and cryolite, *in* Gillson, J.L., ed., Industrial minerals and rocks—Nonmetallics other than fuels (3d ed., completely revised): New York, N.Y., American Institute of Mining, Metallurgical, and Petroleum Engineers, p. 363–382.

Grogan, R.M., 1964, Finding sources of fluorine [abs.]: Mining Engineering, v. 16, no. 1, p. 65.

Gulbrandsen, R.A., 1966, Chemical composition of phosphorites of the Phosphoria Formation: Geochimica et Cosmochimica Acta, v. 30, no. 8, p. 769–778. [Also available at http://dx.doi.org/10.1016/0016-7037(66)90131-1.]

Gunow, A.J., Ludington, Steve, and Munoz, J.L., 1980, Fluorine in micas from the Henderson molybdenite deposit, Colorado: Economic Geology, v. 75, p. 1127–1137. [Also available at http://dx.doi.org/10.2113/gsecongeo.75.8.1127.]

Gwalani, L.G., Rock, N.M.S., Chang, W.-J., Fernandez, S., Allègre, C.J., and Prinzhofer, A., 1993, Alkaline rocks and carbonatites of Amba Dongar and adjacent areas, Deccan igneous province, Gujarat, India—1. Geology, petrography and petrochemistry: Mineralogy and Petrology, v. 47, nos. 2–4, p. 219–253. [Also available at http://dx.doi.org/10.1007/bf01161569.]

Hall, W.E., and Friedman, Irving, 1963, Composition of fluid inclusions, Cave-in-Rock fluorite district, Illinois, and Upper Mississippi Valley lead-zinc district: Economic Geology, v. 58, p. 886–911. [Also available at http://dx.doi.org/10.2113/gsecongeo.58.6.886.]

Hall, W.E., and Heyl, A.V., 1968, Distribution of minor elements in ore and host rock, Illinois-Kentucky fluorite district and Upper Mississippi Valley zinc-lead district: Economic Geology, v. 63, p. 655–670. [Also available at http://dx.doi.org/10.2113/gsecongeo.63.6.655.]

Han Yuchuan, Xia Xuehui, Pang Siyu, and Xu Shaokang, 2012, Hydrothermal sedimentary mineralization of the super-large Bamianshan fluorite deposit in Zhejiang Province, China: Acta Geologica Sinica (English ed.), v. 86, no. 3, p. 762–768. [Also available at http://dx.doi.org/10.1111/j.1755-6724.2012.00701.x.]

Hanor, J.S., 1987, Origin and migration of subsurface sedimentary brines: Tulsa, Okla., Society of Economic Paleontologists and Mineralogists, Short Course Series Lecture Notes, no. 21, 247 p.

Hanor, J.S., 1997, Controls on the solubilization of lead and zinc in basinal brines, *in* Sangster, D.F., ed., Carbonate-hosted lead-zinc deposits—[Society of Economic Geologists] 75th anniversary volume: Littleton, Colo., Society of Economic Geologists Special Publication no. 4, p. 483–500.

Hatton, C.J., and Sharpe, M.R., 1989, Significance and origin of boninite-like rocks associated with the Bushveld Complex, *in* Crawford, A.M., ed., Boninites: London, United Kingdom, Unwin Hyman, p. 174–208.

Hayes, T.S., and Anderson, W.H., 1992, Regionwide correlation of the hydrothermal paragenesis of the Illinois-Kentucky fluorspar district [extended abs.], *in* Goldhaber, M.B., and Eidel, J.J., eds., Mineral resources of the Illinois Basin in the context of basin evolution—St. Louis, Missouri, January 22–23,1992—Program and Abstracts: U.S. Geological Survey Open-File Report 92–1, p. 19–22. [Also available at http://pubs.er.usgs.gov/publication/ofr921.]

Hayes, T.S., Palmer, J.R., and Rowan, E.L., 1990, Correlation of hydrothermal dolomite generations across the Mississippi Valley-type mineralizing system of the Ozark Region [abs.], *in* Pratt, W.P., and Goldhaber, M.G., eds., U.S. Geological Survey-Missouri Geological Survey symposium—Mineral resource potential of the Midcontinent; program and abstracts, St. Louis, Missouri, April 11–12, 1989: U.S. Geological Survey Circular 1043, p. 10. [Also available at http://pubs.usgs.gov/circ/1990/1043/report.pdf.]

Hayes, T.S., Sutley, S.J., Al-Shanti, Mahmoud, Al-Shammary, Abdullah, Al-Eissa, Abdullah, Nadra, Aymon, and Siddiqui, A.A., 2001, Jabal Dhaylan district, Saudi Arabia—Salt-related carbonate-hosted zinc-lead deposits formed in the Red Sea early passive margin, *in* Piestrzyński, Adam, and others, eds., Mineral deposits at the beginning of the 21st century—Proceedings of the Joint Sixth Biennial SGA-SEG Meeting, Kraków, Poland, 26–29 August 2001: Lisse, Netherlands, A.A. Balkema, p. 137–140.

Hayes, T.S., Sutley, S.J., Kadi, K.A., Balkhyour, M.B., Siddiqui, A.A., Beshir, Zacharia, and Hashem, H.I., 2002, Jabal Dhaylan zinc-lead deposits—Geologic setting, genesis, and 1996–2000 exploration programs: Saudi Geological Survey Open-File Report SGS–OF–2001–5, 71 p.

Henderson, Thomas, 1985, Geochemistry of ground-water in two sandstone aquifer systems in the northern Great Plains in parts of Montana and Wyoming—Regional aquifer system analysis: U.S. Geological Survey Professional Paper 1402–C, p. C1–C84. [Also available at http://pubs.er.usgs.gov/publication/pp1402C.]

Heyl, A.V., Delevaux, M.H., Zartman, R.E., and Brock, M.R., 1966, Isotopic study of galenas from the Upper Mississippi Valley, the Illinois-Kentucky and some Appalachian Valley mineral districts: Economic Geology, v. 61, p. 933–961. [Also available at http://dx.doi.org/10.2113/gsecongeo.61.5.933.]

Heyl, A.V., and West, W.S., 1982, Outlying mineral occurrences related to the Upper Mississippi Valley mineral district, Wisconsin, Iowa, Illinois, and Minnesota: Economic Geology, v. 77, p. 1803–1817. [Also available at http://dx.doi.org/10.2113/gsecongeo.77.8.1803.]

Higazy, R.A., 1954, Trace elements of volcanic ultrabasic potassic rocks of southwestern Uganda and adjoining part of the Belgian Congo: Geological Society of America Bulletin, v. 65, no. 1, p. 39–70. [Also available at http://dx.doi.org/10.1130/0016-7606(1954)65[39:teovup]2.0.co;2.]

Hildreth, Wes, 1981, Gradients in silicic magma chambers—Implications for lithospheric magmatism: Journal of Geophysical Research, v. 86, no. B11, p. 10153–10192. [Also available at http://dx.doi.org/10.1029/jb086ib11p10153.]

Hodge, Brian, 2012, Fluorspar illuminated: Industrial Minerals, no. 541, October, p. 39–52. [Also available at http://www.indmin.com/pdfs/697/86771/Fluorspar%20illuminated4%201.pdf.]

Holmes, Arthur, and Harwood, H.F., 1932, Petrology of the volcanic fields east and south-east of Ruwenzori, Uganda: Quarterly Journal of The Geological Society of London, v. 88, February, p. 370–442. [Also available at http://dx.doi.org/10.1144/gsl.jgs.1932.088.01-04.16.]

Hudson, Travis, and Arth, J.G., 1983, Tin granites of Seward Peninsula, Alaska: Geological Society of America Bulletin, v. 94, no. 6, p. 768–790. [Also available at http://dx.doi.org/10.1130/0016-7606(1983)94%3C768:tgospa%3E2.0.co;2.]

Hudson, T.L., and Reed, B.L., 1997, Tin deposits in Alaska, *in* Goldfarb, R.J., and Miller, L.D., eds., Mineral deposits of Alaska: Lancaster, Pa., Economic Geology Publishing Co., Economic Geology Monograph Series no. 9, p. 450–465.

Huspeni, J.R., Kesler, S.E., Ruiz, Joaquin, Tuta, Zane, Sutter, J.F., and Jones, L.M., 1984, Petrology and geochemistry of rhyolites associated with tin mineralization in northern Mexico: Economic Geology, v. 79, p. 87–105. [Also available at http://dx.doi.org/10.2113/gsecongeo.79.1.87.]

Imai, Hideki, Kawasaki, Masashi, Yamaguchi, Mitsuo, and Takahashi, Mikio, 1985, Mineralization and paragenesis of the Huanzala Mine, central Peru: Economic Geology, v. 80, p. 461–478. [Also available at http://dx.doi.org/10.2113/gsecongeo.80.2.461.]

Ineson, P.R., Mitchell, J.G., and Vokes, F.M., 1975, K-Ar dating of epigenetic mineral deposits; an investigation of the Permian metallogenic province of the Oslo region, southern Norway: Economic Geology, v. 70, p. 1426–1436. [Also available at http://dx.doi.org/10.2113/gsecongeo.70.8.1426.]

Ingebritsen, S.E., and Appold, M.S., 2012, The physical hydrogeology of ore deposits: Economic Geology, v. 107, p. 559–584. [Also available at http://dx.doi.org/10.2113/econgeo.107.4.559.]

Jacks, Gunnar, Bhattacharya, Prosun, Chaudhary, Vikas, and Singh, K.P., 2005, Controls on the genesis of some high-fluoride groundwaters in India: Applied Geochemistry, v. 20, no. 2, p. 221–228. [Also available at http://dx.doi.org/10.1016/j.apgeochem.2004.07.002.]

Jahns, R.H., and Glass, J.J., 1944, Beryllium and tungsten deposits of the Iron Mountain district, Sierra and Socorro Counties, New Mexico, with a section on the beryllium minerals: U.S. Geological Survey Bulletin 945–C, 35 p., 14 pls. [Also available at http://pubs.er.usgs.gov/publication/b945C.]

Jaskula, B.W., 2013, Beryllium [advance release], *in* Metals and minerals: U.S. Geological Survey Minerals Yearbook 2011, v. I, p. 11.1–11.7, accessed March 1, 2013, at http://minerals.usgs.gov/minerals/pubs/commodity/beryllium/myb1-2011-beryl.pdf.

Johnson, K.L., and Younger, P.L., 2002, Hydrological and geochemical consequences of the abandonment of Frazer's Grove carbonate hosted Pb/Zn fluorspar mine, North Pennines, UK, *in* Younger, P.L., and Robins, N.S., eds., Mine water hydrogeology and geochemistry: Geological Society of London Special Publication, v. 198, p. 347–363. [Also available at http://dx.doi.org/10.1144/gsl.sp.2002.198.01.24.]

Jones, B.F., 1965, The hydrology and mineralogy of Deep Springs Lake, Inyo County, California: U.S. Geological Survey Professional Paper 502–A, 56 p. [Also available at http://pubs.er.usgs.gov/publication/pp502A.]

Jones, B.F., Eugster, H.P., and Rettig, S.L., 1977, Hydrochemistry of the Lake Magadi Basin, Kenya: Geochimica et Cosmochimica Acta, v. 41, no. 1, p. 53–72. [Also available at http://dx.doi.org/10.1016/0016-7037(77)90186-7.]

Kabata-Pendias, Alina, and Mukherjee, A.B., 2007, Trace elements from soil to human: Berlin, Germany, Springer-Verlag, 550 p.

Kabata-Pendias, Alina, and Pendias, Henryk, 2001, Trace elements in soils and plants (3d ed.): Boca Raton, Fla., CRC Press, 413 p.

Kendrick, M.A., Burgess, R., Pattrick, R.A.D., and Turner, G., 2002, Hydrothermal fluid origins in a fluorite-rich Mississippi Valley-type district—Combined noble gas (He, Ar, Kr) and halogen (Cl, Br, I) analysis of fluid inclusions from the South Pennine ore field, United Kingdom: Economic Geology, v. 97, p 435–451. [Also available at http://dx.doi.org/10.2113/gsecongeo.97.3.435.]

Kesler, S.E., 1977, Geochemistry of manto fluorite deposits, northern Coahuila, Mexico: Economic Geology, v. 72, p. 204–218. [Also available at http://dx.doi.org/10.2113/gsecongeo.72.2.204.]

Kesler, S.E., Appold, M.S., Martini, A.M., Walter, L.M., Huston, T.J., and Kyle, J.R., 1995, Na-Cl-Br systematics of mineralizing brines in Mississippi Valley-type deposits: Geology, v. 23, no. 7, p. 641–644. [Also available at http://dx.doi.org/10.1130/0091-7613(1995)023%3C0641:ncbsom%3E2.3.co;2.]

Kilham, Peter, and Hecky, R.E., 1973, Fluoride—Geochemical and ecological significance in East African waters and sediments: Limnology and Oceanography, v. 18, no. 6, p. 932–945. [Also available at http://dx.doi.org/10.4319/lo.1973.18.6.0932.]

Kirkemo, Harold, 1978, Final report—OME exploration project; OME-6873 (fluorspar-beryllium-rare earths-thorium-niobium), Hicks Dome Property, Hardin County, Illinois: U.S. Geological Survey, Office of Minerals Exploration, November, variously paged. [Also available at http://minerals.usgs.gov/dockets/scans/il/ome/6873_OME.pdf.] (Note: Downloaded file is 189 MB in size.)

Kislov, E.V., Imetkhenov, A.B., and Sandakova, D.M., 2010, The Yermakovskoye fluorite-beryllium deposit—Avenues for improving ecological security of revitalization of the mining operations: Geography and Natural Resources, v. 31, no. 4, p. 324–329. [Also available at http://dx.doi.org/10.1016/j.gnr.2010.11.004.]

Kleemann, G.J., and Twist, David, 1989, The compositionally-zoned sheet-like granite pluton of the Bushveld Complex—Evidence bearing on the nature of A-type magmatism: Journal of Petrology, v. 30, no. 6, p. 1383–1414. [Also available at http://dx.doi.org/10.1093/petrology/30.6.1383.]

Kogut, A.I., Hagni, R.D., and Schneider, G.I.C., 1997, The Okorusu, Namibia, carbonatite-related fluorite deposits, and a comparison with the Illinois-Kentucky fluorite district/Hicks Dome, *in* Sangster, D.F., ed., Carbonate-hosted lead-zinc deposits—[Society of Economic Geologists] 75th anniversary volume: Littleton, Colo., Society of Economic Geologists Special Publication no. 4, p. 290–297.

Koplus, A.V., Puzanov, L.S., and Zubov, M.A., 1977, Endogenic geochemical halos of concealed fluorspar mineralization of Kazakhstan (as in the Taskaynar-Yuzhnyy deposit): International Geology Review, v. 19, no. 12, p. 1441–1447. [Also available at http://dx.doi.org/10.1080/00206817709471157.]

Kovalenko, V.I., Kuz'min, M.I., Antipin, V.S., and Petrov, L.L., 1971, Topaz-bearing quartz keratophyre (ongonite), a new variety of subvolcanic igneous vein rock: Doklady Akademia Nauk, S.S.S.R., Earth Science Sections, v. 199, nos. 1–6, p. 132–134.

Kovalenko, V.I., and Yarmolyuk, V.V., 1995, Endogenous rare metal ore formations and rare metal metallogeny of Mongolia: Economic Geology, v. 90, p. 520–529. [Also available at http://dx.doi.org/10.2113/gsecongeo.90.3.520.]

Kraynov, S.R., Mer'kov, A.N., Petrova, N.G., Baturinskaya, I.V., and Zharikova, V.M., 1969, Highly alkaline (pH 12) fluosilicate waters in the deeper zones of the Lovozero massif: Geochemistry International, v. 6, no. 4, p. 635–640.

Kunasz, I.A., 1974, Lithium occurrence in the brines of Clayton Valley, Esmeralda County, Nevada, *in* Coogan, A.S., ed., Fourth Symposium on Salt, Houston, Texas, April 8–12, 1973, Proceedings: Cleveland, Ohio, Northern Ohio Geological Society, v. 1., p. 57–66. [Also available at http://www.worldsaltsymposium.org/download/lithium-occurrence-in-the-brines-of-clayton-valley-esmeralda-county/.]

Kwak, T.A.P., and Askins, P.W., 1981, Geology and genesis of the F-Sn-W(-Be-Zn) skarn (wrigglite) at Moina, Tasmania: Economic Geology, v. 76, p. 439–467. [Also available at http://dx.doi.org/10.2113/gsecongeo.76.2.439.]

Kyle, J.R., and Saunders, J.A., 1997, Metallic deposits of the Gulf Coast Basin—Diverse mineralization styles in a young sedimentary basin, *in* Sangster, D.F., ed., Carbonate-hosted lead-zinc deposits—[Society of Economic Geologists] 75th anniversary volume: Littleton, Colo., Society of Economic Geologists Special Publication no. 4, p. 218–229.

Ladoo, R.B., 1927, Fluorspar—Its mining, milling, and utilization, with a chapter on cryolite: U.S. Bureau of Mines Bulletin 244, 185 p. [Also available at http://digital.library.unt.edu/ark:/67531/metadc12426/m1/1/.]

Land, L.S., 1995, Na-Ca-Cl saline formation waters, Frio Formation (Oligocene), south Texas, USA—Product of diagenesis: Geochimica et Cosmochimica Acta, v. 59, no. 11, p. 2163–2174. [Also available at http://dx.doi.org/10.1016/0016-7037(95)00098-k.]

Landis, G.P., and Hofstra, A.H., 1991, Fluid inclusion gas chemistry as a potential minerals exploration tool—Case studies from Creede, CO, Jerritt Canyon, NV, Coeur d'Alene district, ID and MT, southern Alaska mesothermal veins, and mid-continent MVT's: Journal of Geochemical Exploration, v. 42, no. 1, p. 25–59. [Also available at http://dx.doi.org/10.1016/0375-6742(91)90059-4.]

Lapierre, H., Jahn, B.M., Charvet, J., and Yu, Y.W., 1997, Mesozoic felsic arc magmatism and continental olivine tholeiites in Zhejiang Province and their relationship with the tectonic activity in southeastern China: Tectonophysics, v. 274, no. 4, p. 321–338. [Also available at http://dx.doi.org/10.1016/s0040-1951(97)00009-7.]

Leach, D.L., Plumlee, G.S., Hofstra, A.H., Landis, G.P., Rowan, E.L., and Viets, J.B., 1991, Origin of late dolomite cement by CO_2-saturated deep basin brines—Evidence from the Ozark region, central United States: Geology, v. 19, no. 4, p. 348–351. [Also available at http://dx.doi.org/10.1130/0091-7613(1991)019%3C0348:ooldcb%3E2.3.co;2.]

Leach, D.L., and Rowan, E.L., 1986, Genetic link between Ouachita foldbelt tectonism and the Mississippi Valley-type lead-zinc deposits of the Ozarks: Geology, v. 14, no. 11, p. 931–935. [Also available at http://dx.doi.org/10.1130/0091-7613(1986)14%3C931:glboft%3E2.0.co;2]

Leach, D.L., Sangster, D.F., Kelley, K.D., Large, R.R., Garven, Grant, Allen, C.R., Gutzmer, Jens, and Walters, Steve, 2005, Sediment-hosted lead-zinc deposits—A global perspective, *in* Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., and Richards, J.P., eds., Economic Geology—One hundredth anniversary volume, 1905–2005: Littleton, Colo., Society of Economic Geologists, p. 561–607. [Appendixes are on a CD–ROM inside the back cover.]

Leach, D.L., Viets, J.B., Foley-Ayuso, Nora, and Klein, D.P., 1995, Mississippi Valley-type Pb-Zn deposits, chap. 30 *of* du Bray, E.A., ed., Preliminary compilation of descriptive geoenvironmental mineral deposit models: U.S. Geological Survey Open-File Report 95–831, p. 234–243. [Also available at http://pubs.usgs.gov/of/1995/ofr-95-0831.]

Lecuyer, N.L., Agnerian, Hrayr, and Peach, A.D., 2013, Technical report—Updated preliminary feasibility study of the St. Lawrence fluorspar project, Newfoundland and Labrador, Canada, NI 43–101 report prepared for Canada Fluorspar (NL) Inc. [Filing date March 15, 2013]: Toronto, Ontario, Canada, Roscoe Postle Associates Inc., 248 p., accessed December 10, 2014, at http://www.canadafluorspar.com/pdf/2013-03-06NI43101Report.pdf. [Also available at http://www.sedar.com]

Levinson, A.A., 1962, Beryllium-fluorine mineralization at Aguachile Mountain, Coahuila, Mexico: American Mineralogist, v. 47, p. 67–74. [Also available at http://www.minsocam.org/ammin/am47/am47_67.pdf.]

Lewis, R.D., and Mitchell, R.H., 1987, Alnöite intrusions associated with rifting in the New Madrid seismic zone, 1987 [abs.]: Geological Society of America Abstracts with Programs, v. 19, no. 7, p. 745.

Li Changjiang, Xu Youlang, and Jiang Xuliang, 1998, Neodymium and strontium isotope geochemistry of Wuyi-Dongyang fluorite deposits, Zhejiang Province, southeast China, *in* Proceedings of the Ninth Quadrennial IAGOD Symposium—Papers presented at the symposium on topics related to general problems on the genesis of ore deposits and on studies of the ore geology of specific districts or deposits: Stuttgart, Germany, E. Schweizerbart'sche Verlagbuchhandlung, p. 259–268.

Lindsey, D.A., 1982, Tertiary volcanic rocks and uranium in the Thomas Range and northern Drum Mountains, Juab County, Utah: U.S. Geological Survey Professional Paper 1221, 71 p. [Also available at http://pubs.er.usgs.gov/publication/pp1221.]

Lismore-Scott, Siobhan, 2013, Fluorspar—Developing projects for 'at-risk' mineral: Industrial Minerals, no. 551, p. 47–50, August. [Also available at http://www.indmin.com/Article/3233636/Channel/204638/Fluorspar-Developing-projects-for-at-risk-mineral.html.]

Liu Daorong, Yan Shengxian, Chen Yin, Wang Meihua, and Zheng Dan, 2012, Geochemical characteristics of the Yanqian high-F granite and its relationship with the new-type Bamianshan fluorite deposit in northwest Zhejiang Province: Geology and Prospecting, v. 48, no. 5, p. 884–893. [In Chinese with English abstract.]

Lkhamsuren, Jargalyn, and Hamasaki, Satoshi, 1998, Fluorite deposits in Mongolia—An outline: Bulletin of the Geological Survey of Japan, v. 49, no. 6, p. 309–318. [Also available at https://www.gsj.jp/data/bull-gsj/49-06_08.pdf.]

Luino, F., and De Graff, J.V., 2012, The Stave mudflow of 19 July 1985 (northern Italy)—A disaster that effective regulation might have prevented: Natural Hazards and Earth System Sciences, v. 12, p. 1029–1044. [Also available at http://dx.doi.org/10.5194/nhess-12-1029-2012.]

Lykhin, D.A., Kovalenko, V.I., Yarmolyuk, V.V., Kotov, A.B., and Kovach, V.P., 2010, The Yermakovsky deposit, western Transbaikal region, Russia—Isotopic and geochemical parameters and sources of beryllium-bearing granitoids and other rocks: Geology of Ore Deposits, v. 52, no. 4, p. 289–301. [Also available at http://dx.doi.org/10.1134/s1075701510040045.]

MacDonald, R., Bailey, D.K., and Sutherland, D.S., 1970, Oversaturated peralkaline glassy trachytes from Kenya: Journal of Petrology, v. 11, no. 3, p. 507–517. [Also available at http://dx.doi.org/10.1093/petrology/11.3.507.]

Mahlknecht, J., Steinich, B., and Navarro de León, I., 2004, Groundwater chemistry and mass transfers in the Independence aquifer, central Mexico, by using multivariate statistics and mass-balance models: Environmental Geology, v. 45, no. 6, p. 781–795. [Also available at http://dx.doi.org/10.1007/s00254-003-0938-3.]

Martini, J.E.J., 1976, The fluorite deposits in the Dolomite Series of the Marico district, Transvaal, South Africa: Economic Geology, v. 71, p. 625–635. [Also available at http://dx.doi.org/10.2113/gsecongeo.71.3.625.]

Martini, J.E.J., 1986, The Zeerust fluorspar deposits, western Transvaal, *in* Anhaeusser, C.R., and Maske, S., eds., Mineral deposits of southern Africa, v. I: Johannesburg, South Africa, Geological Society of South Africa, p. 837–841, 1 pl. in pocket.

Masan Group, 2013, Nui Phao: Masan Group Web page, accessed May 9, 2013, at http://www.masangroup.com/masanresources/en/projects/nui-phao.

Mastrangelo, Federico, 1976, I giacimenti [The deposits], *in* Le fluoriti sedimentarie Laziali [Latium sedimentary fluorspars]: Societa Italiana di Mineralgia e Petrologia [Society of Mineralogy and Petrology of Italy] Rendiconti [Statements], v. XXXII, no. 1, p. 29–46. [Also available at http://rruff.info/rdsmi/V32/V32.html.]

Matteucci, Elio, 1976, Ipotesi e problemi genetici [Genetic hypotheses and problems], *in* Le fluoriti sedimentarie Laziali [Latium sedimentary fluorspars]: Societa Italiana di Mineralgia e Petrologia [Society of Mineralogy and Petrology of Italy] Rendiconti [Statements], v. XXXII, no. 1, p. 47–63. [Also available at http://rruff.info/rdsmi/V32/V32.html.]

Maxwell, C.H., Foord, E.E., Oakman, M.R., and Harvey, D.B., 1986, Tin deposits of the Black Range tin district, *in* Clemmons, R.E., King, W.E., Mack, G.H., and Zidek, J., eds., Truth or Consequences region—New Mexico Geological Society Thirty-Seventh Annual Fall Field Conference, October 16–18, 1986: Socorro, N. Mex., New Mexico Geological Society 37th Annual Fall Field Conference Guidebook, p. 273–281. [Also available at http://nmgs.nmt.edu/publications/guidebooks/downloads/37/37_p0273_p0281.pdf.]

McAnulty, W.N., Sr., 1974, Fluorspar in Texas: Texas Bureau of Economic Geology Handbook 3, 31 p. [Also available at http://www.lib.utexas.edu/books/landscapes/detail_viewer.php?work_id=297877.]

McAnulty, W.N., Sewell, C.R., Atkinson, D.R., and Rasberry, J.M., 1963, Aguachile beryllium-bearing fluorspar district, Coahuila, Mexico: Geological Society of America Bulletin, v. 74, no. 6, p. 735–743, 2 pls. [Also available at http://dx.doi.org/10.1130/0016-7606(1963)74[735:abfdcm]2.0.co;2.]

McDougal, R.B., and Roberts, L.C., 1958, Fluorspar and cryolite, *in* Metals and minerals (except fuels): U.S. Bureau of Mines Minerals Yearboook 1957, v. I, p. 499–516.

Miller, M.M., 2002, Fluorspar, *in* Metals and minerals: U.S. Geological Survey Minerals Yearbook 2000, v. I, p. 29.1–29.13. [Also available at http://minerals.usgs.gov/minerals/pubs/commodity/fluorspar/index.html#myb.]

Miller, M.M., 2012, Fluorspar: U.S. Geological Survey Mineral Commodity Summaries 2012, p. 56–57. [Also available at https://minerals.usgs.gov/minerals/pubs/commodity/fluorspar/mcs-2012-fluor.pdf.]

Miller, M.M., 2013, Fluorspar: U.S. Geological Survey Mineral Commodity Summaries 2013, p. 56–57. [Also available at https://minerals.usgs.gov/minerals/pubs/commodity/fluorspar/mcs-2013-fluor.pdf.]

Miller, M.M., 2016, Fluorspar [advance release], *in* Metals and minerals: U.S. Geological Survey Minerals Yearbook 2012, v. I, p. 26.1–26.11. [Also available at https://minerals.usgs.gov/minerals/pubs/commodity/fluorspar/myb1-2012-fluor.pdf.]

Mining Atlas, 2016, Speewah: Mining Atlas, accessed July 29, 2016, via https://mining-atlas.com/project/Speewah-Fluorspar-Mine-Project.php.

Modreski, P.J., Armbrustmacher, T.J., and Hoover, D.B., 1995, Carbonatite deposits (Model 10; Singer, 1986a), chap. 6 *of* du Bray, E.A., ed., Preliminary compilation of descriptive geoenvironmental mineral deposit models: U.S. Geological Survey Open-File Report 95–831, p. 47–49. [Also available at http://pubs.usgs.gov/of/1995/ofr-95-0831/.]

Molycorp, Inc., 2015a, Molycorp Mountain Pass: Molycorp, Inc. Web page, accessed October 19, 2015, at http://www.molycorp.com/about-us/our-facilities/molycorp-mountain-pass/.

Molycorp, Inc., 2015b, Molycorp to move its Mountain Pass rare earth facility to 'care and maintenance' mode: Greenwood Village, Colo., Molycorp, Inc. press release, August 26, accessed October 29, 2015, at http://www.molycorp.com/molycorp-to-move-its-mountain-pass-rare-earth-facility-to-care-and-maintenance-mode/.

Morrison, H.I., Villeneuve, P.J., Lubin, J.H., and Schaubel, D.E., 1998, Radon-progeny exposure and lung cancer risk in a cohort of Newfoundland fluorspar miners: Radiation Research, v. 150, no. 1, p. 58–65. [Also available at http://dx.doi.org/10.2307/3579646.]

Munoz, Marguerite, Premo, W.R., and Courjault-Radé, Pierre, 2005, Sm-Nd dating of fluorite from the worldclass Montroc fluorite deposit, southern Massif Central, France: Mineralium Deposita, v. 39, no. 8, p. 970–975. [Also available at http://dx.doi.org/10.1007/s00126-004-0453-9.]

Narayana, B.L., Mallikharjuna Rao, J., Subba Rao, M.V., Murthy, N.N., and Divakara Rao, V., 2000, Geochemistry and origin of Early Proterozoic Dongargarh Rapakivi granite complex, central India—An example for magma mixing and differentiation: Gondwana Research, v. 3, no. 4, p. 507–520. [Also available at http://dx.doi.org/10.1016/s1342-937x(05)70757-7.]

Nash, J.T., and Cunningham, C.G., Jr., 1973, Fluid-inclusion studies of the fluorspar and gold deposits, Jamestown district, Colorado: Economic Geology, v. 68, p. 1247–1262. [Also available at http://dx.doi.org/10.2113/gsecongeo.68.8.1247.]

National Research Council, 2006, Fluoride in drinking water—A scientific review of EPA's Standards: Washington, D.C., The National Academies Press, 531 p., accessed April 18, 2013, at http://www.nap.edu/catalog.php?record_id=1157.

Natural Earth, 2014, Small scale data: Natural Earth map dataset, scale 1:110,000,000, accessed February 12, 2014, at http://www.naturalearthdata.com/.

Newton, V.C., Jr., and Baggs, Donald, 1971, Geologic evaluation of the Alkali Lake disposal site: State of Oregon, Department of Geology and Mineral Industries Open-File Report O–71–2, 93 p. [Also available at http://www.oregongeology.org/pubs/ofr/O-71-02.pdf.]

Nie FengJun, Xu DongQin, Jiang SiHong, and Liu Yan, 2008, Geological features and origin of Sumoqagan Obo superlarge independent fluorite deposit, Inner Mongolia: Kuangchuang Dizhi [Mineral Deposits], v. 27, no. 1, p. 1–13 [in Chinese with English abstract]. [Also available at http://caod.oriprobe.com/articles/13546494/Geological_features_and_origin_of_Sumoqagan_Obo_superlarge_independent.htm.]

Nielsen, J.M., 1999, East African magadi (trona)—Fluoride concentration and mineralogical composition: Journal of African Earth Sciences, v. 29, no. 2, p. 423–428. [Also available at http://dx.doi.org/10.1016/s0899-5362(99)00107-4.]

Norman, D.I., Ting, Wupoa, Putnam, B.R., III, and Smith, R.W., 1985, Mineralization of the Hansonburg Mississippi-Valley-type deposit, New Mexico—Insight from composition of gases in fluid inclusions: Canadian Mineralogist, v. 23, no. 3, p. 353–368. [Also available at http://canmin.geoscienceworld.org/content/23/3/353.]

Nyambok, I.O., and Gaciri, S.J., 1975, Geology of the fluorite deposits in Kerio Valley, Kenya: Economic Geology, v. 70, p. 299–307. [Also available at http://dx.doi.org/10.2113/gsecongeo.70.2.299.]

Obolenskiy, A.A., Rodionov, S.M., Ariunbileg, Sodov, Dejidmaa, Gunchin, Distanov, E.G., Dorjgotov, Dangindorjiin, Gerel, Ochir, Hwang, D.-H., Sun, Fengyue, Gotovsuren, Ayurzana, Letunov, S.N., Li, Xujun, Nokleberg, W.J., Ogasawara, Masatsugu, Seminsky, Z.V., Smelov, A.P., Sotnikov, V.I., Spiridinov, A.A., Zorina, L.V., and Yan, Honquan, 2010, Mineral deposit models for northeast Asia, chap. 3 *of* Nokleberg, W.J., ed., Metallogenesis and tectonics of northeast Asia: U.S. Geological Survey Professional Paper 1765, p. 3-1–3-75. [Also available at http://pubs.usgs.gov/pp/1765/p1765.pdf.]

Occupational Safety and Health Administration, 2013, Regulations (Standards 29 CFR), Part no. 1910—Occupational safety and health standards—Toxic and hazardous substances—1910.1000 Table Z–1, Limits for air contaminants: Washington, D.C., U.S. Department of Labor, accessed February 15, 2013, at http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=standards&p_id=9992.

Orgeval, J.J., 1994, Peridiapiric metal concentration—Example of the Bou Grine deposit (Tunisian Atlas), *in* Fontboté , L., and Boni, M., eds., Sediment-hosted Zn-Pb ores: Berlin, Germany, Springer-Verlag, Society for Geology Applied to Mineral Deposits Special Publication no. 10, p. 354–389. [Also available at http://dx.doi.org/10.1007/978-3-662-03054-7_19.]

Orris, G.J., 1992, Grade and tonnage model of fluorite veins [Model 26b], *in* Orris, G.J., and Bliss, J.D., eds., Industrial minerals deposit models—Grade and tonnage models: U.S. Geological Survey Open-File Report 92–437, p. 29–31. [Also available at http://pubs.er.usgs.gov/publication/ofr92437.]

O'Shea-Stone, Maureen, 2011, Burlington Mine VCUP case history—An ecological approach to mine site remediation, *in* Tailings and Mine Waste 2011—Proceedings of the 15th International Conference on Tailings and Mine Waste, Vancouver, British Columbia, Canada, November 6–9, 2011: Vancouver, British Columbia, Canada, Norman B. Keevil Institute of Mining Engineering, University of British Columbia, 14 p. [Also available at http://www.infomine.com/library/publications/docs/O'Shea-Stone2011.pdf.]

Osinsky, D., and Stellman, J.M., 1998, Minerals and agricultural chemicals, chap. 62 *of* Stellman, J.M., ed., Encyclopedia of occupational health and safety, 4th ed., v. 3, pt. 9, p. 62.1—62.41. [Also available at http://www.ilocis.org/documents/chpt62e.htm.]

Palmer, D.A.S., and Williams-Jones, A.E., 1996, Genesis of the carbonatite-hosted fluorite deposit at Amba Dongar, India—Evidence from fluid inclusions, stable isotopes, and whole rock-mineral geochemistry: Economic Geology, v. 91, p. 934–950. [Also available at http://dx.doi.org/10.2113/gsecongeo.91.5.934.]

Palmer, J.R., and Hayes, T.S., 1989, Late Cambrian lithofacies and their control on the Mississippi Valley-type mineralizing system in the Ozark Region (extended abs.), *in* Schindler, K.S., ed., U.S. Geological Survey research on mineral resources, 1989, Fifth Annual V.E. McKelvey Forum on Mineral and Energy Resources: U.S. Geological Survey Circular 1035, p. 51–54. [Also available at http://pubs.usgs.gov/circ/1988/1035/report.pdf.]

Partey, F., Lev, S., Casey, R., Widom, E., Lueth, V.W., and Rakovan, J., 2009, Source of fluorine and petrogenesis of the Rio Grande Rift-type barite-fluorite-galena deposits: Economic Geology, v. 104, p. 505–520. [Also available at http://dx.doi.org/10.2113/gsecongeo.104.4.505.]

Pattee, O.H., Wiemeyer, S.N., and Swineford, D.M., 1988, Effects of dietary fluoride on reproduction in eastern screech-owls: Archives of Environmental Contamination and Toxicology, v. 17, no. 2, p. 213–218. [Also available at http://dx.doi.org/10.1007/bf01056027.]

Perthuisot, V., and Rouvier, H., 1995, Lead-zinc deposits related to Triassic evaporites in diapiric structures of the eastern Maghreb [abs.], *in* Leach, D.L., and Goldhaber, M.B., eds., Extended abstracts—International field conference on carbonate-hosted lead-zinc deposits [Proceedings of International Field Conference on the Scientific and Economic Aspects of Carbonate-Hosted Lead-Zinc Deposits, St. Louis, Mo.]: Littleton, Colo., Society of Economic Geologists, p. 239–241.

Pettijohn, F.J., 1963, Chemical composition of sandstones—Excluding carbonate and volcanic sands, chap. S *of* Fleischer, Michael, ed., Data of geochemistry (6th ed.): U.S. Geological Survey Professional Paper 440–S, 21 p. [Also available at http://pubs.er.usgs.gov/publication/pp440S.]

Pfaff, Katharina, Staude, Sebastian, and Markl, Gregor, 2012, On the origin of sellaite (MgF_2)-rich deposits in Mg-poor environments: American Mineralogist, v. 97, no. 11–12, p. 1987–1997. [Also available at http://dx.doi.org/10.2138/am.2012.4113.]

Pickard, G.W., 1974, Geology of Mexican fluorspar deposits, *in* Hutcheson, D.W., ed., A symposium on the geology of fluorspar—Proceedings of the Ninth Forum on Geology of Industrial Minerals, Paducah, Ky., April 26–28, 1973: Lexington, Ky., Kentucky Geological Survey Special Publication, series X, no. 22, p. 23–30.

Piqué, Àngels, Canals, Àngels, Grandia, Fidel, and Banks, D.A., 2008, Mesozoic fluorite veins in NE Spain record regional base metal-rich brine circulation through basin and basement during extensional events: Chemical Geology, v. 257, nos. 1–2, p. 139–152. [Also available at http://dx.doi.org/10.1016/j.chemgeo.2008.08.028.]

Plumlee, G.S., Goldhaber, M.B., and Rowan, E.L., 1995, The potential role of magmatic gases in the genesis of Illinois-Kentucky fluorspar deposits; implications from chemical reaction path modeling: Economic Geology, v. 90, p. 999–1011. [Also available at http://dx.doi.org/10.2113/gsecongeo.90.5.999.]

Plumlee, G.S., Leach, D.L., Hofstra, A.H., Landis, G.P., Rowan, E.L., and Viets, J.G., 1994, Chemical reaction path modeling of ore deposition in Mississippi Valley-type Pb-Zn deposits of the Ozark Region, U.S. Midcontinent: Economic Geology, v. 89, p. 1361–1383. [Also available at http://dx.doi.org/10.2113/gsecongeo.89.6.1361.]

Price, P.E., Kyle, J.R., and Wessel, G.R., 1983, Salt dome related zinc-lead deposits, *in* Kisvarsanyi, Geza, Grant, S.K., Pratt, W.P., and Koenig, J.W., eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, 2d, Rolla, Mo., Proceedings: Rolla, Mo., University of Missouri-Rolla, p. 558–571.

Putnam, B.R., III, Norman, D.I., and Smith, R.W., 1983, Mississippi Valley-type lead-fluorite-barite deposits of the Hansonburg mining district, *in* Chapin, C.E., and Callender, J.F., eds., Socorro region II—New Mexico Geological Society Fall Field Conference Guidebook, v. 34, October 13–15: Socorro, N. Mex., New Mexico Geological Society, p. 253–259. [Also available at http://nmgs.nmt.edu/publications/guidebooks/downloads/34/34_p0253_p0260.pdf.]

Reed, M.H., 1982, Calculation of multicomponent chemical equilibria and reaction processes in systems involving minerals, gases and an aqueous phase: Geochimica et Cosmochimica Acta, v. 46, no. 4, p. 513-–528. [Also available at http://dx.doi.org/10.1016/0016-7037(82)90155-7.]

Reimann, Clemens, and de Caritat, Patrice, 1998, Chemical elements in the environment—Factsheets for the geochemist and environmental scientist: Berlin, Germany, Springer-Verlag, 398 p.

Reyf, F.G., 2004, Immiscible phases of magmatic fluid and their relation to Be and Mo mineralization at the Yermakovka F-Be deposit, Transbaikalia, Russia: Chemical Geology, v. 210, nos. 1–4, p. 49–71. [Also available at http://dx.doi.org/10.1016/j.chemgeo.2004.06.004.]

Reyf, F.G., 2008, Alkaline granites and Be (phenakite-bertrandite) mineralization—An example of the Orot and Ermakovka deposits: Geochemistry International, v. 46, no. 3, p. 213–232. (Originally published in Geokhimiya, v. 46, no. 3, p. 243–263.) [Also available at http://dx.doi.org/10.1134/s0016702908030014.]

Reynolds, R.L., Goldhaber, M.B., and Snee, L.W., 1997, Paleomagnetic and $^{40}Ar/^{39}Ar$ results from the Grant intrusive breccia and comparison to the Permian Downeys Bluff sill—Evidence for Permian igneous activity at Hicks Dome, southern Illinois Basin: U.S. Geological Survey Bulletin 2094–G, 16 p. [Also available at http://pubs.er.usgs.gov/publication/b2094G.]

Rhodes, D., Lantos, E.A., Webb, R.J., and Owens, D.C., 1984, Pine Point orebodies and their relationship to stratigraphy, structure, dolomitization, and karstification of the Middle Devonian barrier complex: Economic Geology, v. 79, p. 991–1054. [Also available at http://dx.doi.org/10.2113/gsecongeo.79.5.991.]

Richards, J.P., Dang, T., Dudka, S.F., and Wong, M.L., 2003, The Nui Phao tungsten-fluorite-copper-gold-bismuth deposit, northern Vietnam—An opportunity for sustainable development: Exploration and Mining Geology, v. 12, nos. 1–4, p. 61–70. [Also available at http://dx.doi.org/10.2113/0120061.]

Richardson, C.K., and Holland, H.D., 1979, Fluorite deposition in hydrothermal systems: Geochimica et Cosmochimica Acta, v. 43, no. 8, p. 1327–1335. [Also available at http://dx.doi.org/10.1016/0016-7037(79)90122-4.]

Richardson, C.K., and Pinckney, D.M., 1984, The chemical and thermal evolution of the fluids in the Cave-in-Rock fluorspar district, Illinois; mineralogy, paragenesis, and fluid inclusions: Economic Geology, v. 79, p. 1833–1856. [Also available at http://dx.doi.org/10.2113/gsecongeo.79.8.1833.]

Richardson, C.K., Rye, R.O., and Wasserman, M.D., 1988, The chemical and thermal evolution of the fluids in the Cave-in-Rock fluorspar district, Illinois; stable isotope systematics at the Deardorff Mine: Economic Geology, v. 83, p. 765–783. [Also available at http://dx.doi.org/10.2113/gsecongeo.83.4.765.]

Roberts, Jessica, 2012, Projects in the pipeline—New sources threaten to topple China's fluorspar dominance: Industrial Minerals, April, p. 35–38. [Also available http://www.indmin.com/Article/2997061/Projects-in-the-Pipeline-New-sources-threaten-to-topple.html.]

Rooney, T.P., Jones, B.F., and Neal, J.T., 1969, Magadiite from Alkali Lake, Oregon: American Mineralogist, v. 54, nos. 7–8, p. 1034–1043. [Also available at http://www.minsocam.org/ammin/am54/am54_1034.pdf.]

Roqueñí, N., Ugarte, L.C., Martínez, G.M., and Alvarez, J.V., 2005, Fluoride contamination of water stream in Moscona Mine area, Asturias, *in* Mine Water 2005—Mine closure—International Mine Water Association Congress, 9th, Oviedo, Spain, Proceedings: Wendelstein, Germany, International Mine Water Association, p. 507–511. [Also available at http://www.imwa.de/docs/imwa_2005/IMWA2005_071_Roqueni.pdf.]

Ruiz, Joaquin, 1983, Geology and geochemistry of fluorite ore deposits and associated rocks in northern Mexico: Ann Arbor, Mich., University of Michigan Ph.D. dissertation, 202 p.

Ruiz, Joaquin, Kesler, S.E., Jones, L.M., and Sutter, J.F., 1980, Geology and geochemistry of the Las Cuevas fluorite deposit, San Luis Potosi, Mexico: Economic Geology, v. 75, p. 1200–1209. [Also available at http://dx.doi.org/10.2113/gsecongeo.75.8.1200.]

Ryan, P.J., 1986, The Witkop fluorspar mine near Zeerust, western Transvaal, *in* Anhaeusser, C.R., and Maske, S., eds., Mineral deposits of southern Africa, v. I: Johannesburg, South Africa, Geological Society of South Africa, p. 843–849, 1 pl. in pocket.

Ryazantseva, M.D., 1998, Excursion I—The Voznesenka ore district, *in* Seltmann, R., Gonevchuk, G., and Khanchuk, A., eds., Anatomy and textures of ore-bearing granitoids of Sikhote Alin (Primorye region, Russia) and related mineralization—Excursion guidebook: Potsdam, Germany, GeoForschungsZentrum Potsdam, p. 9–22.

Sánchez, V., Corbella, M., Fuenlabrada, J.M., Vindel, E., and Martín-Crespo, T., 2006, Sr and Nd isotope data from the fluorspar district of Asturias, northern Spain: Journal of Geochemical Exploration, v. 89, nos. 1–3, p. 348–350. [Also available at http://dx.doi.org/10.1016/j.gexplo.2005.11.058.]

Sánchez, V., Vindel, E., Martín-Crespo, T., Corbella, M., Cardellach, E., and Banks, D., 2009, Sources and compositions of fluids associated with fluorite deposits of Asturias (N Spain): Geofluids, v. 9, no. 4, p. 338–355. [Also available at http://dx.doi.org/10.1111/j.1468-8123.2009.00259.x.]

Sato, Kohei, Suzuki, Kazuhiro, Nedachi, Munetomo, Terashima, Shigeru, Ryazantseva, M.D., Vrublevsky, A.A., and Khanchuk, A.I., 2003, Fluorite deposits at Voznesenka in the Khanka Massif, Russia—Geology and age of mineralization: Resource Geology, v. 53, no. 3, p. 193–211. [Also available at http://dx.doi.org/10.1111/j.1751-3928.2003.tb00169.x.]

Saunders, J.A., and Swann, C.T., 1994, Mineralogy and geochemistry of a cap-rock Zn-Pb-Sr-Ba occurrence at the Hazlehurst salt dome, Mississippi: Economic Geology, v. 89, p. 381–390. [Also available at http://dx.doi.org/10.2113/gsecongeo.89.2.381.]

Schwartz, M.O., and Friedrich, G.H., 1973, Secondary dispersion patterns of fluoride in the Osor area, Province of Gerona, Spain: Journal of Geochemical Exploration, v. 2, no. 2, p. 103–114. [Also available at http://dx.doi.org/10.1016/0375-6742(73)90009-5.]

Schweitzer, J.K., Hatton, C.J., and De Waal, S.A., 1997, Link between the granitic and volcanic rocks of the Bushveld Complex, South Africa: Journal of African Earth Sciences, v. 24, nos. 1–2, p. 95–104. [Also available at http://dx.doi.org/10.1016/s0899-5362(97)00029-8.]

Shacklette, H.T., and Boerngen, J.G., 1984, Element concentrations in soils and other surficial materials of the conterminous United States: U.S. Geological Survey Professional Paper 1270, 105 p. [Also available at http://pubs.er.usgs.gov/publication/pp1270.

Shawe, D.R., ed., 1976, Geology and resources of fluorine in the United States, *with sections by* D.R. Shawe, R.E. Van Alstine, R.G. Worl, A.V. Heyl, R.D. Trace, R.L. Parker, W.R. Griffitts, C.L. Sainsbury, and J.B. Cathcart: U.S. Geological Survey Professional Paper 933, 99 p. [Also available at http://pubs.er.usgs.gov/publication/pp933.]

Sheppard, R.A., and Gude, A.J., III, 1969, Authigenic fluorite in Pliocene lacustrine rocks near Rome, Malheur County, Oregon, chap. D *of* Geological Survey research 1969: U.S. Geological Survey Professional Paper 650–D, p. D69–D74. [Also available at http://pubs.er.usgs.gov/publication/pp650D.]

Sheppard, S.M.F., Charef, A., and Bouhlel, S., 1997, Diapirs and Zn-Pb mineralization—A general model based on Tunisian (N. Africa) and Gulf Coast (U.S.A.) deposits, *in* Sangster, D.F., ed., Carbonate-hosted lead-zinc deposits—[Society of Economic Geologists] 75th anniversary volume: Littleton, Colo., Society of Economic Geologists Special Publication no. 4, p. 230–243.

Sheridan, D.M., Taylor, R.B., and Marsh, S.P., 1968, Rutile and topaz in Precambrian gneiss, Jefferson and Clear Creek Counties, Colorado: U.S. Geological Survey Circular 567, 7 p. [Also available at http://pubs.er.usgs.gov/publication/cir567.]

Sherlock, S.C., Lucks, Tim, Kelley, S.P., and Barnicoat, Andy, 2005, A high resolution record of multiple diagenetic events—Ultraviolet laser microprobe Ar/Ar analysis of zoned K-feldspar overgrowths: Earth and Planetary Science Letters, v. 238, nos. 3–4, p. 329–341. [Also available at http://dx.doi.org/10.1016/j.epsl.2005.07.018.]

Shivdasan-Gebhardt, Purnima, and Hagni, R.D., 2008, Fluorspar deposits at Okorusu, Namibia, with emphasis upon electron microprobe analyses of carbonatite minerals and fluorite fluid inclusion temperatures and salinities, *in* Australasian Institute of Mining and Metallurgy, Ninth International Conference for Applied Mineralogy—September 8–10, 2008, Brisbane, Queensland, Australia—Proceedings: Carlton, Victoria, Australia, Australasian Institute of Mining and Metallurgy, Publication Series no. 8/2008, p. 631–641.

Simonetti, Antonio, and Bell, Keith, 1995, Nd, Pb, and Sr isotope systematics of fluorite at the Amba Dongar carbonatite complex, India; evidence for hydrothermal and crustal fluid mixing: Economic Geology, v. 90, p. 2018–2027. [Also available at http://dx.doi.org/10.2113/gsecongeo.90.7.2018.]

Simonetti, A., Bell, K., and Viladkar, S.G., 1995, Isotopic data from the Amba Dongar carbonatite complex, west-central India—Evidence for an enriched mantle source: Chemical Geology, v. 122, nos. 1–4, p. 185–198. [Also available at http://dx.doi.org/10.1016/0009-2541(95)00004-6.]

Singleton, R.H., 1989, The mineral industry of Denmark and Greenland, *in* Area reports—International: U.S. Bureau of Mines Minerals Yearbook 1987, v. III, p. 257–274. [Also available at http://images.library.wisc.edu/EcoNatRes/EFacs2/MineralsYearBk/MinYB1987v3/reference/econatres.minyb1987v3.rsingleton.pdf.]

Sizaret, Stanislas, Marcoux, Eric, Jébrak, Michel, and Touray, J.C., 2004, The Rossignol fluorite vein, Chaillac, France—Multiphase hydrothermal activity and intravein sedimentation: Economic Geology, v. 99, p. 1107–1122. [Also available at http://dx.doi.org/10.2113/gsecongeo.99.6.1107.]

Smith, G.I., 1979, Subsurface stratigraphy and geochemistry of Late Quaternary evaporites, Searles Lake, California, *with a section on* Radiocarbon ages of stratigraphic units, by Minze Stuiver and George I. Smith: U.S. Geological Survey Professional Paper 1043, 130 p. [Also available at http://pubs.er.usgs.gov/publication/pp1043.]

Steven, T.A., 1960, Geology and fluorspar deposits, Northgate district, Colorado: U.S. Geological Survey Bulletin 1082–F, p. 323–422, 4 pls. [Also available at http://pubs.er.usgs.gov/publication/b1082F.]

Stewart, F.H., 1963, Marine evaporites, chap. Y *of* Fleischer, Michael, ed., Data of geochemistry (6th ed.): U.S. Geological Survey Professional Paper 440–Y, p. Y1–Y53. [Also available at http://pubs.er.usgs.gov/publication/pp440Y.]

Stoffel, B., Appold, M.S., Wilkinson, J.J., McClean, N.A., and Jeffries, T.E., 2008, Geochemistry and evolution of Mississippi Valley-type mineralizing brines from the Tri-State and Northern Arkansas districts determined by LA-ICP-MS microanalysis of fluid inclusions: Economic Geology, v. 103, p. 1411–1435. [Also available at http://dx.doi.org/10.2113/gsecongeo.103.7.1411.]

Strong, D.F., Fryer, B.J., and Kerrich, R., 1984, Genesis of the St. Lawrence fluorspar deposits as indicated by fluid inclusion, rare earth element, and isotopic data: Economic Geology, v. 79, p. 1142–1158. [Also available at http://dx.doi.org/10.2113/gsecongeo.79.5.1142.]

Surdam, R.C., and Eugster, H.P., 1976, Mineral reactions in the sedimentary deposits of the Lake Magadi region, Kenya: Geological Society of America Bulletin, v. 87, no. 12, p. 1739–1752. [Also available at http://dx.doi.org/10.1130/0016-7606(1976)87%3C1739:mritsd%3E2.0.co;2.]

Suter, G.W., II, 1996, Toxicological benchmarks for screening contaminants of potential concern for effects on freshwater biota: Environmental Toxicology and Chemistry, v. 15, no. 7, p. 1232–1241. [Also available at http://dx.doi.org/10.1002/etc.5620150731.]

Swarup, D., Dwivedi, S.K., Dey, S., and Ray, S.K., 1998, Fluoride intoxication in bovines due to industrial pollution: The Indian Journal of Animal Sciences, v. 68, no. 7, p. 605–608.

Taylor, C.D., Rowan, E.L., Goldhaber, M.B., and Hayes, T.S., 1992, A relationship between Hicks Dome and temperature zonation in fluorite in the Illinois-Kentucky district—A fluid inclusion study [extended abs.], *in* Goldhaber, M.B., and Eidel, J.J., eds., Mineral resources of the Illinois Basin in the context of basin evolution—St. Louis, Missouri, January 22–23,1992 [program and abs.]: U.S. Geological Survey Open-File Report 92–1, p. 62–64. [Also available at http://pubs.usgs.gov/of/1992/0001/report.pdf.]

Taylor, R.G. [with chaps. by Cuff, C.], 1979, Geology of tin deposits: Amsterdam, Netherlands, Elsevier Scientific Publishing Co., Developments in Economic Geology Series, no. 11, 543 p.

Temple, A.K., and Grogan, R.M., 1963, Manto deposits of fluorspar, northern Coahuila, Mexico: Economic Geology, v. 58, p. 1037–1053. [Also available at http://dx.doi.org/10.2113/gsecongeo.58.7.1037.]

Teng, H.C., and Strong, D.R., 1976, Geology and geochemistry of the St.. Lawrence peralkaline granite and associated fluorite deposits, southeast Newfoundland: Canadian Journal of Earth Sciences, v. 13, no. 10, p. 1374–1385. [Also available at http://dx.doi.org/10.1139/e76-142.]

Tertiary Minerals plc, 2014, Building a strategic position in the fluorspar sector—Company presentation, August 20, 2013: Tertiary Metals plc, accessed February 11, 2014, at http://www.tertiaryminerals.com/downloads/Tertiary%20Minerals%20plc%20Company%20Presentation%2020%20August%202013.pdf.

Tertiary Minerals plc, 2015, MB fluorspar project, Nevada, USA: Tertiary Minerals plc Web page, accessed January 24, 2016, at http://www.tertiaryminerals.com/projects/fluorspar-projects/mb-fluorspar-nevada-usa/.

Tischendorf, G., 1978, Geochemical and petrographic characteristics of silicic magmatic rocks associated with rare-element mineralization, *in* Štemprok, Miroslav, ed., Metallization associated with acid magmatism: Prague, Czechoslovakia, Ústřední Ústav Geologický [Central Geological Survey], v. 2, p. 41–96.

Tourtelot, H.A., 1962, Preliminary investigation of the geologic setting and chemical composition of the Pierre Shale, Great Plains region: U.S. Geological Survey Professional Paper 390, 74 p., 4 pls. [Also available at http://pubs.er.usgs.gov/publication/pp390.]

U.S. Bureau of Mines, 1972–96, Minerals yearbook 1970–1994: U.S. Bureau of Mines, variously paged. [The Minerals Yearbook 1970 through 1993 is also available at http://minerals.usgs.gov/minerals/pubs/usbmmyb.html; the Minerals Yearbook 1994 is available at http://minerals.usgs.gov/minerals/pubs/myb.html.]

U.S. Environmental Protection Agency, 2002, Fluorine (soluble fluoride) (rev. December 3, 2002)—Integrated risk information system summaries, *in* Integrated risk information system: Washington, D.C., U.S. Environmental Protection Agency Chemical Assessment Summary, CASRN 7782–41–4, accessed April 16, 2013, at http://www.epa.gov/iris/subst/0053.htm.

U.S. Environmental Protection Agency, 2009, National primary drinking water regulations: U.S. Environmental Protection Agency EPA 816–F–09–004, May, 6 p., accessed April 17, 2013, at http://water.epa.gov/drink/contaminants/upload/mcl-2.pdf.

U.S. Environmental Protection Agency, 2011, Protection of stratospheric ozone—New substitute in the motor vehicle air conditioning sector under the Significant New Alternatives Policy (SNAP) Program: Federal Register, v. 76, no. 60, March 29, accessed April 30, 2013, at http://www.gpo.gov/fdsys/pkg/FR-2011-03-29/html/2011-6268.htm.

U.S. Environmental Protection Agency, 2012, Regional screening levels (RSL) summary table—November 2012: U.S. Environmental Protection Agency, accessed March 12, 2013, at http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/Generic_Tables/pdf/master_sl_table_run_NOV2012.pdf.

U.S Geological Survey, 1996, Global 30 arc-second elevation (GTOPO30): Reston, Va., U.S Geological Survey dataset (digital elevation model), accessed February 12, 2014, at https://lta.cr.usgs.gov/GTOPO30.

U.S. Geological Survey, 1997–2016, Minerals yearbook 1995–2012: U.S. Geological Survey, variously paged. [Also available at http://minerals.usgs.gov/minerals/pubs/myb.html.]

U.S. Geological Survey, 2016, National Water Information System (NWISWeb)—Water quality data for South Dakota: U.S. Geological Survey database, accessed October 12, 2016, at http://nwis.waterdata.usgs.gov/sd/nwis/qw.

Van Alstine, R.E., 1944, The fluorspar deposits of St. Lawrence, Newfoundland: Economic Geology, v. 39, p. 109–132. [Also available at http://dx.doi.org/10.2113/gsecongeo.39.2.109.]

Van Alstine, R.E., 1965, Geochemical prospecting in the Browns Canyon fluorspar district, Chaffee County, Colorado, chap. D *of* Geological Survey research 1965: U.S. Geological Survey Professional Paper 525–D, p. D59–D64. [Also available at http://pubs.usgs.gov/pp/0525-D/report.pdf.]

Van Alstine, R.E., 1969, Geology and mineral deposits of the Poncha Springs NE quadrangle, Chaffee County, Colorado, *with a section on* Fluorspar mines and prospects, by R.E. Van Alstine and D.C. Cox: U.S. Geological Survey Professional Paper 626, 52 p., 6 pls. [Also available at http://pubs.er.usgs.gov/publication/pp626.]

Van Alstine, R.E., 1976, Continental rifts and lineaments associated with major fluorspar districts: Economic Geology, v. 71, p. 977–987. [Also available at http://dx.doi.org/10.2113/gsecongeo.71.6.977.]

Vanderburg, W.O., 1940, Reconnaissance of mining districts in Churchill County, Nev.: U.S. Bureau of Mines Information Circular 7093, 57 p.

Velasco, F., Herrero, J.M., Gil, P.P., Alvarez, L., and Yusta, I., 1994, Mississippi Valley-type, SEDEX, and iron deposits in Lower Cretaceous rocks of the Basque-Cantabrian Basin, northern Spain, *in* Fontboté, Lluís, and Boni, Maria, eds., Sediment-hosted Zn-Pb ores: New York, N.Y., Society for Geology Applied to Mineral Deposits Special Publication no. 10, p. 246–270.

Viets, J.G., Hofstra, A.H., and Emsbo, Poul, 1997, Solute compositions of fluid inclusions in sphalerite from North American and European Mississippi Valley-type ore deposits; ore fluids derived from evaporated seawater, *in* Sangster D.F., ed., Carbonate-hosted lead-zinc deposits—[Society of Economic Geologists] 75th anniversary volume: Society of Economic Geologists Special Publication no. 4, p. 465–482.

von Knorring, O., and DuBois, C.G.B., 1961, Carbonatitic lava from Fort Portal in western Uganda: Nature, v. 192, no. 4807, p. 1064–1065. [Also available at http://dx.doi.org/10.1038/1921064b0.]

Wallace, A.R., 2010, Fluorine, fluorite, and fluorspar in central Colorado: U.S. Geological Survey Scientific Investigations Report 2010–5113, 61 p., 6 pls., 1 CD–ROM. [Also available at http://pubs.er.usgs.gov/publication/sir20105113.]

Weller, J.M., Grogan, R.M., and Tippie, F.E., 1952, Geology of the fluorspar deposits of Illinois: Illinois State Geological Survey Bulletin no. 76, 147 p. [Also available at http://hdl.handle.net/2142/43663.]

Wenz, Z.J., Appold, M.S., Shelton, K.L., and Tesfaye, Samson, 2012, Geochemistry of Mississippi Valley-type mineralizing fluids of the Ozark Plateau—A regional synthesis: American Journal of Science, v. 312, no. 1, p. 22–80. [Also available at http://dx.doi.org/10.2475/01.2012.02.]

White, D.E., 1965, Saline waters of sedimentary rocks, *in* Young, Addison, and Galley, J.E., eds., Fluids in subsurface environments—A symposium—The Transactions of the 6th Annual Meeting of the Southwestern Federation of Geological Societies, at Midland, Texas, January 30 and 31 and February 1, 1964: American Association of Petroleum Geologists Memoir no. 4, p. 342–366.

White, D.E., and Waring, G.A., 1963, Volcanic emanations, chap. K *of* Fleischer, Michael, ed., Data of geochemistry (6th ed.): U.S. Geological Survey Professional Paper 440–K, 29 p. [Also available at http://pubs.usgs.gov/pp/0440k/report.pdf.]

World Health Organization, 2008, Guidelines for drinking-water quality—Volume 1—Recommendations (3d ed., incorporating first and second addenda): Geneva, Switzerland, World Health Organization, 668 p., accessed March 28, 2013, at http://www.who.int/water_sanitation_health/dwq/gdwq3rev/en/index.html.

Wright, D.A., Davison, A.W., and Johnson, M.S., 1978, Fluoride accumulation by long-tailed field mice (*Apodemus sylvaticus* L.) and field voles (*Microtus agrestis* L.) from polluted environments: Environmental Pollution, v. 17, no. 4, p. 303–310. [Also available at http://dx.doi.org/10.1016/0013-9327(78)90095-2.]

Xu DongQing, 2009, Geological setting, features, and origin of the Sumochagan Obo super-large fluorite mineralized district [abs.]: Beijing, China, Chinese Academy of Geological Sciences, 3 p. accessed June 12, 2012, at http://www.dissertationtopic.net/doc/1535306.

Xu DongQing, Nie FengJun, Jiang SiHong, Zhang Wanyi, and Qian MingPing, 2008, Yanshanian peraluminous granite in Sumochagan area, Inner Mongolia: Yanshi Kuangwuxue Zazhi (Acta Petrologica et Mineralogica), v. 27, no. 2, p. 89–100. [In Chinese with English abs.]

Yilmaz, P.O., Norton, I.O., Leary, D., and Chuchla, R.J., 1996, Tectonic evolution and paleogeography of Europe, *in* Ziegler, P.A., and Horvàth, F., eds., Peri-Tethys memoir 2—Structure and prospects of Alpine basins and forelands: Paris, France, Mémoire du Musée National d'Histoire Naturelle [Memoir of the National Museum of Natural History] series, v. 170, p. 47–60, 30 pls. in accompanying case.

Yong Huang, Changchun Wang, Yonggang Wu, Hong Gao, Liqing Yu, and Anson Xu, 2011, Technical report on Sumochaganaobao fluorite mine, Siziwangqi Wulanchabu city, Inner Mongolia Autonomous Region, The People's Republic of China, report for China Shen Zhou Mining and Resources, Inc.: Vancouver, British Columbia, Canada, SRK Consulting Inc., 73 p., accessed July 3, 2012, at http://www.chinaszmg.com/pdf/SCN230_Report_Sumo_Fluorite_Mine_110718.pdf.

Yoshida, Mitsuo, Kallali, Hamadi, Ayari, Fethia, and Kotah, Takayuki, 2002, Characterization of open-dumped solid waste at Hammam Jedidi barite mine and Hammam Zriba fluorite mine, northern Tunisia, *in* EPCOWM'2002—Proceedings of International Symposium on Environmental Pollution Control and Waste Management, January 7–10, 2002, Tunis, Tunisia, p. 287–292. [Also available at http://www.geocities.jp/epcowmjp/EPCOWM2002/287-292Yoshida.pdf.]

Yuzhou Li, 1990, Be-bearing perthitic rock—Its alteration and significance in ore exploration: Geology and Prospecting, v. 26, no. 6, p. 29–35.

Zhang, L., Wei, W., Jin, S., Ye, G., Jia, D., Dong, H., and Xie, C., 2010, Integrated VLF and AMT survey for the exploration of a fluorite deposit at eastern Inner Mongolia, China [abs.]: San Francisco, Calif., American Geophysical Union Fall Meeting Abstracts, abs. no. NS41B–1514. [Also available at http://adsabs.harvard.edu/abs/2010AGUFMNS41B1514Z.]

Zhang Ronghua, Hu Shumin, Wang Jun, Yu Wenbing, and Xu Leiming, 1997, Fluorite mineralization in the Mesozoic volcanic terrains of eastern China, *in* Pei Rongfu, ed., Proceedings of the 30th International Geological Congress—Energy and mineral resources for the 21st century—Geology of mineral deposits—Mineral economics: Utrecht, Netherlands, VSP International Science Publishers, v. 9, p. 393–403.

Appendix G1. Selected Fluorspar Districts, Deposits, and Prospects of the World

The tabulations contained in this appendix do not include all world fluorspar deposits and districts, nor even all the largest of them. They instead include characteristic examples of fluorspar deposits and districts scattered throughout the world and provide examples of all fluorspar deposit classes in as many places as possible. Collectively, the tables include most large fluorspar deposits and districts. All the deposits that were compiled in examinations of the distributions of fluorspar vein deposit grades and tonnages by Orris (1992) are included. The grades and tonnages listed here have not been confirmed by the U.S. Geological Survey (USGS), and the USGS does not endorse or assure any of the grade and tonnage measurements. The grades and tonnages of deposits are listed as given in the general geologic and mining literature, unrevised by any additional knowledge. Some of the values given probably reflect only the resources known at a particular instant of time, although, where possible, the listed values are thought to be the total identified resources, and have included past production and unmined resources of the deposits or prospects.

The division between large and small deposits was made arbitrarily in a way that placed the largest 20 deposits in China from the tabulation of Kamitani and others (2007) in the large (L) class and all others in China in the small (S) class. The boundary between L and S classes by that procedure lies at about 1.5 million metric tons of total calcium fluoride (CaF_2).

Where possible, the deposits were located on imagery from Google Earth, and where Google Earth is listed as the source of location data, the latitude and longitude provided are directly from Google Earth; these latitudes and longitudes have not been corrected to any of the accepted standard geodetic spheroids, such as World Geodetic System 1984 (WGS 84). Latitude and longitude from Google Earth, in degrees, were rounded to four decimal places, which correspond approximately to the nearest 1-second of latitude or longitude. Where possible on Google Earth imagery, the latitude-longitude location is placed on the headframe of the shaft of the working or abandoned underground mine, or in the approximate center of the open pit mine. Any other placement of the location point is explained in the Comments column. Negative values for latitude indicate that the deposit is in the Southern Hemisphere; negative values for longitude indicate that the deposit is in the Western Hemisphere.

The table is sorted alphabetically by continent, then alphabetically by country, then alphabetically by deposit name. The complete reference citations corresponding to the reference callouts in the table appear at the end of this appendix. The grades and tonnages of selected deposits have been plotted in text figure G6; those that are included in that graph are listed at the end of this table.

The following is the key to the the identification numbers given in the deposit class column in the table:

1. Carbonatite-related
2. Alkaline-intrusion-related veins, skarns, and carbonate replacements
3. Alkaline-volcanic-related epithermal veins, breccia-fills, and carbonate replacements

4a. Mississippi Valley-type

4b. Salt-related carbonate-hosted

5. Skarns, greisens, veins, and replacements related to strongly differentiated granites
6. Subalkaline-volcanic-related epithermal veins and replacements
7. Apparently conformable in tuffaceous, limy lacustrine sediments
8. Deposit class uncertain or not known

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.

[*Deposit is included in the Orris (1992) grade and tonnage modeling of fluorite veins. **Grade and tonnage data are from Kamitani and others (2007); for these entries, it is not clear whether these are the total resources of each deposit or just a resource currently available to the mine that may be subject to updating with further exploration. ***Location data are from the Mineral Resources Data System (MRDS). The key to the identification numbers in the deposit class column is on page G53. Deposit size: L, identified resources are greater than 1.5 million metric tons of CaF_2; S, identified resources are less than 1.5 million metric tons of CaF_2; n.a., not available. Elements and compounds: Ag, silver; Au, gold; BeO, beryllium oxide; Bi, bismuth; CaF_2 calcium fluoride; Cd, cadmium; Cu, copper; Fe, iron; Ge, germanium; In, indium; Mo, molybdenum; Nb, niobium; Pb, lead; REE, rare-earth element; Sn, tin; Sr, strontium; Th, thorium; U, uranium; W, tungsten; Y, yttrium; Zn, zinc. Units of measure: g/t, gram per metric ton; km, kilometer; m, meter; Mt, million metric tons; %, percent]

Deposit name[1]	Country	Latitude (decimal degrees)	Longitude (decimal degrees)	Source of location data	Deposit class	Comments	Deposit size
Africa							
Kimwarer	Kenya	0.33	35.63	Google Earth (2013), at the approximate center of the Kimwarer pit, as identified by Nyambok and Gaciri (1975, figs. 2 and 5)	8	Deposit class is 1, 2, or 3; resources are given at cutoff grade of 20% CaF_2 and minimum vein width of 5 m	L
*El Hammam	Morocco	33.56	–5.81	Google Earth (2013), Van Alstine and Schruben (1980) and Cheilletz and others (2010)	5	None	L
*Jebel Tirremi	Morocco	34.44	–3.00	Google Earth (2014) and Van Alstine and Schruben (1980)	2	None	S
*Canxixe area	Mozambique	–17.58	34.31	Google Earth (2012); see comments	8	Location given is for the village of the same name; no fluorspar workings identifiable nearby on Google Earth	S
*Chioco-Djanguire area	Mozambique	–16.40	32.58	Van Alstine and Schruben (1980)	8	None	S
*Macossa	Mozambique	–17.93	34.20	Van Alstine and Schruben (1980)	8	None	S
Mount Muambe	Mozambique	–16.32	34.08	Woolley and Kjarsgaard (2008)	1	None	S
*Okorusu	Namibia	–20.07	16.77	Woolley and Kjarsgaard (2008)	1	None	L
*Buffalo	South Africa	–24.48	28.66	Google Earth (2013); see comments	5	Location given is centered between 3 open pits	L
*Hlabisa	South Africa	–28.13	31.90	Van Alstine and Schruben (1980)	8	None	S
Vergenoeg	South Africa	–25.26	28.58	Google Earth (2013)	5	Some interpret that the deposit class is 1	L
Marico district	South Africa	–25.72	26.09	Google Earth (2013)	4a	None	L

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

[*Deposit is included in the Orris (1992) grade and tonnage modeling of fluorite veins. **Grade and tonnage data are from Kamitani and others (2007); for these entries, it is not clear whether these are the total resources of each deposit or just a resource currently available to the mine that may be subject to updating with further exploration. ***Location data are from the Mineral Resources Data System (MRDS). The key to the identification numbers in the deposit class column is on page G53. Deposit size: L, identified resources are greater than 1.5 million metric tons of CaF_2; S, identified resources are less than 1.5 million metric tons of CaF_2; n.a., not available. Elements and compounds: Ag, silver; Au, gold; BeO, beryllium oxide; Bi, bismuth; CaF_2, calcium fluoride; Cd, cadmium; Cu, copper; Fe, iron; Ge, germanium; In, indium; Mo, molybdenum; Nb, niobium; Pb, lead; REE, rare-earth element; Sn, tin; Sr, strontium; Th, thorium; U, uranium; W, tungsten; Y, yttrium; Zn, zinc. Units of measure: g/t, gram per metric ton; km, kilometer; m, meter; Mt, million metric tons; %, percent]

Published resource (tonnage and grade, in weight percent CaF_2)	Source of resource data	Predominant geometry of orebody(ies)	Source of geologic description	Deposit name
		Africa—Continued		
17.1 Mt at 35.4% (indicated); and approximately 5 Mt at 35.3% (inferred); see comments	Agnerian, 2010	Epithermal/mesothermal vein and replacement deposits in Precambrian crystalline marble and gneiss; some occupy faults of the Rift Valley system; veins in Miocene volcanic rocks; alkaline volcanic-related epithermal; or possibly carbonatite-related	Nyambok and Gaciri (1975)	Kimwarer
2.82 Mt at 35% to 45% (as of 2011); 5 Mt at 57% (as of 1976)	Managem, Inc. (2011); Van Alstine and Schruben (1980)	Veins	Cheilletz and others (2010); Jébrak and others (1988)	*El Hammam
1.5 Mt at 40%	U.S. Bureau of Mines (1973)	Veins and replacements of limestone associated with alkaline intrusive rocks	Van Alstine and Schruben (1980); Bouabdellah and others (2014)	*Jebel Tirremi
0.16 Mt at >35%	Van Alstine and Schruben (1980)	Veins	n.a.	*Canxixe area
0.698 Mt at >35%	Van Alstine and Schruben (1980)	Veins	n.a.	*Chioco-Djanguire area
0.043 Mt at 35%	Van Alstine and Schruben (1980)	Veins	Van Alstine and Schruben (1980)	*Macossa
1.63 Mt at 19%	Globe Metals and Mining (2012)	Replacement masses in carbonatite(?)	Globe Metals and Mining (2012)	Mount Muambe
6 Mt at 56%	Notholt and others (1990, p. B76)	Replacement masses in carbonatite and carbonate wallrock	Kogut and others (1997)	*Okorusu
60 Mt at 16%	Crocker and Martini (1976)	Dense stockwork	Absolom (1986)	*Buffalo
0.400 Mt at 35%	Van Alstine and Schruben (1980)	Veins and stockworks	Van Alstine and Schruben (1980)	*Hlabisa
122 Mt at 35 to 40% (mined 2.03 Mt at 42.0% CaF_2 in 2005 through 2008)	For tonnage: Minersa Group (2012). For grade and period of production: Metorex, Ltd. (2008, p. 34)	Breccia pipe in Bushveld-related rhyolite and tuffaceous sedimentary rocks, including ironstones	Goff and others (2004)	Vergenoeg
100 to 150 Mt at 15%	Martini (1976)	Peneconcordant strata-bound replacement bodies in dolomites; Witkop Mine, Bulhoek Mine, Doornhoek prospect	Ryan (1986)	Marico district

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

[*Deposit is included in the Orris (1992) grade and tonnage modeling of fluorite veins. **Grade and tonnage data are from Kamitani and others (2007); for these entries, it is not clear whether these are the total resources of each deposit or just a resource currently available to the mine that may be subject to updating with further exploration. ***Location data are from the Mineral Resources Data System (MRDS). The key to the identification numbers in the deposit class column is on page G53. Deposit size: L, identified resources are greater than 1.5 million metric tons of CaF_2; S, identified resources are less than 1.5 million metric tons of CaF_2; n.a., not available. Elements and compounds: Ag, silver; Au, gold; BeO, beryllium oxide; Bi, bismuth; CaF_2, calcium fluoride; Cd, cadmium; Cu, copper; Fe, iron; Ge, germanium; In, indium; Mo, molybdenum; Nb, niobium; Pb, lead; REE, rare-earth element; Sn, tin; Sr, strontium; Th, thorium; U, uranium; W, tungsten; Y, yttrium; Zn, zinc. Units of measure: g/t, gram per metric ton; km, kilometer; m, meter; Mt, million metric tons; %, percent]

Deposit name[1]	Country	Latitude	Longitude	Source of location data	Deposit class	Comments	Deposit size
		(decimal degrees)					
			Africa—Continued				
*Zwartkloof	South Africa	–24.86	28.17	Google Earth (2013)	5	None	S
*Jebel Semeih (J. Sumayh)	Sudan	12.73	30.84	Google Earth (2013); see comments	8	Location given is atop the jebel (hill) —artisanal workings may be to the southeast along the base of the hill	S
Hammam Zriba	Tunisia	36.34	10.20	Google Earth (2014)	4b	None	L
			Asia				
Badu	China	28.03	118.90	Kamitani and others (2007)	6	None	L
Chenlou	China	33.77	112.08	Kamitani and others (2007)	8	None	L
Donggangshan	China	29.18	112.98	Kamitani and others (2007)	6	None	L
Houshu	China	28.92	119.70	Kamitani and others (2007)	6	None	L
Huahe	China	31.40	114.57	Kamitani and others (2007)	2	None	L
Huayuan district	China	28.59	109.47	Schneider and others (2002)	4a	Location given is at the major intersection in Huayuan city	S
Hushan	China	28.67	118.93	Kamitani and others (2007)	6	None	L
Jianshan	China	32.53	113.85	Kamitani and others (2007)	6	None	L
Mahuaping	China	27.30	100.08	Kamitani and others (2007)	5	None	L
Maoniuping	China	28.46	101.98	Woolley and Kjarsgaard (2008)	1	None	L
Shizhuyuan	China	25.77	113.18	Google Earth (2014); see comments	5	Location given is at an adit, but that may be a different nearby mine	L
Shuangjiangkou	China	26.95	112.87	Kamitani and others (2007)	8	None	L

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

[*Deposit is included in the Orris (1992) grade and tonnage modeling of fluorite veins. **Grade and tonnage data are from Kamitani and others (2007); for these entries, it is not clear whether these are the total resources of each deposit or just a resource currently available to the mine that may be subject to updating with further exploration. ***Location data are from the Mineral Resources Data System (MRDS). The key to the identification numbers in the deposit class column is on page G53. Deposit size: L, identified resources are greater than 1.5 million metric tons of CaF_2; S, identified resources are less than 1.5 million metric tons of CaF_2; n.a., not available. Elements and compounds: Ag, silver; Au, gold; BeO, beryllium oxide; Bi, bismuth; CaF_2, calcium fluoride; Cd, cadmium; Cu, copper; Fe, iron; Ge, germanium; In, indium; Mo, molybdenum; Nb, niobium; Pb, lead; REE, rare-earth element; Sn, tin; Sr, strontium; Th, thorium; U, uranium; W, tungsten; Y, yttrium; Zn, zinc. Units of measure: g/t, gram per metric ton; km, kilometer; m, meter; Mt, million metric tons; %, percent]

Published resource (tonnage and grade, in weight percent CaF_2)	Source of resource data	Predominant geometry of orebody(ies)	Source of geologic description	Deposit name
		Africa—Continued		
7 Mt at 13.7%	Brian Hodge, consultant on world fluorspar deposits, written commun., (2013), based on contemporary data published by the operating company	Veins	Van Alstine and Schruben (1980)	*Zwartkloof
~0.2 Mt at about 26.5%	Van Alstine and Schruben (1980)	Vein	Van Alstine and Schruben (1980)	*Jebel Semeih (J. Sumayh)
5 Mt at 15 to 35%, or 6 Mt at 50%	Bouhlel and others (1988) or Van Alstine and Schruben (1980)	Peneconcordant replacement bodies in limestone; dolomitizatioin of wallrocks	Souissi and others (1997)	Hammam Zriba
		Asia—Continued		
5.1 Mt at 50.8%**	Kamitani and others (2007)	n.a.	n.a.	Badu
2.5 Mt at 67.25%**	Kamitani and others (2007)	n.a.	n.a.	Chenlou
5.97 Mt at 30.49%** (plus recoverable Pb and Zn)	Kamitani and others (2007)	n.a.	n.a.	Donggangshan
7.7 Mt at 46.6%**	Kamitani and others (2007)	Vein	n.a.	Houshu
3.72 Mt at 60%**	Kamitani and others (2007)	Veins	Wen (1998)	Huahe
n.a.	n.a.	Peneconcordant strata-bound replacement bodies in carbonates	Schneider and others (2002)	Huayuan district
8.5 Mt at 51.5%**	Kamitani and others (2007)	n.a.	n.a.	Hushan
4.8 Mt at about 57.5%**	Kamitani and others (2007)	Veins	Chen and others (1996)	Jianshan
10.02 Mt at 22.96%** (plus recoverable W and Bi)	Kamitani and others (2007)	Skarn and greisen veinlet stockwork	Kamitani and others (2007)	Mahuaping
n.a.	n.a.	n.a.	n.a.	Maoniuping
46 Mt at 21.7% (plus W, Sn, Bi, and Mo)	Brian Hodge, consultant on world fluorspar deposits (written commun., 2013); that grade and tonnage given also by Somerley Ltd. (2011, p. 35)	Large skarns, greisens, and stockworks in limestone adjacent to biotite granite	Mao and others (1996)	Shizhuyuan
4.03 Mt at 60.26%**	Kamitani and others (2007)	n.a	n.a.	Shuangjiangkou

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

[*Deposit is included in the Orris (1992) grade and tonnage modeling of fluorite veins. **Grade and tonnage data are from Kamitani and others (2007); for these entries, it is not clear whether these are the total resources of each deposit or just a resource currently available to the mine that may be subject to updating with further exploration. ***Location data are from the Mineral Resources Data System (MRDS). The key to the identification numbers in the deposit class column is on page G53. Deposit size: L, identified resources are greater than 1.5 million metric tons of CaF$_2$; S, identified resources are less than 1.5 million metric tons of CaF$_2$; n.a., not available. Elements and compounds: Ag, silver; Au, gold; BeO, beryllium oxide; Bi, bismuth; CaF$_2$, calcium fluoride; Cd, cadmium; Cu, copper; Fe, iron; Ge, germanium; In, indium; Mo, molybdenum; Nb, niobium; Pb, lead; REE, rare-earth element; Sn, tin; Sr, strontium; Th, thorium; U, uranium; W, tungsten; Y, yttrium; Zn, zinc. Units of measure: g/t, gram per metric ton; km, kilometer; m, meter; Mt, million metric tons; %, percent]

Deposit name[1]	Country	Latitude	Longitude	Source of location data	Deposit class	Comments	Deposit size
		(decimal degrees)					
				Asia—Continued			
Sumochagan Obo	China	43.12	111.27	Google Earth (2012)	6	Deposit class instead may be 7, and the deposit geologically older and grain-coarsened than other 7s. Deposit class may be 5; grades to skarn in the same beds to the south	L
Taolin	China	29.37	113.45	Roedder and Howard (1988)	5	None	S
Yangjia-Wuyi	China	28.99	119.89	Google Earth (2012); see comments	6	Location given is at Yangjia in an open cut along a vein	L
Yinzishan	China	30.58	119.87	Kamitani and others (2007)	6	Deposit class instead may be 5	L
Zhuancum	China	30.53	118.77	Kamitani and others (2007)	8	None	L
Amba Dongar	India	22.00	74.06	Google Earth (2014)	1	None	L
Karadzhal	Kazakhstan	49.87	78.04	Google Earth (2016); probable location; see comments	5	Location given at left is 170 km southwest of Semey, Kazakhstan, as given by Ulba Metallurgical Plant Joint Stock Co. (2015). Location given at left “lies on the northern exo-contact of the granite massif [of the Degelen Mountains]” on geology map of (Böttger and others, 1998, p. 127, 203). The location is marked as “Karadzhal” on a map in Vakulchuk and Gjerde (2014, p. 16). That location is interpreted as a large excavation on a low-resolution image presented by Google Earth	L? (resource at right is considered unlikely to be a total resource)
Taskainar (Taskaynar)	Kazakhstan	43.13	75.14	Seltmann and others (2012)	5	None	L
Taskainar (Taskaynar) South	Kazakhstan	43.15	75.10	Seltmann and others (2012)	8	None	L
Adag	Mongolia	46.50	109.33	Kamitani and others (2007)	3	None	L
Berkh	Mongolia	47.77	111.17	Google Earth (2013)	3	None	S

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

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Published resource (tonnage and grade, in weight percent CaF$_2$)	Source of resource data	Predominant geometry of orebody(ies)	Source of geologic description	Deposit name
		Asia—Continued		
20 Mt at 56.52%	Kamitani and others (2007)	Peneconcordant strata-bound replacement(?) body in tuffaceous limestone, within section mixed with high-K calcalkaline volcanics, nearby peraluminous granite intrusive	Chen and others (1996)	Sumochagan Obo
6.1 Mt at 14.3% (plus recoverable Pb, Zn, Cd, Ge, and In)	Somerly, Ltd. (2011)	Veins	Roedder and Howard (1988)	Taolin
3.38 Mt at about 47.5%**	Kamitani and others (2007)	Veins	Chen and others (1996)	Yangjia-Wuyi
5.1 Mt at 38.6%**	Kamitani and others (2007)	Veins	n.a.	Yinzishan
3.45 Mt at about 50%**	Kamitani and others (2007)	n.a.	n.a.	Zhuancum
12.0 Mt, or 11.6 Mt at 30%	For tonnage: Indian Bureau of Mines (2015). For tonnage and grade: Palmer (1994)	Hydrothermal veins and replacement masses in carbonatite and potassium feldspar fenite host rocks	Palmer and Williams-Jones (1996)	Amba Dongar
1.55 Mt at 40.5% (calculated), or given grade at 25%	Tonnage and grade calculated from Interfax-Kazakhstan (2006). Given grade: Powell and Throop (2011)	Beryllium-bearing, fluorite-magnetite-garnet-skarn	Aleksandrov, (1998, table 8, p. 80).	Karadzhal
>15.625 Mt at 32%	Calculated from Seltmann and others (2012) and Koplus and others (1977)	Mineralized breccia at limestone/siliciclastics contact associated with "porphyrite" dikes or with granodiorite sill	Koplus and others (1977)	Taskainar (Taskaynar)
>5 Mt fluorite	Seltmann and others (2012)	n.a.	n.a.	Taskainar (Taskaynar) South
4.6 Mt at about 33%**	Kamitani and others (2007)	Adularia-sericite epithermal vein associated with alkaline basalt-trachyte-rhyolite series	Lkhamsuren and Hamasaki (1998)	Adag
1.6 Mt at 81.8%**	Kamitani and others (2007)	Adularia-sericite epithermal veins associated with alkaline basalt-trachyte-rhyolite series	Lkhamsuren and Hamasaki (1998)	Berkh

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

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Deposit name[1]	Country	Latitude	Longitude	Source of location data	Deposit class	Comments	Deposit size
		(decimal degrees)					
Asia—Continued							
Bor Ondor	Mongolia	46.27	109.44	Google Earth (2013)	3	None	L
Mushugai-Khudag	Mongolia	44.37	104.16	Google Earth (2013)	1	None	S
Urgun (Örgön)	Mongolia	44.71	110.74	Google Earth (2013)	3	None	L?
Zuum-Tsagaan-Del	Mongolia	46.37	110.04	Google Earth (2013)	3	None	S
Kalat district	Pakistan	29.44	67.15	Durrani (1980) and Google Earth (2014)	4a	None	S?
Auninsky	Russia	54.90	113.12	Ocean Policy Research Foundation (2012)	2	None	L
Chailag-Khem	Russia	51.91	92.40	Bolonin and others (2009)	1	None	L
Kalangui	Russia	51.01	116.53	Google Earth (2013)	6	None	L
Karasug	Russia	51.31	92.13	Transcribed from the map of Nikiforov and others (2005)	1	None	L
Naransky	Russia	50.92	105.62	Ocean Policy Research Foundation (2012)	2	None	L

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

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Published resource (tonnage and grade, in weight percent CaF_2)	Source of resource data	Predominant geometry of orebody(ies)	Source of geologic description	Deposit name
		Asia—Continued		
8.4 Mt at 32.25%**	Kamitani and others (2007)	Adularia-sericite epithermal veins associated with alkaline basalt-trachyte-rhyolite series	Lkhamsuren and Hamasaki (1998)	Bor Ondor
n.a.	n.a.	Apatite-magnetite-fluorite intrusive rock and later quartz-celestite-fluorite-barite-ankerite-phlogopite-bastnaesite veins in alkaline ultramafics	Lkhamsuren and Hamasaki (1998)	Mushugai-Khudag
?18.6 Mt at 61.3% (notation is unclear in reference)	Kamitani and others (2007)	Adularia-sericite epithermal vein associated with alkaline basalt-trachyte-rhyolite series	Lkhamsuren and Hamasaki (1998)	Urgun (Örgön)
3.4 Mt at about 34%**	Kamitani and others (2007)	Adularia-sericite epithermal veins associated with alkaline basalt-trachyte-rhyolite series	Lkhamsuren and Hamasaki (1998)	Zuum-Tsagaan-Del
n.a.	n.a.	Veins and peneconcordant replacement bodies in carbonates; Dilband and at least 5 other mineralized areas	Durrani (1980)	Kalat district
n.a.	n.a.	(?)Stockworks and skarns of fluorite-bertrandite or phenakite veinlets associated with aegerine- or reibeckite-granites	By spatial association with Yermakovskoye	Auninsky
See Karasug; Chailag-Khem is part of the same carbonatite "province" as Karasug	Nikiforov and others (2005)	See Karasug	Nikiforov and others (2005)	Chailag-Khem
10.5 Mt at 60%	Rodionov and others (2010)	Epithermal veins	Rodionov and others (2010)	Kalangui
At least tens of Mt of about 10% CaF_2; tonnage and grade not better known. Mean compositions of 18 weathered-zone samples of siderite carbonatite (CaF_2-Fe-barite-Sr ore) from Karasug field: 9.73% CaF_2; 10.26% siderite; 18.15% hematite; 19.84% goethite; 15.74% barite; 11.47% baritocelestite; 8.92% quartz and other fragments; 4.47% calcite; 0.98% REE minerals; 0.43% apatite	Nikiforov and others (2005)	Breccias from plug-like to dike-like, to partial ring dikes; ?intrusive- or ?hydrothermal-matrix-breccia	Nikiforov and others (2005)	Karasug
Tonnage not known at 31%	Rodionov and others (2010)	Swarm of parallel veins	Rodionov and others (2010)	Naransky

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

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Deposit name[1]	Country	Latitude (decimal degrees)	Longitude (decimal degrees)	Source of location data	Deposit class	Comments	Deposit size
				Asia—Continued			
Suran I & Suran II	Russia	Possibly 53.84	Possibly 57.81	Google Earth (2014); see comments	8	Deposit class is most likely 6. Location is uncertain. That given by Ocean Policy Research Foundation (2012) is inconsistent with description in Ellmies and others (1999)	L
Voznesenka and Pogranichny (the Yaroslavskoye or Yoroslavsky Mine)	Russia	44.17	132.19	Google Earth (2013); center of the Voznesenka pit	5	Grade is rounded to the nearest 5% from the mean of seven ore samples reported by Kupriyanova and Shpanov (1997, p. 385) and four ore samples reported by Ryazantseva (1998, p. 22). Tonnage includes B and C1 categories, which are approximately equivalent to “measured” and “indicated” resources, respectively	L
Yermakovskoye (Yermakovska, Yermakovsky, Ermakovsky, Ermakovskoye)	Russia	51.67	109.56	Google Earth (2013)	2	None	L
Takob	Tajikistan	38.84	68.94	Google Earth (2012); see comments	8	Location given is at the village of the same name	S?
Ban Hong	Thailand	18.21	98.82	Google Earth (2015)	8	Deposit class could be 6; tin deposits in same area but fluorite deposit is epithermal	L
Doi Tao district	Thailand	17.88	98.78	Gardner and Smith (1965)	8	None	S?
Yang Hak district	Thailand	13.37	99.47	Gardner and Smith (1965)	8	None	S?
Kizilcaören (also known as Beylikahir)	Turkey	39.62	31.37	Woolley and Kjarsgaard (2008)	Probably 1	None	L
Suppatash	Uzbekistan	41.21	70.53	Seltmann and others (2012)	8	None	S

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

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Published resource (tonnage and grade, in weight percent CaF_2)	Source of resource data	Predominant geometry of orebody(ies)	Source of geologic description	Deposit name
		Asia—Continued		
n.a.	n.a.	Veins	Ellmies and others (1999)	Suran I & Suran II
22 Mt at about 40% (Note that this tonnage disagrees dramatically from that given in Nokleberg and others (1996). Calculations of tonnage using deposit maps and sections with reasonable assumptions of average ore density yield results more than an order of magnitude smaller than the tonnage given by Nokleberg and others (1996) [450 Mt])	Tonnage: United Company RUSAL (2012). Grade: see comments	Fluorite skarn and greisen-veinlet stockwork in limestone enveloping 2 separated greisenized granite cupolas	Kupriyanova and Shpanov (1997); Ryazantseva (1998); Sato and others (2003); and Obolenskiy and others (2010)	Voznesenka and Pogranichny (the Yaroslavskoye or Yoroslavsky Mine)
0.875 Mt at 17.7% (plus 0.97% BeO) (reserves as of 2007 for the mine's proposed re-opening; past production not available)	Kislov and others, (2010)	Small skarns and stockworks	Lykhin and others (2010)	Yermakovskoye (Yermakovska, Yermakovsky, Ermakovsky, Ermakovskoye)
n.a.	n.a.	n.a.	n.a.	Takob
>3.55 Mt at 46.6 %	Gardner and Smith (1965)	Veins cutting metasedimentary rocks	Gardner and Smith (1965)	Ban Hong
n.a.	n.a.	Veins cutting porphyritic granite	Gardner and Smith (1965)	Doi Tao district
n.a.	n.a.	Veins cutting granite, phyllite, and quartzite	Gardner and Smith (1965)	Yang Hak district
12.4 Mt at 37.4% (plus barite, REE [ΣREE=3%], and Th [0.2%])	Engin (1988)	Veins, breccia-fills, and replacements in alkalic (aegerine-bearing) tuffs near phonolite plugs. REE minerals, including bastnaesite, brockite, florencite, and monazite, suggest a relation to carbonatite	Kirikoglu (2002)	Kizilcaören (also known as Beylikahir)
5.147 Mt at 27.5%	ITE-Uzbekistan (2012?)	Epithermal vein in volcanic host rocks	State Committee of the Republic of Uzbekistan for Geology and Mineral Resources (2011?)	Suppatash

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

[*Deposit is included in the Orris (1992) grade and tonnage modeling of fluorite veins. **Grade and tonnage data are from Kamitani and others (2007); for these entries, it is not clear whether these are the total resources of each deposit or just a resource currently available to the mine that may be subject to updating with further exploration. ***Location data are from the Mineral Resources Data System (MRDS). The key to the identification numbers in the deposit class column is on page G53. Deposit size: L, identified resources are greater than 1.5 million metric tons of CaF_2; S, identified resources are less than 1.5 million metric tons of CaF_2; n.a., not available. Elements and compounds: Ag, silver; Au, gold; BeO, beryllium oxide; Bi, bismuth; CaF_2, calcium fluoride; Cd, cadmium; Cu, copper; Fe, iron; Ge, germanium; In, indium; Mo, molybdenum; Nb, niobium; Pb, lead; REE, rare-earth element; Sn, tin; Sr, strontium; Th, thorium; U, uranium; W, tungsten; Y, yttrium; Zn, zinc. Units of measure: g/t, gram per metric ton; km, kilometer; m, meter; Mt, million metric tons; %, percent]

Deposit name[1]	Country	Latitude	Longitude	Source of location data	Deposit class	Comments	Deposit size
		(decimal degrees)					
				Asia—Continued			
Nui Phao	Vietnam	21.65	105.67	Richards and others (2003) and Google Earth (2014)	5	Other commodity grades for the 52.5 Mt: W, 0.21%; Bi, 0.10%; Cu, 0.21%; Au, 0.22 g/t	L
				Australia			
Moina	Australia	–41.49	146.07	Google Earth (2013); see comments	5	Location given is for the village of the same name	L
Speewah	Australia	–16.41	127.98	Gwalani and others (2010)	1	None	L
				Europe			
*Argentolle	France	Possibly 46.97	Possibly 4.08	Google Earth (2013); see comments	8	Location uncertain. The given location is at an industrial site between the villages of Les Chaux and Crot Morin, Burgundy, France. The two villages are 1.74 km distant from one another.	S
*Escaro	France	42.54	2.31	Google Earth (2013)	8	Either class 4b or 2	S
Montroc	France	43.82	2.38	Google Earth (2013)	8	Either class 4b or 2	S
*Le Barlet	France	45.05	3.50	Google Earth (2013)	8	Either class 4b or 2	S
Le Burc	France	43.87	2.41	Google Earth (2013); see comments	8	Either class 4b or 2; location uncertain	S
Rossignol	France	46.42	1.31	Google Earth (2013)	8	Either class 4b or 2	S
*Pakozd	Hungary	47.22	18.51	Google Earth (2013)	5	Location is among a group of exploration trenches	S
Bruncu Molentinu	Italy (Sardinia)	39.44	9.48	Google Earth (2013)	8	None	L(?)
*Muscadroxiu-GennaTres Montis-S'Acqua Frida (Silius Mine)	Italy (Sardinia)	39.52	9.26	Google Earth (2013)	8	Either class 4b or class 5	L
Castel Giuliano-Pianciano	Italy	42.07	12.14	Google Earth (2013); see comments	7	Location given is at outcrop #5 of Mastrangelo (1976, p. 44–45), fairly central to the fluorspar body	L
Santo Maria di Sala	Italy	42.58	11.75	Google Earth (2013); see comments	7	Location given is at outcrop #1 of Mastrangelo (1976, p. 41), towards the north-west of the fluorspar body	L

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

[*Deposit is included in the Orris (1992) grade and tonnage modeling of fluorite veins. **Grade and tonnage data are from Kamitani and others (2007); for these entries, it is not clear whether these are the total resources of each deposit or just a resource currently available to the mine that may be subject to updating with further exploration. ***Location data are from the Mineral Resources Data System (MRDS). The key to the identification numbers in the deposit class column is on page G53. Deposit size: L, identified resources are greater than 1.5 million metric tons of CaF_2; S, identified resources are less than 1.5 million metric tons of CaF_2; n.a., not available. Elements and compounds: Ag, silver; Au, gold; BeO, beryllium oxide; Bi, bismuth; CaF_2, calcium fluoride; Cd, cadmium; Cu, copper; Fe, iron; Ge, germanium; In, indium; Mo, molybdenum; Nb, niobium; Pb, lead; REE, rare-earth element; Sn, tin; Sr, strontium; Th, thorium; U, uranium; W, tungsten; Y, yttrium; Zn, zinc. Units of measure: g/t, gram per metric ton; km, kilometer; m, meter; Mt, million metric tons; %, percent]

Published resource (tonnage and grade, in weight percent CaF_2)	Source of resource data	Predominant geometry of orebody(ies)	Source of geologic description	Deposit name
		Asia—Continued		
52.5 Mt at 8.0% (plus recoverable W, Cu, Au, and Bi) (proven and probable)	Masan Group (2012)	Skarn and greisen veinlet stockwork	Richards and others (2003)	Nui Phao
		Australia—Continued		
24.6 Mt at 15.7% (plus Sn, W, Fe)	Bucci and others (2012)	Skarn	Kwak and Askins (1981)	Moina
6.7 Mt at 24.6%	Gwalani and others (2010)	Vein/dike of “replacement fluorite rock” and carbonatite cutting dolerite	Alvin and others (2004)	Speewah
		Europe—Continued		
0.313 Mt at 48%	Bouladon (1989)	Vein cutting Mississippian volcanics and fine-grained granite basement rocks	Marchand and others (1976)	*Argentolle
1.5 Mt at 50%	Clarke (1980)	Peneconcordant strata-bound replacement body in carbonates	Bouladon (1989)	*Escaro
1.3 Mt at 50%	Deloule (1982)	Vein	Deloule (1982)	Montroc
1.2 Mt at 45%	Bouladon (1989)	Vein	Bouladon (989)	*Le Barlet
0.48 Mt at 75%	Bouladon (1989)	Vein	Bouladon (989)	Le Burc
0.8 Mt at about 55%	Sizaret and others (2004)	Vein “venting to distal” stratiform barite body with minor amounts of fluorite	Sizaret and others (2004)	Rossignol
0.0187 Mt at 46%	Morvai (1982)	Veins in schist near contact with peraluminous granite	Morvai (1982)	*Pakozd
n.a.	n.a.	Vein	Cortecci and others (1987)	Bruncu Molentinu
8.0 Mt at ~42.5%	Fulton and Montgomery (1994)	Veins	Boni and others (2009)	*Muscadroxiu-GennaTres Montis-S’Acqua Frida (Silius Mine)
10 to 15 Mt at 33% to 50% (plus barite)	Matteucci (1976)	Stratiform body in tuffaceous lacustrine silt/mudstone/marl within peralkaline volcanic pile	Mastrangelo (1976)	Castel Giuliano-Pianciano
40 to 50 Mt at about 12% (plus barite)	Matteucci (1976)	Stratiform body in tuffaceous lacustrine silt/mudstone/marl within peralkaline volcanic pile	Mastrangelo (1976)	Santo Maria di Sala

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

[*Deposit is included in the Orris (1992) grade and tonnage modeling of fluorite veins. **Grade and tonnage data are from Kamitani and others (2007); for these entries, it is not clear whether these are the total resources of each deposit or just a resource currently available to the mine that may be subject to updating with further exploration. ***Location data are from the Mineral Resources Data System (MRDS). The key to the identification numbers in the deposit class column is on page G53. Deposit size: L, identified resources are greater than 1.5 million metric tons of CaF_2; S, identified resources are less than 1.5 million metric tons of CaF_2; n.a., not available. Elements and compounds: Ag, silver; Au, gold; BeO, beryllium oxide; Bi, bismuth; CaF_2, calcium fluoride; Cd, cadmium; Cu, copper; Fe, iron; Ge, germanium; In, indium; Mo, molybdenum; Nb, niobium; Pb, lead; REE, rare-earth element; Sn, tin; Sr, strontium; Th, thorium; U, uranium; W, tungsten; Y, yttrium; Zn, zinc. Units of measure: g/t, gram per metric ton; km, kilometer; m, meter; Mt, million metric tons; %, percent]

Deposit name[1]	Country	Latitude (decimal degrees)	Longitude (decimal degrees)	Source of location data	Deposit class	Comments	Deposit size
				Europe—Continued			
Asturias region	Spain	43.43	–5.62	Google Earth (2012); see comments	4a	Location given is at the mined-out La Collada Mine in La Collada (middle) sector of the mining region	L
*Osor	Spain	41.95	2.59	Google Earth (2013)	8	Deposit class is most likely 4b	S
Bétic Cordillera region: 9 small-to medium-sized districts in Almeria and Granada Provinces, Andalusia region	Spain	36.89	–2.63	Location as given by Hellerman (2015)	8	Deposit class is most likely 4b. Location given is for the Mina Del Carmen located 3.2 km northeast of Felix, Almeria, Andalusia, Spain, in the Sierra de Gádor	L?
Northern Pennine Orefield	United Kingdom	54.79	–2.17	Google Earth (2013); see comments	4a	Location given is for Frazer's Hush Dib (dib = an inclined shaft) of the Frazer's Grove mine in the northeastern part of the Orefield	L
Southern Pennine Orefield	United Kingdom	53.27	–1.69	Google Earth (2012); see comments	4a	Location given is for Stony Middleton Mill about 1.7 km north of Longstone Edge vein system	L
				North America			
*Fission (Richardson) Mine	Canada	45.06	–78.19	***MRDS (U.S. Geological Survey, 2012), ID no. I005021	1	None	S
*St. Lawrence district	Canada	46.92	–55.41	Google Earth (2013); see comments	2	Location given is for the Blue Beach North vein	L

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

[*Deposit is included in the Orris (1992) grade and tonnage modeling of fluorite veins. **Grade and tonnage data are from Kamitani and others (2007); for these entries, it is not clear whether these are the total resources of each deposit or just a resource currently available to the mine that may be subject to updating with further exploration. ***Location data are from the Mineral Resources Data System (MRDS). The key to the identification numbers in the deposit class column is on page G53. Deposit size: L, identified resources are greater than 1.5 million metric tons of CaF_2; S, identified resources are less than 1.5 million metric tons of CaF_2; n.a., not available. Elements and compounds: Ag, silver; Au, gold; BeO, beryllium oxide; Bi, bismuth; CaF_2, calcium fluoride; Cd, cadmium; Cu, copper; Fe, iron; Ge, germanium; In, indium; Mo, molybdenum; Nb, niobium; Pb, lead; REE, rare-earth element; Sn, tin; Sr, strontium; Th, thorium; U, uranium; W, tungsten; Y, yttrium; Zn, zinc. Units of measure: g/t, gram per metric ton; km, kilometer; m, meter; Mt, million metric tons; %, percent]

Published resource (tonnage and grade, in weight percent CaF_2)	Source of resource data	Predominant geometry of orebody(ies)	Source of geologic description	Deposit name
		Europe—Continued		
15 Mt at about 38.5%	Sánchez and others (2009) and Garcia Iglesias and Loredo (1994)	(1) Veins; (2) Peneconcordant strata-bound replacement bodies in calcite-cemented sandstone capped by marl-clay; and (3) Peneconcordant strata-bound bodies in “red breccia/conglomerate” immediately overlying basement of limestone and slate, also capped by marl-clay	Garcia Iglesias and Loredo (1994)	Asturias region
2 Mt at 45%	Lipperheide Wicke and Barrenechea Guimon (1983)	Vein	Piqué and others (2008)	*Osor
Single deposit; for example, Mina Lújar, Granada, as of 1987: 2.275 Mt proven and probable at 34% (plus 1.85% Pb)	Marina and Vazquez Guzmán (1987)	Veins and peneconcordant strata-bound replacement bodies in carbonates	Martin and others (1987)	Bétic Cordillera region: 9 small-to medium-sized districts in Almeria and Granada Provinces, Andalusia region
n.a.	n.a.	Veins and lesser peneconcordant strata-bound replacement bodies in carbonates	Dunham (1983)	Northern Pennine Orefield
Estimated, for example, *Sallet Hole No. 1 Adit deposit on Longstone Edge: 2.5 Mt at 40% to 50%; This grade and tonnage have not been used in figure G6	Calculated tonnage estimate uses the predicted rate of production for 1990 from Bramley (1990) projected for the full mine life—1965 to 1999. This method of estimation was suggested by Dr. Brian Hodge	Veins and lesser peneconcordant strata-bound replacement bodies in carbonates	Dunham (1983); Mason (1974)	Southern Pennine Orefield
		North America—Continued		
0.27 Mt at 26.7% (plus U)	Canada Department of Energy, Mines, and Resources (1984)	Calcite-fluorite-apatite vein/dikes in the Bancroft carbonatite province	***MRDS (U.S. Geological Survey, 2012), record no. I005021	*Fission (Richardson) Mine
10.04 Mt at 41.%*	Agnerian and others (2011)	Large veins cutting aegerine granite	Van Alstine (1944) and Strong and others (1984)	*St. Lawrence district

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

[*Deposit is included in the Orris (1992) grade and tonnage modeling of fluorite veins. **Grade and tonnage data are from Kamitani and others (2007); for these entries, it is not clear whether these are the total resources of each deposit or just a resource currently available to the mine that may be subject to updating with further exploration. ***Location data are from the Mineral Resources Data System (MRDS). The key to the identification numbers in the deposit class column is on page G53. Deposit size: L, identified resources are greater than 1.5 million metric tons of CaF_2; S, identified resources are less than 1.5 million metric tons of CaF_2; n.a., not available. Elements and compounds: Ag, silver; Au, gold; BeO, beryllium oxide; Bi, bismuth; CaF_2, calcium fluoride; Cd, cadmium; Cu, copper; Fe, iron; Ge, germanium; In, indium; Mo, molybdenum; Nb, niobium; Pb, lead; REE, rare-earth element; Sn, tin; Sr, strontium; Th, thorium; U, uranium; W, tungsten; Y, yttrium; Zn, zinc. Units of measure: g/t, gram per metric ton; km, kilometer; m, meter; Mt, million metric tons; %, percent]

Deposit name[1]	Country	Latitude (decimal degrees)	Longitude (decimal degrees)	Source of location data	Deposit class	Comments	Deposit size
North America—Continued							
Aguachile	Mexico	29.26	–102.54	Google Earth (2013) and McAnulty and others (1963)	3	None	L
El Refugio Mine	Mexico	21.57	–100.18	Google Earth (2015)	6	El Realito Mine with similar geology located just 6 km northwest	L
Encantada-Buenavista	Mexico	28.54	–102.50	Google Earth (2012); see comments	4a(?)	Location given is for Las Sabinas Mine near southeastern extreme of district, which stretches more than 30 km northwestward from there	L
Las Cuevas	Mexico	21.94	–100.58	Google Earth (2013)	6	None	L
Parral district	Mexico	26.85	–105.86	Google Earth (2014); see comments	8	Location given is for the Frisco Mine	L
La Azul deposit, Taxco district	Mexico	18.59	–99.54	Google Earth (2014); see comments	8	Location in the open pit	S?
Brown's Canyon district	United States	38.63	–106.07	Google Earth (2015); see comments	8	Deposit class is most likely 6; location is for the mouth of the Colorado-American adit	S
Crystal Mountain	United States	46.01	–113.89	Google Earth (2013)	8	Deposit class is most likely 5, or possibly 1	S
Daisy Mine	United States	36.89	–116.68	Google Earth (2013) and ***MRDS (U.S. Geological Survey, 2013), ID no. M241867	3	None	S

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

[*Deposit is included in the Orris (1992) grade and tonnage modeling of fluorite veins. **Grade and tonnage data are from Kamitani and others (2007); for these entries, it is not clear whether these are the total resources of each deposit or just a resource currently available to the mine that may be subject to updating with further exploration. ***Location data are from the Mineral Resources Data System (MRDS). The key to the identification numbers in the deposit class column is on page G53. Deposit size: L, identified resources are greater than 1.5 million metric tons of CaF_2; S, identified resources are less than 1.5 million metric tons of CaF_2; n.a., not available. Elements and compounds: Ag, silver; Au, gold; BeO, beryllium oxide; Bi, bismuth; CaF_2, calcium fluoride; Cd, cadmium; Cu, copper; Fe, iron; Ge, germanium; In, indium; Mo, molybdenum; Nb, niobium; Pb, lead; REE, rare-earth element; Sn, tin; Sr, strontium; Th, thorium; U, uranium; W, tungsten; Y, yttrium; Zn, zinc. Units of measure: g/t, gram per metric ton; km, kilometer; m, meter; Mt, million metric tons; %, percent]

Published resource (tonnage and grade, in weight percent CaF_2)	Source of resource data	Predominant geometry of orebody(ies)	Source of geologic description	Deposit name
North America—Continued				
For example, >0.6 Mt at about 70% (produced from 1966 to 1972) (plus Be, 0.3%)	Pickard (1974)	250 m-high, 50 m-wide replacement bodies in carbonates along their contact with peralkaline rhyolite-porphyry ring dike	McAnulty and others (1963)	Aguachile
about 2.6 Mt at 85%	Pickard (1974)	Breccia pipe (chimney) replaced by fluorite at contacts between limestone and intrusive rhyolite	Pickard (1974) and Fraga (1991)	El Refugio Mine
For example, Las Sabinas concession: 13 Mt at 60%	Mexichem (2012) and Hodge (2012)	Peneconcordant strata-bound replacement bodies (mantos) in carbonates	Gonzalez-Partida and others (2003)	Encantada-Buenavista
45 Mt at 84%	Tonnage: Mexichem (2012); grade: Hodge (2012)	Breccia body along the faulted contact between Jurassic limestone and Tertiary rhyolite	Ruiz and others (1980)	Las Cuevas
n.a., plus Ag, Pb, and Zn	Pickard (1974)	Quartz-sulfide veins with calc-silicate wallrock alteration cutting shale and andesite and some localized along intrusive rhyolite dikes; fluorite earlier discarded as gangue and formed a 40 Mt tailings resource at 15% to 20% CaF_2	Pickard (1974); Grant and Ruiz (1988)	Parral district
0.2 to 0.5 Mt at 63%	Pickard (1974)	Manto—Peneconcordant replacement body in limestone associated with fault contact between host Cretaceous limestone and Eocene-Oligocene felsic volcanics	Tritlla and others (2007)	La Azul deposit, Taxco district
n.a.	n.a.	Veins	Van Alstine (1969)	Brown's Canyon district
Unknown tonnage at 97.2% (plus trace U, Th, Nb, and REE)	Sahinen (1962)	Massive, sill-like erosional remnants lying relatively flat atop (Idaho batholith) biotite granite; one body enveloped in coarse quartz; contains thortveitite (monoclinic $[Sc,Y]Si_2O_7$), a mineral elsewhere found in pegmatites, in one tin skarn, in a U-Be-Zr-mineralized breccia related to granite intrusion, and at Franklin, New Jersey, as well as fergusonite (tetragonal $[Ce, Nd, La, Y][Nb, Ti]O_4$), a mineral elsewhere found with carbonatites or pegmatites	Sahinen (1962) and Parker and Havens (1963)	Crystal Mountain
n.a.	n.a.	Fault-controlled replacement body in limestone	Cornwall and Kleinhampl (1961)	Daisy Mine

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

[*Deposit is included in the Orris (1992) grade and tonnage modeling of fluorite veins. **Grade and tonnage data are from Kamitani and others (2007); for these entries, it is not clear whether these are the total resources of each deposit or just a resource currently available to the mine that may be subject to updating with further exploration. ***Location data are from the Mineral Resources Data System (MRDS). The key to the identification numbers in the deposit class column is on page G53. Deposit size: L, identified resources are greater than 1.5 million metric tons of CaF_2; S, identified resources are less than 1.5 million metric tons of CaF_2; n.a., not available. Elements and compounds: Ag, silver; Au, gold; BeO, beryllium oxide; Bi, bismuth; CaF_2, calcium fluoride; Cd, cadmium; Cu, copper; Fe, iron; Ge, germanium; In, indium; Mo, molybdenum; Nb, niobium; Pb, lead; REE, rare-earth element; Sn, tin; Sr, strontium; Th, thorium; U, uranium; W, tungsten; Y, yttrium; Zn, zinc. Units of measure: g/t, gram per metric ton; km, kilometer; m, meter; Mt, million metric tons; %, percent]

Deposit name[1]	Country	Latitude (decimal degrees)	Longitude (decimal degrees)	Source of location data	Deposit class	Comments	Deposit size
North America—Continued							
*Great Eagle	United States	32.73	–108.68	Google Earth (2013) and ***MRDS (U.S. Geological Survey, 2013), ID no. D009524	3	None	S
Hicks Dome	United States	37.52	–88.35	Trace and Amos (1984)	1	Igneous carbonatite has not yet been identified at and published for Hicks Dome, but mineralogy and elemental signatures suggest this class	L
*Huckleberry Mine	United States	33.32	–108.82	Google Earth (2013) and ***MRDS (U.S. Geological Survey, 2013), ID no. US35038	3	None	S
Illinois-Kentucky fluorspar district	United States	37.30	–88.24	Trace and Amos, 1984; see comments	4a	Location point is approximately at the district centroid; the centroid is located approximately 1 mile north of the Eagle-Babb Mine, north of Salem, Kentucky	L
Indian Peak district	United States	38.22	–113.83	Google Earth (2013), and ***MRDS (U.S. Geological Survey, 2013), ID no. W006953	3	Location point is at the Cougar Spar Mine	S
Jamestown district	United States	40.13	–105.40	Google Earth (2013) and Goddard (1946)	2	Location point is at the Burlington Mine	S?
Lost River	United States	65.48	–167.16	MRDS (U.S. Geological Survey, 2013), ID no. A016009	5	Location point is at the “New No. 3 Adit” of Plate 2 of Sainsbury (1964)	L
Meyers Cove	United States	44.85	–114.50	Google Earth (2013) and Cox (1954)	8	Location point is at Big Lead Mine. Deposit class is most likely 6	S
Northgate district	United States	40.92	–106.27	Google Earth (2013) and Steven (1960)	8	Location point is at Pender Mine. Deposit class is most likely 3	L
Rome occurrence	United States	42.81	–117.72	Google Earth (2013) and Sheppard and Gude (1969)	7	None	S
Spor Mountain district (Thomas Range)	United States	39.70	–113.17	Google Earth (2013) and Staatz and Osterwald (1959)	3	Location point is at the Ben Hill Mine, pit 1	S
Sweetwater district	United States	35.60	–84.46	Google Earth (2013); see comments	4a	No actual mine or exploration workings. Location given is for the center of the town square of Sweetwater, Tennessee	L

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

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Published resource (tonnage and grade, in weight percent CaF_2)	Source of resource data	Predominant geometry of orebody(ies)	Source of geologic description	Deposit name
North America—Continued				
0.191 at 43.1%	McAnulty (1978)	Vein	Gillerman (1964)	*Great Eagle
>>11.3 Mt at 11.5% (plus potentially recoverable REE, Nb, Y, Be, barite, Zn, and Pb)	Kirkemo (1978) (tens of additional exploratory holes have been drilled since 1978)	Variably hydrothermally mineralized breccia body(s). The dome, though spatially northwestern in the greater Illinois-Kentucky fluorspar district (below), is that district's thermal center	Taylor and others (1992); Joseph Porter (oral commun., 1990)	Hicks Dome
0.085 Mt at 35%	McAnulty (1978)	Vein	McAnulty (1978)	*Huckleberry Mine
30 Mt at 30%; an example single vein deposit is the Klondike II vein: 1.6 Mt at 60%	Grade and tonnage: Kogut and others (1997). Klondike II grade and tonnage: Feytis (2009)	Veins and peneconcordant strata-bound replacement bodies in carbonates ("bedding replacement deposits"). Hicks Dome (above), which is considered probably related to carbonatite, is a thermal center for this areally extensive district)	Shawe (1976)	Illinois-Kentucky fluorspar district
n.a.	n.a.	n.a.	n.a.	Indian Peak district
>0.7 Mt at 60 to 85% (plus Pb, Ag, and Au)	Goddard (1946)	Veins and breccia pipes, lenticular in plan and nearly vertical	Goddard (1946)	Jamestown district
23.5 Mt at 16.4% (plus recoverable Sn and W)	Watts, Griffiths, and McQuat, Ltd. (1972), as referenced by Hudson and Reed, 1997	Skarn and stockwork of exogreisen veinlets	Dobson (1982); Hudson and Reed (1997)	Lost River
n.a.	n.a.	Veins	Cox (1954)	Meyers Cove
n.a.	n.a.	Veins	Steven (1960)	Northgate district
Typically 0.84 m thickness at 3.98%	Sheppard and Gude (1969)	Conformable layer in tuffaceous lacustrine silt/mudstone within basalts	Sheppard and Gude (1969)	Rome occurrence
0.033 at 45% (plus Be, U)	Bullock (1976)	Breccia pipes	Staatz and Osterwald (1959)	Spor Mountain district
n.a.	n.a.	Breccia bodies involving several tens of meters of stratigraphy and peneconcordant replacement bodies in carbonates	Misra and others (1989)	Sweetwater district

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

[*Deposit is included in the Orris (1992) grade and tonnage modeling of fluorite veins. **Grade and tonnage data are from Kamitani and others (2007); for these entries, it is not clear whether these are the total resources of each deposit or just a resource currently available to the mine that may be subject to updating with further exploration. ***Location data are from the Mineral Resources Data System (MRDS). The key to the identification numbers in the deposit class column is on page G53. Deposit size: L, identified resources are greater than 1.5 million metric tons of CaF_2; S, identified resources are less than 1.5 million metric tons of CaF_2; n.a., not available. Elements and compounds: Ag, silver; Au, gold; BeO, beryllium oxide; Bi, bismuth; CaF_2, calcium fluoride; Cd, cadmium; Cu, copper; Fe, iron; Ge, germanium; In, indium; Mo, molybdenum; Nb, niobium; Pb, lead; REE, rare-earth element; Sn, tin; Sr, strontium; Th, thorium; U, uranium; W, tungsten; Y, yttrium; Zn, zinc. Units of measure: g/t, gram per metric ton; km, kilometer; m, meter; Mt, million metric tons; %, percent]

Deposit name[1]	Country	Latitude (decimal degrees)	Longitude (decimal degrees)	Source of location data	Deposit class	Comments	Deposit size
				North America—Continued			
*White Eagle	United States	32.61	–107.75	Google Earth (2013), and ***MRDS (U.S. Geological Survey, 2013), ID no. W006929	3	None	S
				South America			
Cerros Negros	Argentina	–32.50	–64.79	Google Earth (2014) and Coniglio and others (2000)	6	None	S
Mato Preto	Brazil	–24.75	–49.18	Google Earth (2014) and Jenkins (1987); see comments	1	Location given is for the approximate center of the Clugger orebody	L
Santa Catarina district	Brazil	–26.62	–49.26	Google Earth (2014), and Bastos Neto and others (1991)	8	Deposit class is most likely 2, but might be 4b. Location given is at Shaft 3 on the Segunda Linha Torrens vein	L

[1] Grade and tonnage information from the following deposits have been plotted in text figure G6.

Fluorspar vein or vein-and-replacement deposits

1. El Hammam, Morocco
2. Canxixe, Mozambique
3. Chioco-Djanguire, Mozambique
4. Macossa, Mozambique
5. Zwartkloof, South Africa
6. Jebel Semeih, Sudan
7. Houshu, China
8. Huahe, China
9. Hushan, China
10. Jianshan, China
11. Yangjia-Wuyi, China
12. Yinzishan, China
13. Adag, Mongolia
14. Berkh, Mongolia
15. Bor Ondor, Mongolia
16. Zuum-Tsagaan-Del, Mongolia
17. Kalangui, Russia
18. Ban Hong, Thailand
19. Suppatash, Uzbekistan
20. Speewah, Australia
21. Argentolle, France
22. Montroc, France
23. Le Barlet, France
24. Le Burc, France
25. Rossignol, France
26. Muscadroxiu-Genna Tres Montis-S'Acqua Frida, Sardinia, Italy
27. Osor, Spain
28. Fission (Richardson), Canada
29. Blue Beach North vein, St. Lawrence district, Canada
30. El Refugio Mine, Mexico
31. Las Cuevas Mine, Mexico
32. Great Eagle, New Mexico, United States
33. Huckleberry Mine, New Mexico, United States
34. Klondike II deposit, Illinois-Kentucky fluorspar district, United States
35. White Eagle, New Mexico, United States
36. Cerros Negros, Argentina

Carbonatite-related fluorspar deposits

1. Mount Muambe, Mozambique
2. Okorusu, Namibia
3. Amba Dongar, India
4. Speewah, Australia
5. Mato Preto, Brazil

Skarn, greisens, and replacement fluorspar deposits related to strongly differentiated granites

1. Buffalo, South Africa
2. Vergenoeg, South Africa
3. Mahuaping, China
4. Shizhuyuan, China
5. Taskainar (Taskaynar), Kazakhstan
6. Voznesenka I & Pogranichny, Russia
7. Nui Phao, Vietnam
8. Moina, Tasmania, Australia
9. Lost River, Alaska, United States

Table G1–1. Selected fluorspar districts, deposits, and prospects of the world.—Continued

[*Deposit is included in the Orris (1992) grade and tonnage modeling of fluorite veins. **Grade and tonnage data are from Kamitani and others (2007); for these entries, it is not clear whether these are the total resources of each deposit or just a resource currently available to the mine that may be subject to updating with further exploration. ***Location data are from the Mineral Resources Data System (MRDS). The key to the identification numbers in the deposit class column is on page G53. Deposit size: L, identified resources are greater than 1.5 million metric tons of CaF_2; S, identified resources are less than 1.5 million metric tons of CaF_2; n.a., not available. Elements and compounds: Ag, silver; Au, gold; BeO, beryllium oxide; Bi, bismuth; CaF_2, calcium fluoride; Cd, cadmium; Cu, copper; Fe, iron; Ge, germanium; In, indium; Mo, molybdenum; Nb, niobium; Pb, lead; REE, rare-earth element; Sn, tin; Sr, strontium; Th, thorium; U, uranium; W, tungsten; Y, yttrium; Zn, zinc. Units of measure: g/t, gram per metric ton; km, kilometer; m, meter; Mt, million metric tons; %, percent]

Published resource (tonnage and grade, in weight percent CaF_2)	Source of resource data	Predominant geometry of orebody(ies)	Source of geologic description	Deposit name
		North America—Continued		
0.179 Mt at 54.3%	McAnulty (1978)	Vein	McAnulty (1978)	*White Eagle
		South America—Continued		
0.27 Mt at 56%	Coniglio and others (2000)	Vein	Coniglio and others (2000)	Cerros Negros
2.65 Mt at 60%	Jenkins (1987)	Lensatic hydrothermal masses replacing calcitic carbonatite and lesser syenite, enveloping phonolite dikes intruded along the contact between carbonatite and nepheline syenite	Woolley (1987) and Jenkins, (1987)	Mato Preto
n.a.	n.a.	Veins	Bastos Neto and others (1991)	Santa Catarina district

Appendix G1 References Cited

Note: All Web links listed were active as of the access date but may no longer be available.

Absolom, S.S., 1986, The Buffalo fluorspar deposit, Naboomspruit district, *in* Anhaeusser, C.R., and Maske, S., eds., Mineral deposits of southern Africa: Johannesburg, Geological Society of South Africa, v. 2, p. 1337–1341, 1 map in folder pocket.

Agnerian, Hrayr, 2010, Kimwarer fluorspar project, Kimwarer, Kerio Valley, Kenya, technical report prepared for Kenya Fluorspar Company, Ltd.: Toronto, Ontario, Canada, Scott Wilson Roscoe Postle Associates, Inc., January 15, 189 p.

Agnerian, Hrayr, Lecuyer, N.L., Bailey, Ray, and Wawrzkow, Michel, 2011, Preliminary feasibility study of the St. Lawrence fluorspar project, Newfoundland and Labrador, Canada, NI 43–101 technical report prepared for Canada Fluorspar (NL), Inc. [Filing date May 11, 2011]: Toronto, Ontario, Canada, Roscoe Postle Associates, Inc., April 29, 246 p., accessed November 19, 2012, via http://www.sedar.com/search/search_form_pc_en.htm.

Aleksandrov, S.M., 1998, Geochemistry of skarn and ore formation in dolomites: Utrecht, Netherlands, VSP BV, 300 p.

Alvin, M.P., Dunphy, J.M., and Groves, D.I., 2004, Nature and genesis of a carbonatite-associated fluorite deposit at Speewah, East Kimberley region, Western Australia: Mineralogy and Petrology, v. 80, nos. 3–4, p. 127–153. [Also available at http://dx.doi.org/10.1007/s00710-003-0015-3.]

Bastos Neto, Artur, Charvet, Jacques, Touray, J.-C., and Dardenne, Marcelle, 1991, Evolution tectonique du district à fluorine de Santa Catarina (Brésil) en relation avec l'ouverture de l'Atlantique Sud [Tectonic evolution of the Santa Catarina fluorite district (Brazil) in relation with the South Atlantic opening]: Bulletin de la Société Géologique de France [Geological Society of France Bulletin], v. 162, no. 3, p. 503–513. [In French with English abs.]

Bolonin, A.V., Nikiforov, A.V., Lykhin, D.A., and Sugrakova, A.M., 2009, The Chailag-Khem fluorite-barium-strontium rare earth carbonatite occurrence, in the western Sayan Range, Russia: Geology of Ore Deposits, v. 51, no. 1, p. 17–32. [Also available at http://dx.doi.org/10.1134/S1075701509010024.]

Boni, Maria, Balassone, Giuseppina, Fedele, Luca, and Mondillo, Nicola, 2009, Post-Variscan hydrothermal activity and ore deposits in southern Sardinia (Italy)—Selected examples from Gerrei (Silius vein system) and the Iglesiente district: Periodico di Mineralogia, v. 78, no. 3, p. 19–35. [Also available at http://dx.doi.org/10.2451/2009pM0010.]

Böttger, G., Denecke, C. Görner, R., Viehweg, M., Krause, H., and Schneider, L., 1998, Evaluation of the suitability of the sites and facilities at Degelen and Azgir in the Republic of Kazakhstan as a final repository for radioactive waste—Final report prepared by C&E Consulting und Engineering GmbH and Stoller Ingenieurtechnik: Luxembourg, Luxembourg, European Commission, Publication no. EUR 17633 EN, 217 p. [Also available at http://bookshop.europa.eu/en/evaluation-of-the-suitability-of-the-sites-and-facilities-at-degelen-and-azgir-in-the-republic-of-kazakhstan-as-a-final-repository-for-radioactive-waste-pbCRNA17633/.]

Bouabdellah, Mohammed, Castorina, Francesca, Bodnar, R.J., Banks, David, Jébrak, Michel, Prochaska, Walter, Lowry, Dave, Klügel, Andreas, and Hoernle, Kaj, 2014, Petroleum migration, fluid mixing, and halokinesis as the main ore-forming processes at the peridiapiric Jbel Tirremi fluorite-barite hydrothermal deposit, northeastern Morocco: Economic Geology, v. 109, p. 1223–1256. [Also available at http://dx.doi.org/10.2113/econgeo.109.5.1223.]

Bouhlel, S., Fortuné, J.-P., Guilhaumou, N., and Touray, J.-C., 1988, Les minéralisations stratiformes à F-Ba de Hammam Zriba, Jebel Guébli (Tunisie nord orientale)—L'apport des études d'inclusions fluides à la modélisation génétique [Stratiform F-Ba mineralization at Hammam Zriba, Jebel Guebli (northeast Tunisia)—The contribution of fluid inclusion studies to genetic modeling]: Mineralium Deposita, v. 23, no. 3, p. 166–173. [In French with English abs. Also available at http://dx.doi.org/10.1007/bf00204295.]

Bouladon, J., 1989, France and Luxembourg, *in* Dunning, F.W., Garrard, P., Haslam, A.W., and Ixer, R.A. eds., Southwest and Eastern Europe, with Iceland, v. 4–5: London, United Kingdom, Institution of Mining and Metallurgy, Mineral Deposits of Europe Series, p. 37–104.

Bramley, J.V., 1990, Fluorspar mining in Derbyshire: Mining Magazine, v. 163, no. 5, November, p. 328–333.

Bucci, Louis, Chan, Gavin, and Povey, Brian, 2012, Independent technical assessment of the assets of TNT Mines Limited, report prepared for TNT Mines Limited: Melbourne, Victoria, Australia, SRK Consulting (Australasia) Pty. Ltd., 118 p., accessed December 8, 2012, at http://www.tntmines.com.au/documents/TNTMines-technical_report_2012dec.pdf.

Bullock, K.C., 1976, Fluorite occurrences in Utah: Utah Geological and Mineral Survey Bulletin, no. 110, 89 p.

Canada Department of Energy, Mines and Resources, 1984, Canadian mineral deposits not being mined in 1983: Canada Department of Energy, Mines and Resources Bulletin 198, May, 308 p.

Cheilletz, Alain, Gasquet, Dominique, Filali, Fouad, Archibald, D.A., and Nespolo, Massimo, 2010, A late Triassic $^{40}Ar/^{39}Ar$ age for the El Hammam high-REE fluorite deposit (Morocco)—Mineralization related to the Central Atlantic magmatic province?: Mineralium Deposita, v. 45, no. 4, p. 323–329. [Also available at http://dx.doi.org/10.1007/s00126-010-0282-y.]

Chen Xianpei, Gao Jiyuan, and Cao Junchen, 1996, Barite and fluorite deposits of China, *in* Editorial Committee of the Mineral Deposits of China, eds. [Responsible ed. Liu Nailong], Mineral deposits of China, v. 5: Beijing, China, Geological Publishing House, p. 52–117.

Clarke, Gerry, 1980, Industrial minerals of France: Industrial Minerals, no. 159, December, p. 23–55.

Coniglio, Jorge, Perez-Xavier, Roberto, Pinotti, Lucio, and D'Eramo, Fernando, 2000, Ore-forming fluids of vein-type fluorite deposits of the Cerro Aspero Batholith, southern Cordoba Province, Argentina: International Geology Review, v. 42, no. 4, p. 368–383. [Also available at http://dx.doi.org/10.1080/00206810009465088.]

Cornwall, H.R., and Kleinhampl, F.J., 1961, Geology of the Bare Mountain quadrangle, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ–157, scale 1:62,500, accessed October 8, 2015, at http://pubs.er.usgs.gov/publication/gq157.

Cortecci, G., Reyes, E., Leone, G., and Turi, B., 1987, Sulfur, oxygen, carbon, and strontium isotope geochemistry of the Sarrabus-Gerrei mining district, southeastern Sardinia, Italy: Economic Geology, v. 82, p. 1592–1610. [Also available at http://dx.doi.org/10.2113/gsecongeo.82.6.1592.]

Cox, D.C., 1954, Fluorspar deposits near Meyers Cove, Lemhi County, Idaho: U.S. Geological Survey Bulletin 1015–A, 21 p., 5 pls. [Also available at http://pubs.er.usgs.gov/publication/b1015A.]

Crocker, I.T., and Martini, J.E.J., 1976, Fluorspar, *in* Coetzee, C.B., ed., Mineral resources of the Republic of South Africa (5th ed.): Pretoria, South Africa, South Africa Geological Survey Handbook no. 7, p. 357–363.

Deloule, E., 1982, The genesis of fluorspar hydrothermal deposits at Montroc and Le Burc, the Tarn, as deduced from fluid inclusion analysis: Economic Geology, v. 77, p. 1867–1874. [Also available at http://dx.doi.org/10.2113/gsecongeo.77.8.1867.]

Dobson, D.C., 1982, Geology and alteration of the Lost River tin-tungsten-fluorine deposit, Alaska: Economic Geology, v. 77, p. 1033–1052. [Also available at http://dx.doi.org/10.2113/gsecongeo.77.4.1033.]

Dunham, Kingsley, 1983, Ore genesis in the English Pennines—A fluoritic subtype, *in* Kisvarsanyi, Geza, Grant, S.K., Pratt, W.P., and Koenig, J.W., eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, 2d, Rolla, Mo., 1982, proceedings: Rolla, Mo., University of Missouri-Rolla, p. 86–112.

Durrani, N.A., 1980, Structural control and genesis of the fluorspar deposit near Dilband and the surrounding areas, *in* Proceedings of the International Committee on Geodynamics, Group 6, Meeting Peshawar, November 23–29, 1979: Geology Bulletin, University of Peshawar [Pakistan], Special issue, v. 13, p. 199–206. [Also available at http://nceg.uop.edu.pk/GeologicalBulletin/Vol-13-1979/Vol-13-1979-Paper22.pdf.]

Ellmies, R., Germann, K., Krupenin, M.T., Möller, P., and Echtler, H.P., 1999, The fluorite-sellaite deposits of Suran, Bashkir Meganticline, Urals, *in* Stanley, C.J., and others, eds., Mineral deposits—Processes to processing—Proceedings of the Fifth Biennial SGA Meeting and the Tenth Quadrennial IAGOD Symposium, London, United Kingdom, August 22–25, 1999: Brookfield, Vt., A.A. Balkema, p. 841–844.

Engin, Tandogan, 1988, General geological setting & mineral resources of Turkey, *in* Griffiths, J.B., and Dickson, E.M., eds., Turkey's industrial minerals—Production, potential, investment and trade: Industrial Minerals supplement, March, p. 5–11.

Feytis, Alex, 2009, Fluorspar supply fortified: Industrial Minerals Web page, accessed January 9, 2010, at http://www.indmin.com/Article/2299402/Fluorspar-supply-fortified.html.

Fraga, M.P., 1991, Geology and mineralization of the El Realito Mine, Rio Santa Maria district, Guanajuato, Mexico, *in* Salas, G.P., ed., Economic geology, Mexico: Boulder, Colo., Geological Society of America, Geology of North America series, v. P–3, 287–289.

Fulton, R.B., and Montgomery, G., 1994, Fluorspar, *in* Carr, D.D., and others, eds., Industrial minerals and rocks (6th ed.): Littleton, Colo., Society for Mining, Metallurgy, and Exploration Inc., p. 509–522.

Garcia Iglesias, Jesús, and Loredo, Jorge, 1994, Geological, geochemical, and mineralogical characteristics of the Asturias fluorspar district, northern Spain: Exploration and Mining Geology, v. 3, no. 1, p. 31–37. [Also available at http://www.cim.org/en/Publications-and-Technical-Resources/Publications/Technical_Papers/1994/1/BULL-1994-01-08.aspx.]

Gardner, L.S., and Smith, R.M., 1965, Fluorspar deposits of Thailand: Bangkok, Thailand, Department of Mineral Resources, Report of Investigation no. 10, 42 p., 3 pls.

Gillerman, Elliot, 1964, Mineral deposits of western Grant County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 83, 213 p., illustrations folded in pocket.

Globe Metals and Mining, 2012, Project profile, Mount Muambe REE-fluorite project: Globe Metals and Mining Web page, 2 p., accessed February 26, 2013, at http://www.globemetalsandmining.com.au/Files/Projects/Mount-Muambe/Project-Flyer-%28Muambe%29-English.aspx.

Goddard, E.N., 1946, Fluorspar deposits of the Jamestown district, Boulder County, Colorado: Colorado Scientific Society, Proceedings, v. 15, no. 1, 47 p.

Goff, B.H., Weinberg, R., Groves, D.I., Vielreicher, N.M., and Fourie, P.J., 2004, The giant Vergenoeg fluorite deposit in a magnetite-fluorite-fayalite REE pipe—A hydrothermally-altered carbonatite-related pegmatoid?: Mineralogy and Petrology, v. 80, nos. 3–4, p. 173–199. [Also available at http://dx.doi.org/10.1007/s00710-003-0012-6.]

González-Partida, E., Carrillo-Chávez, A., Grimmer, J.O.W., Pironon, J., Mutterer, J., and Levresse, G., 2003, Fluorite deposits of Encantada-Buenavista, Mexico—Products of Mississippi Valley-type processes: Ore Geology Reviews, v. 23, nos. 3–4, p. 107—124. [Also available at http://dx.doi.org/10.1016/s0169-1368(03)00018-0.]

Google Earth, 2012–16, Various latitude and longitude data from Google Earth online database: Google Inc. Web site, available at https://www.google.com/earth/.

Grant, G.J., and Ruiz, Joaquin, 1988, The Pb-Zn-Cu-Ag deposits of the Granadeña Mine, San Francisco del Oro-Santa Barbara district, Chihuahua: Economic Geology, v. 83, p. 1683–1702. [Also available at http://dx.doi.org/10.2113/gsecongeo.83.8.1683.]

Gwalani, L.G., Rogers, K.A., Demény, A., Groves, D.I., Ramsay, R., Beard, A., Downes, P.J., and Eves, A., 2010, The Yungul carbonatite dykes associated with the epithermal fluorite deposit at Speewah, Kimberley, Australia—Carbon and oxygen isotope constraints on their origin: Mineralogy and Petrology, v. 98, nos. 1–4, p. 123–141. [Also available at http://dx.doi.org/10.1007/s00710-009-0102-1.]

Hellerman, I.E., 2015, Patrimonio minero de Andalucía oriental—Las Minas de Sierra de Gador: I. Eberhard Hellermann, personal Web page, accessed July 7, 2015, at http://mining-andaluz.de/?page_id=1745. [In English.]

Hodge, Brian, 2012, Fluorspar illuminated: Industrial Minerals, no. 541, October, p. 39–52. [Also available at http://www.indmin.com/pdfs/697/86771/Fluorspar%20illuminated4%201.pdf.]

Hudson, T.L., and Reed, B.L., 1997, Tin deposits in Alaska, *in* Goldfarb, R.J., and Miller, L.D., eds., Mineral deposits of Alaska: Lancaster, Pa., Economic Geology Publishing Co., Economic Geology Monograph Series, no. 9, p. 450–465.

Indian Bureau of Mines, 2015, Gujurat, *in* Part I—State reviews (52d ed.) (final release): Nagpur, India, Indian Minerals Yearbook 2013, v. I, September, p. 11-1–11-7.

Interfax-Kazakhstan, 2006, Ulbynsk metallurgic plant intends to put in operation the concentrating mill for processing the fluorspar of Karadzhal field: Kazakhstan Stock Exchange Web page, accessed July 19, 2016, at http://www.kase.kz/news/show/1005873.

ITE-Uzbekistan, [2012?], List of mineral deposits in Uzbekistan: ITE-Uzbekistan, 32 p., accessed March 21, 2013, at http://www.ite-uzbekistan.uz/ITE-ADVERT/List_depositsEng.pdf.

Jébrak, M., Touray, J.C., and Giret, P., 1988, Geochemical characteristics and genesis of fluorite deposits in Morocco, *in* Zachrisson, Ebbe, ed., Proceedings of the Seventh Quadrennial IAGOD [International Association on the Genesis of Ore Deposits] Symposium, Luleå, Sweden, August 18–22, 1986: Stuttgart, West Germany, E. Schweizerbart'sche Verlagsbuchhandlung, p. 187–195.

Jenkins, R.E., II, 1987, Geology of the Clugger fluorite deposit, Mato Preto, Parana, Brazil: Revista Brasileira de Geosciencias, v. 17, no. 3, p. 288–294.

Kamitani, Masaharu, Okumura, Kimio, Teraoka, Yoji, Miyano, Sumiko, and Watanabi, Yasushi, 2007, Mineral resources map of east Asia: Japan, Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, scale 1:3,000,000.

Kirikoglu, M.S., 2002, Kizilcaoren carbonatitic fluorite-barite-thorium and rare earth deposits, northwest Anatolia, Turkey, *in* Seeger, C.M., ed., Proceedings of the 38th Forum on the Geology of Industrial Minerals, St. Louis Mo., April 28–May 3, 2002: Jefferson City, Mo., Missouri Department of Natural Resources, Geological Survey and Resource Assessment Division, Report of Investigations no. 74, p. 157–166.

Kirkemo, Harold, 1978, Final report—OME exploration project; OME-6873 (fluorspar-beryllium-rare earths-thorium-niobium), Hicks Dome Property, Hardin County, Illinois: U.S. Geological Survey, Office of Minerals Explorations, November, variously paged. [Also available at http://minerals.usgs.gov/dockets/scans/il/ome/6873_OME.pdf.] (Note: Downloaded file is 189 MB in size.)

Kislov, E.V., Imetkhenov, A.B., and Sandakova, D.M., 2010, The Yermakovskoye fluorite-beryllium deposit—Avenues for improving ecological security of revitalization of the mining operations: Geography and Natural Resources, v. 31, no. 4, p. 324–329. [Also available at http://dx.doi.org/10.1016/j.gnr.2010.11.004.]

Kogut, A.I., Hagni, R.D., and Schneider, G.I.C., 1997, The Okorusu, Namibia, carbonatite-related fluorite deposits, and a comparison with the Illinois-Kentucky fluorite district/Hicks Dome, *in* Sangster, D.F., ed., Carbonate-hosted lead-zinc deposits—[Society of Economic Geologists] 75th anniversary volume: Littleton, Colo., Society of Economic Geologists Special Publication no. 4, p. 290–297.

Koplus, A.V., Puzanov, L.S., and Zubov, M.A., 1977, Endogenic geochemical halos of concealed fluorspar mineralization of Kazakhstan (as in the Taskaynar-Yuzhnyy deposit): International Geology Review, v. 19, no. 12, p. 1441–1447. [Also available at http://dx.doi.org/10.1080/00206817709471157.]

Kupriyanova, I.I., and Shpanov, E.P., 1997, Beryllium-fluorite ores at the Voznesensk ore district (Primorskii Krai, Russia): Geology of Ore Deposits, v. 39, no. 5, p. 442–455.

Kwak, T.A.P., and Askins, P.W., 1981, Geology and genesis of the F-Sn-W(-Be-Zn) skarn (wrigglite) at Moina, Tasmania: Economic Geology, v. 76, p. 439–467. [Also available at http://dx.doi.org/10.2113/gsecongeo.76.2.439.]

Lipperheide Wicke, Federico, and Barrenechea Guimon, Alberto, 1983, A review of the Spanish fluorspar industry and its role in world markets, *in* Coope, B.M., and Clarke, G.M., eds., Proceedings of the 5th ‘Industrial Minerals’ International Congress, Madrid, Spain, April 25–28, 1983: London, United Kingdom, Metal Bulletin PLC, p. 51–59.

Lkhamsuren, Jargalyn, and Hamasaki, Satoshi, 1998, Fluorite deposits in Mongolia—An outline: Bulletin of the Geological Survey of Japan, v. 49, no. 6, p. 309–318. [Also available at https://www.gsj.jp/data/bull-gsj/49-06_08.pdf.]

Lykhin, D.A., Kovalenko, V.I., Yarmolyuk, V.V., Kotov, A.B., and Kovach, V.P., 2010, The Yermakovsky deposit, western Transbaikal region, Russia—Isotopic and geochemical parameters and sources of beryllium-bearing granitoids and others rocks: Geology of Ore Deposits, v. 52, no. 4, p. 289–301. [Also available at http://dx.doi.org/10.1134/s1075701510040045.]

Managem, Inc., 2011, Rapport annuel, 2011 [Annual report 2011]: Casablanca, Morocco, Managem, Inc., 127 p. [In French.]

Mao Jingwen, Li Hongyan, Shimazaki, Hidehiko, Raimbault, Louis, and Guy, Bernard, 1996, Geology and metallogeny of the Shizhuyuan skarn-greisen deposit, Hunan Province, China: International Geology Review, v. 38, no. 11, p. 1020–1039.

Marchand, L., Joseph, D., Touray, J.C., and Treuil, M., 1976, Criteres d’analyse géochimique des gisements de fluorine basés sur l’étude de la distribution des lanthanides—Application au gite de Maine (71-Cordesse, France) [Criteria of geochemical analyses of fluorite deposits based on study of the distribution of the lanthanides—Application to the Maine deposit (71-Cordesse, France)]: Mineralium Deposita, v. 11, no. 3, p. 357–379. [Also available at http://dx.doi.org/10.1007/BF00203085.]

Marina, E.F., and Vazquez Guzmán, Fernando, 1987, The mining industry in Spain: Madrid, Spain, Instituto Geologico y Minero de España, 178 p. [Errata slip inserted.]

Martin, J.M., Torres-Ruiz, J., and Fonboté, L., 1987, Facies control of strata-bound ore deposits in carbonate rocks—The F-(Pb-Zn) deposits in the Alpine Triassic of the Alpujárrides, southern Spain: Mineralium Deposita, v. 22, no. 3, p. 216–226. [Also available at http://dx.doi.org/10.1007/bf00206613.]

Martini, J.E.J., 1976, The fluorite deposits in the Dolomite Series of the Marico district, Transvaal, South Africa: Economic Geology, v. 71, p. 625–635. [Also available at http://dx.doi.org/10.2113/gsecongeo.71.3.625.]

Masan Group, 2012, Nui Phao resources and reserves: Masan Group Web page, accessed March, 3, 2014, at http://www.masangroup.com/masanresources/en/projects/nui-phao/resources-reserves.

Mason, J.E., 1974, Geology of the Derbyshire fluorspar deposits, United Kingdom, *in* Hutcheson, D.W., ed., A symposium on the geology of fluorspar—Proceedings of the Ninth Forum on Geology of Industrial Minerals, Paducah, Ky., April 26–28, 1973: Lexington, Ky., Kentucky Geological Survey Special Publication, series X, no. 22, p. 10–22.

Mastrangelo, Federico, 1976, I giacimenti [The deposits], *in* Le fluoriti sedimentarie Laziali [Latium sedimentary fluorspars]: Società Italiana di Mineralogia e Petrologia [Society of Mineralogy and Petrology of Italy] Rendiconti [Statements], v. XXXII, no. 1, p. 29–46. [Also available at http://rruff.info/rdsmi/V32/V32.html.]

Matteucci, Elio, 1976, Ipotesi e problemi genetici [Genetic hypotheses and problems], *in* Le fluoriti sedimentarie Laziali [Latium sedimentary fluorspars]: Società Italiana di Mineralogia e Petrologia [Society of Mineralogy and Petrology of Italy] Rendiconti [Statements], v. XXXII, no. 1, p. 47–63. [Also available at http://rruff.info/rdsmi/V32/V32.html.]

McAnulty, W.N., 1978, Fluorspar in New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir, no. 34, 64 p.

McAnulty, W.N., Sewell, C.R., Atkinson, D.R., and Rasberry, J.M., 1963, Aguachile beryllium-bearing fluorspar district, Coahuila, Mexico: Geological Society of America Bulletin, v. 74, no. 6, p. 735–743, 2 pls. [Also available at http://dx.doi.org/10.1130/0016-7606(1963)74[735:abfdcm]2.0.co;2.]

Metorex, Ltd., 2008, Metorex Limited annual report: Share-Data Online Web page, 130 p., accessed March 3, 2014, at http://www.sharedata.co.za/Data/000886/pdfs/METOREX_ar_08.pdf.

Mexichem, 2012, Mexichem Fluor: Fluorspar 2012 Conference, Vancouver, British Columbia, Canada, October 22–24, 2012, presentation, 35 p., accessed March 3, 2014, at http://www.metalbulletin.com/Event Details/0/5035/Fluorspar-2012.html.

Minersa Group, 2012, Minersa fluorspar expansion: Minersa Group press release, June 11, accessed March 3, 2014, at http://www.minersa.com/eng/news_details.php?id=8.

Misra, K.C., Kopp, O.C., Paris, T.A., and Linkous, M.A., 1989, Mississippi Valley-type fluorite-barite-sphalerite mineralization in the Sweetwater district, Tennessee: Carbonates and Evaporites, v. 4, no. 2, p. 211–230. [Also available at http://dx.doi.org/10.1007/bf03175108.]

Morvai, G., 1982, Hungary, *in* Dunning, F.W., Mykura, W., and Slater, D., eds., Mineral deposits of Europe—Southeast Europe: London, United Kingdom, The Institution of Mining and Metallurgy, Mineral Deposits of Europe Series, v. 2, p. 13–54.

Nikiforov, A.V., Bolonin, A.V., Sugorakova, A.M., Popov, V.A., and Lykhin, D.A., 2005, Carbonatites of central Tuva—Geological structure and mineral and chemical composition: Geology of Ore Deposits, v. 47, no. 4, p. 326–345.

Nokleberg, W.J., Bundtzen, T.K., Dawson, K.M., Eremin, R.A., Goryachev, N.A., Koch, R.D., Ratkin, V.V., Rozenblum, I.S., Shpikerman, V.I., Frolov, Y.F., Gorodinsky, M.E., Melnikov, V.D., Ognyanov, N.V., Petrachenko, E.D., Pozdeev, A.I., Ross, K.V., Wood, D.H., Grybeck, Donald, Khanchuk, A.I., Kovbas, L.I., Nekrasov, I. Ya., and Sidorov, A.A., 1996, Significant metalliferous and selected non-metalliferous lode deposits and placer districts for the Russian Far East, Alaska, and the Canadian Cordillera: U.S. Geological Survey Open-File Report 96–513–A, 385 p. [Also available at http://pubs.er.usgs.gov/publication/ofr96513A.]

Notholt, A.J.G., Highley, D.E., and Deans, T., 1990, Economic minerals in carbonatites and associated alkaline igneous rocks: Transactions of the Institution of Mining and Metallurgy—Section B, Applied Earth Sciences, v. 99, p. B59–B80.

Nyambok, I.O., and Gaciri, S.J., 1975, Geology of the fluorite deposits in Kerio Valley, Kenya: Economic Geology, v. 70, p. 299–307. [Also available at http://dx.doi.org/10.2113/gsecongeo.70.2.299.]

Obolenskiy, A.A., Rodionov, S.M., Ariunbileg, Sodov, Dejidmaa, Gunchin, Distanov, E.G., Dorjgotov, Dangindorjiin, Gerel, Ochir, Hwang, D.-H., Sun, Fengyue, Gotovsuren, Ayurzana, Letunov, S.N., Li, Xujun, Nokleberg, W.J., Ogasawara, Masatsugu, Seminsky, Z.V., Smelov, A.P., Sotnikov, V.I., Spiridinov, A.A., Zorina, L.V., and Yan, Honquan, 2010, Mineral deposit models for northeast Asia, chap. 3 *of* Nokleberg, W.J., ed., Metallogenesis and tectonics of northeast Asia: U.S. Geological Survey Professional Paper 1765, p. 3-1–3-75. [Also available at http://pubs.usgs.gov/pp/1765/p1765.pdf.]

Ocean Policy Research Foundation, 2012, Resources—Mineral resources—Fluorite: Development and Operation Program for Environmental Sustainability in East Eurasia [JANSROP-GIS] Web page, accessed February 4, 2013, at http://jansrop.sof.or.jp/.

Orris, G.J., 1992, Grade and tonnage model of fluorite veins [Model 26b], in Orris, G.J., and Bliss, J.D., eds., Industrial minerals deposit models—Grade and tonnage models: U.S. Geological Survey Open-File report 92–437, p. 29–31. [Also available at http://pubs.er.usgs.gov/publication/ofr92437.]

Palmer, D.A.S., 1994, Geology and geochemistry of the Amba Dongar carbonatite-hosted fluorite deposit, India: Montreal, Quebec, Canada, McGill University, M.S. thesis, 109 p.

Palmer, D.A.S., and Williams-Jones, A.E., 1996, Genesis of the carbonatite-hosted fluorite deposit at Amba Dongar, India—Evidence from fluid inclusions, stable isotopes, and whole rock-mineral geochemistry: Economic Geology, v. 91, p. 934–950. [Also available at http://dx.doi.org/10.2113/gsecongeo.91.5.934.]

Parker, R.L., and Havens, R.G., 1963, Thortveitite associated with fluorite, Ravalli County, Montana, *in* Geological Survey research 1963; short papers in geology and hydrology, articles 1–59: U.S. Geological Survey Professional Paper 475–B, article no. 2, p. B10–B11. [Also available at http://pubs.er.usgs.gov/publication/pp475B.]

Pickard, G.W., 1974, Geology of Mexican fluorspar deposits, *in* Hutcheson, D.W., ed., A symposium on the geology of fluorspar—Proceedings of the Ninth Forum on Geology of Industrial Minerals, Paducah, Ky., April 26–28, 1973: Lexington, Ky., Kentucky Geological Survey Special Publication, series X, no. 22, p. 23–30.

Piqué, Àngels, Canals, Àngels, Grandia, Fidel, and Banks, D.A., 2008, Mesozoic fluorite veins in NE Spain record regional base metal-rich brine circulation through basin and basement during extensional events: Chemical Geology, v. 257, nos. 1–2, p. 139–152. [Also available at http://dx.doi.org/10.1016/j.chemgeo.2008.08.028.]

Powell, Jim, and Throop, Brandon, 2011, Minor metals, major potential: Montreal, Quebec, Canada, Laurentian Bank Securities, May 6, 60 p., accessed July 20, 2016, at https://www.vmbl.ca/Actions/1/Multi-metal%20Initiating%20Coverage_May2011.pdf.

Richards, J.P., Dang, T., Dudka, S.F., and Wong, M.L., 2003, The Nui Phao tungsten-fluorite-copper-gold-bismuth deposit, northern Vietnam—An opportunity for sustainable development: Exploration and Mining Geology, v. 12, nos. 1–4, p. 61–70. [Also available at http://dx.doi.org/10.2113/0120061.]

Rodionov, S.M., Khanchuk, A.I., Obolenskiy, A.A., Ogasawara, Masatsugu, Seminskiy, Z.V., Prokopiev, A.V., Timofeev, V.F., and Nokleberg, W.J., 2010, Middle Jurassic through Quaternary metallogenesis and tectonics of northeast Asia, chap. 8 *of* Nokleberg, W.J., ed., Metallogenesis and tectonics of northeast Asia: U.S. Geological Survey Professional Paper 1765, p. 8-1–8-137. [Also available at http://pubs.usgs.gov/pp/1765/p1765.pdf.]

Roedder, E., and Howard, K.W., 1988, Taolin Zn-Pb-fluorite deposit, People's Republic of China—An example of some problems in fluid inclusion research on mineral deposits: Journal of the Geological Society (London), v. 145, no. 1, p. 163–174. [Also available at http://dx.doi.org/10.1144/gsjgs.145.1.0163.]

Ruiz, Joaquin, Kesler, S.E., Jones, L.M., and Sutter, J.F., 1980, Geology and geochemistry of the Las Cuevas fluorite deposit, San Luis Potosi, Mexico: Economic Geology, v. 75, p. 1200–1209. [Also available at http://dx.doi.org/10.2113/gsecongeo.75.8.1200.]

Ryan, P.J., 1986, The Witkop fluorspar mine near Zeerust, western Transvaal, *in* Anhaeusser, C.R., and Maske, S., eds., Mineral deposits of southern Africa, v. I: Johannesburg, South Africa, Geological Society of South Africa, p. 843–849, 1 pl. in pocket.

Ryazantseva, M.D., 1998, Excursion I—The Voznesenka ore district, *in* Seltmann, R., Gonevchuk, G., and Khanchuk, A., eds., Anatomy and textures of ore-bearing granitoids of Sikhote Alin (Primorye region, Russia) and related mineralization—Excursion guidebook: Potsdam, Germany, GeoForschungsZentrum Potsdam, p. 9–22.

Sahinen, U.M., 1962, Fluorspar deposits in Montana: Montana Bureau of Mines and Geology Bulletin, no. 28, 38 p.

Sainsbury, C.L., 1964, Geology of the Lost River Mine area, Alaska: U.S. Geological Survey Bulletin 1129, 80 p., 10 sheets. [Also available at https://pubs.er.usgs.gov/publication/b1129.]

Sánchez, V., Vindel, E., Martín-Crespo, T., Corbella, M., Cardellach, E., and Banks, D., 2009, Sources and composition of fluids associated with fluorite deposits of Asturias (N Spain): Geofluids, v. 9, no. 4, p. 338–355. [Also available at http://dx.doi.org/10.1111/j.1468-8123.2009.00259.x.]

Sato, Kohei, Suzuki, Kazuhiro, Nedachi, Munetomo, Tershima, Shigeru, Ryazantseva, M.D., Vrublevsky, A.A., and Khanchuk, A.I., 2003, Fluorite deposits at Voznesenka in the Khanka Massif, Russia—Geology and age of mineralization: Resource Geology, v. 53, no. 3, p. 193–211. [Also available at http://dx.doi.org/10.1111/j.1751-3928.2003.tb00169.x.]

Schneider, Jens, Boni, Maria, Lapponi, Fabio, and Bechstädt, Thilo, 2002, Carbonate-hosted zinc-lead deposit in the Lower Cambrian of Hunan, south China—A radiogenic (Pb, Sr) isotope study: Economic Geology, v. 97, p. 1815–1827. [Also available at http://dx.doi.org/10.2113/gsecongeo.97.8.1815.]

Seltmann, Reimar, Shatov, Vitaly, and Yakubchuk, Alexander, 2012, Mineral deposits database and thematic maps of central Asia (Kazakhstan, Kyrgyzstan, Uzbekistan, Tajikistan): London, United Kingdom, Natural History Museum, Department of Earth Sciences, Centre for Russian and Central EurAsian Mineral Studies (CERCAMS), ArcMap 9.2 GIS package, scale 1:1.5 million.

Shawe, D.R., ed., 1976, Geology and resources of fluorine in the United States, *with sections by* D.R. Shawe, R.E. Van Alstine, R.G. Worl, A.V. Heyl, R.D. Trace, R.L. Parker, W.R. Griffitts, C.L. Sainsbury, and J.B. Cathcart: U.S. Geological Survey Professional Paper 933, 99 p. [Also available at http://pubs.er.usgs.gov/publication/pp933.]

Sheppard, R.A., and Gude, A.J., III, 1969, Authigenic fluorite in Pliocene lacustrine rocks near Rome, Malheur County, Oregon, chap. D *of* Geological Survey research 1969: U.S. Geological Survey Professional Paper 650–D, p. D69–D74. [Also available at http://pubs.er.usgs.gov/publication/pp650D.]

Sizaret, Stanislas, Marcoux, Eric, Jébrak, Michel, and Touray, J.C., 2004, The Rossignol fluorite vein, Chaillac, France—Multiphase hydrothermal activity and intravein sedimentation: Economic Geology, v. 99, p. 1107–1122. [Also available at http://dx.doi.org/10.2113/gsecongeo.99.6.1107.]

Somerley, Ltd., 2011, Market report on tungsten, fluorspar, bismuth and copper, report prepared for Masan Group: Hong Kong [China], Somerley, Ltd., August, 77 p., accessed June 5, 2014, at http://www.masangroup.com/static/uploads/block/somerly-report-en-6.pdf.

Souissi, F., Danduran, J.L., and Fortuné, J.P., 1997, Thermal and chemical evolution of fluids during fluorite deposition in the Zaghouan Province, north-eastern Tunisia: Mineralium Deposita, v. 32, no. 3, p. 257–270. [Also available at http://dx.doi.org/10.1007/s001260050091.]

Staatz, M.H., and Osterwald, F.W., 1959, Geology of the Thomas Range fluorspar district, Juab County, Utah: U.S. Geological Survey Bulletin 1069, 97 p., 12 pls. [Also available at http://pubs.er.usgs.gov/publication/b1069.]

State Committee of the Republic of Uzbekistan for Geology and Mineral Resources, [2011?] Mineral resource of the Uzbekistan—New opportunities for Japanese investors [Presentation]: Japan-Uzbekistan Network for Investment Environment Improvement Web page, 30 p., accessed February 26, 2013, at http://www.jp-ca.org/navoiforum/materials/no.3/1georogiya.pdf.

Steven, T.A., 1960, Geology and fluorspar deposits, Northgate district, Colorado: U.S. Geological Survey Bulletin 1082–F, p. 323–422, 4 pls. [Also available at http://pubs.er.usgs.gov/publication/b1082F.]

Strong, D.F., Fryer, B.J., and Kerrich, R., 1984, Genesis of the St. Lawrence fluorspar deposits as indicated by fluid inclusion, rare earth element, and isotopic data: Economic Geology, v. 79, p. 1142–1158. [Also available at http://dx.doi.org/10.2113/gsecongeo.79.5.1142.]

Taylor, C.D., Rowan, E.L., Goldhaber, M.B., and Hayes, T.S., 1992, A relationship between Hicks Dome and temperature zonation in fluorite in the Illinois-Kentucky district—A fluid inclusion study [extended abs.], *in* Goldhaber, M.B., and Eidel, J.J., eds., Mineral resources of the Illinois Basin in the context of basin evolution—St. Louis, Missouri, January 22–23,1992 [program and abs.]: U.S. Geological Survey Open-File Report 92–1, p. 62–64. [Also available at http://pubs.usgs.gov/of/1992/0001/report.pdf.]

Trace, R.D., and Amos, D.H., 1984, Stratigraphy and structure of the Western Kentucky fluorspar district: U.S. Geological Survey Professional Paper 1151–D, p. D1–D41, 1 pl. [Also available at http://pubs.er.usgs.gov/publication/pp1151D.]

Tritlla, Jordi, Levresse, Gilles, Corona-Esquivel, Rodolfo, Banks, D.A., Lamadrid, Hector, Bourdet, Julien, and Pinto-Linares, P.J., 2007, Epigenetic, low-temperature, carbonate-hosted Pb-Zn-Cu-Ba-F-Sr deposits in México—A Mississippi Valley-type classification, *in* Alaniz-Álvarez, S.A., and Nieto-Samaniego, Á.F., eds., Geology of México—Celebrating the centenary of the Geological Society of México: Boulder, Colo., Geological Society of America, Geological Society of America Special Paper series, v. 422, p. 417–432. [Also available at http://dx.doi.org/10.1130/2007.2422(15).]

Ulba Metallurgical Plant Joint Stock Co., 2015, Ulba Fluorine Complex LLP: Ulba Metallurgical Plant Joint Stock Co. Web page, accessed November 9, 2015, at http://www.ulba.kz/en/branch2.htm.

United Company RUSAL, 2012, UC RUSAL to increase its stake in Yaroslavsk GRK to 100%: United Company RUSAL press release, accessed February 28, 2014, at http://www.rusal.ru/en/press-center/news_details.aspx?id=6543&ibt=13&at=0.

U.S. Bureau of Mines, 1973, Morocco: Mineral Trade Notes, v. 70, no. 10, October, p. 23–29. [Also available at http://hdl.handle.net/2027/mdp.39015068576142?urlappend=%3Bseq=249.]

U.S. Geological Survey, 2012–15, Mineral Resources Data System: U.S. Geological Survey database, available at http://mrdata.usgs.gov/mrds/.

Vakulchuk, Roman, and Gjerde, Kristian, *with* Tatiana Balikhina and Kazbek Apsalikov, 2014, Semipalatinsk nuclear testing—The humanitarian consequences: Oslo, Norway, Norwegian Institute of International Affairs Report no. 1.2014, 35 p., accessed June 26, 2016, at http://large.stanford.edu/courses/2014/ph241/powell2/docs/vakulchuk.pdf. [(Report prepared for the Second Conference on Humanitarian Impact of Nuclear Weapons in Nayarit, Mexico, February 13–14, 2014.]

Van Alstine, R.E., 1944, The fluorspar deposits of St. Lawrence, Newfoundland: Economic Geology v. 39, p. 109–32. [Also available at http://dx.doi.org/10.2113/gsecongeo.39.2.109.]

Van Alstine, R.E., 1969, Geology and mineral deposits of the Poncha Springs NE quadrangle, Chaffee County, Colorado, *with a section on* Fluorspar mines and prospects, by R.E. Van Alstine and D.C. Cox: U.S. Geological Survey Professional Paper 626, 52 p., 6 pls. [Also available at http://pubs.er.usgs.gov/publication/pp626.]

Van Alstine, R.E., and Schruben, P.G., 1980, Fluorspar resources of Africa: U.S. Geological Survey Bulletin 1487, 25 p., 1 pl. [Also available at http://pubs.er.usgs.gov/publication/b1487.]

Watts, Griffiths, and McQuat, Ltd., 1972, Preliminary feasibility report on the Lost River fluorite-tin-tungsten: Toronto, Ontario, Canada, Lost River Mining Company, Ltd., 291 p.

Wen Lu, 1998, Fluorspar, *in* Wen Lu, Chinese industrial minerals (Griffiths, Joyce, ed.): Worchester Park, Surrey, United Kingdom, Industrial Minerals Information, Ltd., p. 68–75.

Woolley, A.R., 1987, Alkaline rocks and carbonatites of the world—Part 1—North and South America: London, United Kingdom, British Museum of Natural History, 216 p.

Woolley, A.R., and Kjarsgaard, B.A., 2008, Paragenetic types of carbonatites as indicated by the diversity and relative abundances of associated silicate rocks—Evidence from a global database: Canadian Mineralogist, v. 46, no. 4, p. 741–752. [Also available at http://dx.doi.org/10.3749/canmin.46.4.741.]

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