![USGS science for a changing world]

Rare-Earth Elements

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

Professional Paper 1802–O

Periodic Table of Elements

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

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

Los Alamos NATIONAL LABORATORY

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.   The Mountain Pass Mine, San Bernardino County, California, was the only active producer of rare-earth elements (REEs) in the United States in 2013. The orebody is a tabular carbonatite intrusion and is thought to be the largest REE resource in the United States. Photograph by Bradley S. Van Gosen, U.S. Geological Survey.

Rare-Earth Elements

By Bradley S. Van Gosen, Philip L. Verplanck, Robert R. Seal II, Keith R. Long, and Joseph Gambogi

Chapter O 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–O

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

Contents

Figures

Tables

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

APS	American Physical Society
FCC	fluid catalytic cracking
ft	foot
HREE	heavy rare-earth element
ICP–MS	inductively coupled plasma-mass spectrometry
IOCG	iron oxide-copper-gold
IREL	Indian Rare Earths Ltd.
K_2O	potassium oxide
KMML	Kerala Minerals and Metals Ltd.
LREE	light rare-earth element
m	meter
MOFCOM	Ministry of Commerce (China)
MRI	magnetic resonance imaging
MRS	Materials Research Society
NiMH	nickel-metal-hydride
ppb	part per billion
ppm	part per million
REE	rare-earth element
REO	rare-earth oxide
TRE	Tantalus Rare Earths
TREO	total rare-earth oxide
USGS	U.S. Geological Survey

Rare-Earth Elements

By Bradley S. Van Gosen, Philip L. Verplanck, Robert R. Seal II, Keith R. Long, and Joseph Gambogi

Abstract

The rare-earth elements (REEs) are 15 elements that range in atomic number from 57 (lanthanum) to 71 (lutetium); they are commonly referred to as the "lanthanides." Yttrium (atomic number 39) is also commonly regarded as an REE because it shares chemical and physical similarities and has affinities with the lanthanides. Although REEs are not rare in terms of average crustal abundance, the concentrated deposits of REEs are limited in number.

Because of their unusual physical and chemical properties, the REEs have diverse defense, energy, industrial, and military technology applications. The glass industry is the leading consumer of REE raw materials, which are used for glass polishing and as additives that provide color and special optical properties to the glass. Lanthanum-based catalysts are used in petroleum refining, and cerium-based catalysts are used in automotive catalytic converters. The use of REEs in magnets is a rapidly increasing application. Neodymium-iron-boron magnets, which are the strongest known type of magnets, are used when space and weight are restrictions. Nickel-metal hydride batteries use anodes made of a lanthanum-based alloys.

China, which has led the world production of REEs for decades, accounted for more than 90 percent of global production and supply, on average, during the past decade. Citing a need to retain its limited REE resources to meet domestic requirements as well as concerns about the environmental effects of mining, China began placing restrictions on the supply of REEs in 2010 through the imposition of quotas, licenses, and taxes. As a result, the global rare-earth industry has increased its stockpiling of REEs; explored for deposits outside of China; and promoted new efforts to conserve, recycle, and substitute for REEs. New mine production began at Mount Weld in Western Australia, and numerous other exploration and development projects noted in this chapter are ongoing throughout the world.

The REE-bearing minerals are diverse and often complex in composition. At least 245 individual REE-bearing minerals are recognized; they are mainly carbonates, fluorocarbonates, and hydroxylcarbonates (n=42); oxides (n=59); silicates (n=85); and phosphates (n=26).

Many of the world's significant REE deposits occur in carbonatites, which are carbonate igneous rocks. The REEs also have a strong genetic association with alkaline magmatism. The systematic geologic and chemical processes that explain these observations are not well understood. Economic or potentially economic REE deposits have been found in (a) carbonatites, (b) peralkaline igneous systems, (c) magmatic magnetite-hematite bodies, (d) iron oxide-copper-gold (IOCG) deposits, (e) xenotime-monazite accumulations in mafic gneiss, (f) ion-absorption clay deposits, and (g) monazite-xenotime-bearing placer deposits. Carbonatites have been the world's main source for the light REEs since the 1960s. Ion-adsorption clay deposits in southern China are the world's primary source of the heavy REEs. Monazite-bearing placer deposits were important sources of REEs before the mid-1960s and may be again in the future. In recent years, REEs have been produced from large carbonatite bodies mined at the Mountain Pass deposit in California and, in China, at the Bayan Obo deposit in Nei Mongol Autonomous Region, the Maoniuping deposit in Sichuan Province, the Daluxiang deposit in Sichuan Province, and the Weishan deposit in Anhui Province. Alkaline igneous complexes have recently been targeted for exploration because of their enrichments in the heavy REEs.

Information relevant to the environmental aspects of REE mining is limited. Little is known about the aquatic toxicity of REEs. The United States lacks drinking water standards for REEs. The concentrations of REEs in environmental media are influenced by their low abundances in crustal rocks and their limited solubility in most groundwaters and surface waters. The scarcity of sulfide minerals, including pyrite, minimizes or eliminates concerns about acid-mine drainage for carbonatite-hosted deposits and alkaline-intrusion-related REE deposits. For now, insights into environmental responses of REE mine wastes must rely on predictive models.

Introduction

Until recently, the rare-earth elements (REEs) were familiar to a relatively small number of people, such as chemists, some geologists, and specialized materials and technology engineers. In the 21st century, the REEs have gained considerable visibility through news media and Internet coverage because of (a) recognition of the critical, specialized properties that the REEs contribute in components of our modern technology, combined with (b) the near monopoly on the production and supply of the REEs held by one country (China), and (c) the world's heavy dependence on this controlled supply from China (Long, 2011; Tse, 2011; Hatch, 2012a).

Since the late 1990s, China has provided more than 90 percent of the world's supply of the REEs, on average (Long and others, 2010; Tse, 2011; Hatch, 2012a). In 2010, China announced that it intended to reduce its exports of REEs (Hatch, 2012a). At the same time, the use of REEs in clean energy and defense technologies was continuing to increase (Goonan, 2011; Long, 2011; Tse, 2011; Hatch, 2012a). China's announcement regarding its REE export quotas raised concerns among nations that are highly dependent on specialized technologies, such as Japan, the United States, and members of the European Union. These countries, as well as the World Trade Organization, formally protested China's reduced export quotas for REEs (Hatch, 2012a), and China agreed in 2014 to remove the restrictions. Nonetheless, the political and economic issues surrounding the global supply of REEs in the early 21st century has given these metals more visibility and a greater appreciation of their strategic importance than ever before. As a consequence, exploration activities to discover economic deposits of REEs and efforts to bring them into production increased dramatically. One industry analyst stated that, as of September 2012, during a high period of global exploration for REE deposits, his company was "tracking a total of 442 rare-earth projects in progress associated with 270 different companies in 37 different countries" (Hatch, 2012b).

In recent years, expert panels convened by research institutes and Government agencies highlighted specific REEs as raw materials critical to evolving technologies, such as clean-energy applications, electronics, and high-tech military components. These reports also suggest that a high potential exists for disruptions in the supply of these REEs. As a result, several expert panel analyses ranked REEs high on the "criticality" factor of raw materials—that is, high importance to technologies and economies combined with high risk for supply disruptions. Recent reports by panels and agencies tasked to assess the criticality of REEs and other raw materials include those by the National Research Council (2008), U.S. Department of Energy (2010, 2011), European Commission (2014), American Physical Society (APS) Panel on Public Affairs and Materials Research Society (MRS) (2011), and the Resnick Institute (2011).

The REEs comprise 15 elements (table O1) that range in atomic number from 57 (lanthanum) to 71 (lutetium) on the periodic table of elements. They are commonly referred to as the "lanthanides." The REE promethium (atomic number 61) is not included in discussions of REE deposits because the element is extremely rare and unstable in nature. Yttrium (atomic number 39) is commonly regarded as an REE because it shares chemical and physical similarities and has affinities with the lanthanides and because it typically occurs in the same deposits as other REEs.

Traditionally, the REEs are divided into the following two groups on the basis of atomic weight: (a) the light REEs (LREEs), which include lanthanum through gadolinium (atomic numbers 57 through 64), and (b) the heavy REEs (HREEs), which include terbium through lutetium (atomic numbers 65 through 71) (table O1). Yttrium, although light (atomic number 39), is included with the HREE group because of its common chemical and physical affiliations with the other HREEs.

Table O1. List of the rare-earth elements found in natural deposits—the "lanthanides" plus yttrium.

[Average crustal abundance values are from Lide (2004, p. 17); REE, rare-earth element]

Element[1]	Symbol	Atomic number	Atomic weight	Crustal abundance (part per million)
Light REEs				
Lanthanum	La	57	138.91	39
Cerium	Ce	58	140.12	66.5
Praseodymium	Pr	59	140.91	9.2
Neodymium	Nd	60	144.24	41.5
Samarium	Sm	62	150.36	7.05
Europium	Eu	63	151.96	2.0
Gadolinium	Gd	64	157.25	6.2
Heavy REEs				
Yttrium	Y	39	88.91	33
Terbium	Tb	65	158.92	1.2
Dysprosium	Dy	66	162.50	5.2
Holmium	Ho	67	164.93	1.3
Erbium	Er	68	167.26	3.5
Thulium	Tm	69	168.93	0.52
Ytterbium	Yb	70	173.04	3.2
Lutetium	Lu	71	174.97	0.8

[1]Promethium (Pm, atomic number=61) is not included in this list because it is extremely rare in nature.

Most of the REEs are not as rare as the group's name suggests. They were named "rare-earth" elements because most were identified during the 18th and 19th centuries as "earths" (originally defined as materials that could not be changed further by the sources of heat), and, in comparison with other "earths," such as lime or magnesia, they were relatively rare. Cerium is the most abundant REE (table O1), and it is actually more common in Earth's crust than is copper or lead (Lide, 2004, p. 17). All the REEs except promethium are more abundant than silver, gold, or platinum in Earth's crust, on average (Lide, 2004, p. 17). Thus, REEs are not rare in terms of average crustal abundance, but concentrated and economic deposits of REEs are unusual (Adams and Staatz, 1973). Ore deposits of REEs are found in unusual rock types and uncommon minerals, as described in the sections that follow.

Uses and Applications

To take advantage of their unusual physical and chemical properties, the REEs are used in a variety of industrial and technology applications (Goonan, 2011; Long, 2011). Given their similar chemical nature, many different REEs have related or complementary uses; thus, it is more convenient to describe their uses by application rather than by individual element. In general, the lighter REEs and yttrium are cheaper, are produced in greater quantities, and are more extensively used than the heavier REEs. The least common and most expensive REEs, from holmium to lutetium, are limited to a very few, highly specialized, high-technology applications. Goonan (2011) provided a quantitative study of domestic REE consumption, including estimated consumption of individual REEs as of 2008, addressed according to consumption categories.

The glass industry is the leading consumer of REE raw materials (Goonan, 2011), principally for purposes of glass polishing and as additives to provide color and special optical properties to glass. Cerium oxide is widely used in the production of glass types that require a precision polish, such as flat panel display screens. Cerium is also used to decolorize glass. Lanthanum and lutetium greatly increase the refractive index of optical glass. Lanthanum is widely used in camera lenses, whereas the more expensive lutetium is used in immersion lithography, which requires a high-refractive index. Erbium, holmium, neodymium, praseodymium, ytterbium, and yttrium are used as special colorants and to provide filtering and glare-reduction qualities for glass. Europium is a common dopant (doping agent) for optical fibers.

Catalysts are another major use for REEs. They include lanthanum-based catalysts used in petroleum refining and cerium-based catalysts used in automotive catalytic converters (Goonan, 2011). Catalysts enriched in REEs are essential to cracking (breaking down) heavy hydrocarbon molecules into smaller molecules, which enables petroleum refineries to obtain significantly more product per barrel of oil processed.

Small amounts of neodymium, praseodymium, and yttrium are used as catalysts in catalytic converters to reduce automotive carbon monoxide emissions.

Permanent magnets made from alloys of REEs are a recent, rapidly growing application. Neodymium-iron-boron magnets are the strongest magnets known; they are used wherever space and weight are at a premium. Significant uses include hard disk drives, cell phones, electric motors for hybrid vehicles and windmills, and actuators in aircraft (Goonan, 2011; Long, 2011). Lesser amounts of dysprosium, gadolinium, and praseodymium are also used in these magnets. Dysprosium is of particular importance because substituting it for a small portion of neodymium improves high-temperature performance and resistance to demagnetization. Permanent magnets are used in such demanding applications as electric motors for hybrid cars and wind turbines. Samarium-cobalt magnets, though less powerful than neodymium magnets, have better heat tolerance and are used in lieu of neodymium magnets where heat stress is an issue.

Nickel-metal hydride batteries use a lanthanum-based alloy for anodes (Kopera, 2004). Found in many rechargeable consumer products and some hybrid vehicles, these battery alloys are also a significant application of cerium, neodymium, praseodymium, and samarium. Demand for REEs in battery applications is expected to decrease as lithium ion batteries displace nickel-metal hydride batteries (Anderson and Patiño-Echeverri, 2009). Nickel-metal hydride batteries in hybrid electric cars are significant users of lanthanum, however, employing as much as 10 to 15 kilograms per vehicle.

Cerium, lanthanum, neodymium, and praseodymium, commonly in the form of a mixed oxide known as mischmetal, are used in steelmaking to remove impurities, as well as in the production of special steel alloys (Goonan, 2011). These REEs, along with yttrium, individually or in combination, are also used in various special alloys of chromium, magnesium, molybdenum, tungsten, vanadium, and zirconium.

Many REEs, especially yttrium, cerium, lanthanum, europium, and terbium, are used individually or in combination to make phosphors for many types of cathode ray tube and flat panel display screens, and in some incandescent, fluorescent, and light-emitting diode lighting (Goonan, 2011; Long, 2011). Gadolinium phosphors are used in X-ray imaging and various medical applications, such as magnetic resonance imaging (MRI). Yttrium, lanthanum, cerium, neodymium, and praseodymium are used as pigments for ceramics.

Rare-earth elements are also used in synthetic gems, crystals for lasers, microwave equipment, superconductors, sensors, nuclear control rods, and cryo-coolers. Neodymium is the active constituent in a popular fertilizer in China. Significant potential new uses for REEs include their use as nanofilters and in memory devices, power converters, optical clocks, infrared decoy flares, and fusion energy. Future research is likely to find many new uses for the REEs.

Availability of Supply

China has been the leading producer of REEs for decades (fig. O1), and since the late 1990s, it has accounted for more than 90 percent of global production, on average. When China began restricting the supply of REEs through the imposition of quotas, licenses, and taxes in 2010, it cited limited resources for domestic requirements and environmental concerns as the reasons (Tse, 2011). China's restrictions on REEs changed the world rare-earth industry in several ways, including by fostering increased stockpiling of REEs; increased exploration and development of deposits outside of China; and new efforts to conserve, recycle, and find substitutes for and among the REEs. This is evidenced by new mine production that began in Australia in 2011 and in the United States in 2012, and by additional exploration and development projects in many other countries (Gambogi, 2016). Global reserves of REEs were estimated on a rare-earth-oxide (REO) basis to be 130 million metric tons and were led by, in decreasing order of reserves, China, Brazil, Australia, and India (Gambogi, 2015).

Australia

Heavy-mineral sands produced in Australia contain significant quantities of REEs; however, monazite has not been produced from heavy-mineral sands operations since the 1990s to avoid the concentration of naturally occurring radioactive minerals, primarily owing to the presence of thorium in monazite. Lynas Corporation Ltd. of Australia began production of rare-earth mineral concentrates at its Mount Weld carbonatite complex in Western Australia in 2011. Shipments of mineral concentrates were delayed until 2013 while processing operations were being commissioned in Malaysia. Lynas later increased its capacity to produce mineral concentrates to 22,000 metric tons per year of contained REO. Other REE projects underway in Australia include the Nolans Bore property in the Northern Territory and the Dubbo Zirconia deposit in New South Wales, both of which were at the advanced feasibility study stage (Gambogi, 2016). Australia's reserves of REEs are estimated to be 3.2 million metric tons of REO (Gambogi, 2015).

China

China's rare-earth mine production takes place in the Provinces of Fujian, Guangdong, Hunan, Jiangxi, Shandong, Sichuan, and Yunnan, and in the Autonomous Regions of Guangxi and Nei Mongol. The largest mining operation is Baotou Rare Earth's Bayan Obo Mine, which produces iron ore as well as bastnaesite and monazite as the main rare-earth minerals. REE-bearing ion-adsorption clays are mined in various locations in the southeastern Provinces. In contrast to bastnaesite ores, ion-adsorption clays are valued for their medium REE and HREE content. Reserves of REEs in China are estimated to be 55 million metric tons of contained REO (Gambogi, 2015).
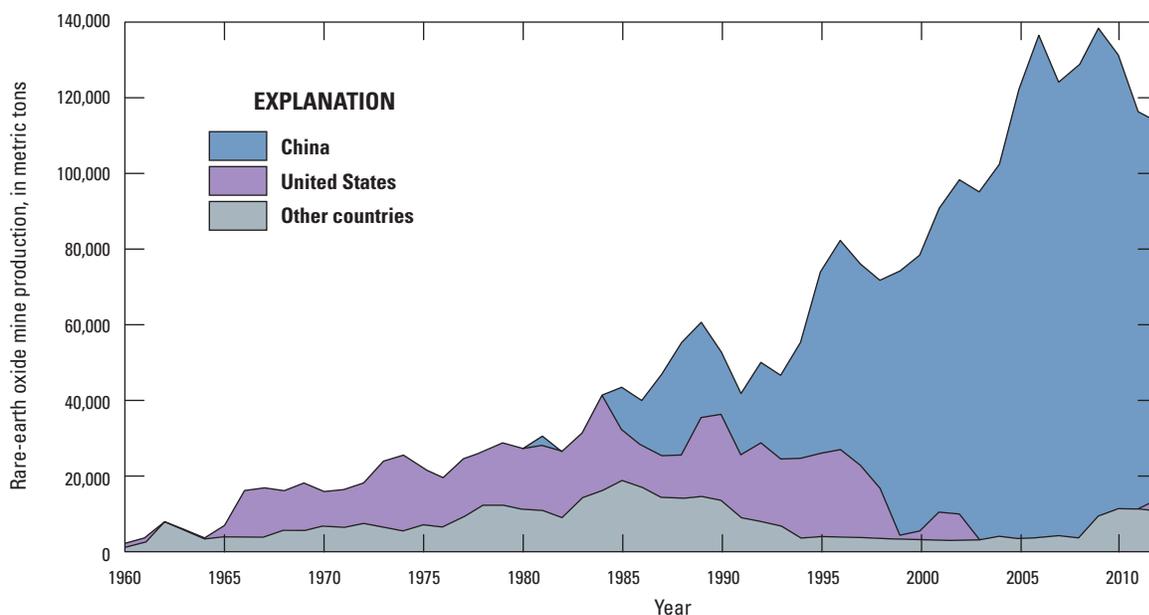

Figure O1.   Graph showing world mine production of rare-earth oxides, by country and year, from 1960 to 2012. The layers of the graph are placed one above the other, forming a cumulative total. Data are from U.S. Bureau of Mines (1961–96) and U.S. Geological Survey (1997–2016).

The leading export markets for China's REEs are Japan, the United States, and France. The supply of REEs to consumers outside of China is determined not by mine capacity but by production and export quotas set by China's Ministry of Commerce (MOFCOM) and the Ministry of Industry and Information Technology. Supply concerns were raised when the MOFCOM set China's export quota for the second half of 2010 at 7,976 metric tons (a 64 percent decrease compared with the quota set in the first half of 2010), which reduced the total exports for 2010 to 20,258 metric tons (a 40 percent decrease compared with exports for the previous year). Following the sudden drop in exports, prices for rare-earth products in 2010 increased sharply (Ministry of Commerce 2010a, b). Export quotas for 2011, 2012, and 2013 were set at 30,246 metric tons, 30,996 metric tons, and 30,999 metric tons, respectively. Prices for most rare-earth products peaked in mid-2011. In 2014, China's rare-earth export quotas were 30,611 metric tons, including 27,006 metric tons for LREEs and 3,605 metric tons for HREEs (Hatch, 2013, 2014). Chinese-owned companies were allocated 74 percent of the rare-earth products export quota, and joint ventures with foreign partners were allocated 26 percent of the quota. Following a World Trade Organization ruling in 2014, China announced the end of export restrictions on rare earths (Yap, 2015). According to the Ministry of Industry and Information Technology, the Government has ongoing efforts to reduce illegal mine production of rare earths, which was estimated to account for more than 40,000 metric tons of REE production in a single year (Global Times, 2013).

India

In India, REEs are produced from monazite contained in heavy-mineral sands. The two Government-owned producers are the Rare Earth Division of Indian Rare Earths Ltd. (IREL) and Kerala Minerals and Metals Ltd. (KMML). Heavy-mineral operations that produce monazite concentrate include IREL's Manavalakurichi operation in the State of Tamil (which had a capacity of 6,000 metric tons per year) and KMML's Chavara operation in Kerala State (240 metric tons per year) (Indian Bureau of Mines, 2015). IREL's capacity to produce rare-earth compounds from monazite was limited, but was reported to be increasing. India's reserves of REEs are estimated to be 3.1 million metric tons of REO (Gambogi, 2015).

Malaysia

In the Malaysian States of Perak and Selangor, REE-bearing monazite and xenotime are recovered from cassiterite mine tailings, which are referred to by the Malaysian mining industry as "amang." Recent monazite production from amang was less than 500 metric tons per year. Malaysia's reserves of REEs are estimated to be 30,000 metric tons of REO, which is less than 1 percent of global reserves (Gambogi, 2015, 2016).

Russia

In Russia, loparite mineral concentrates are produced at the Lovozero mining operation on the Kola Peninsula, Murmanskaya Oblast; the concentrates are shipped to the Solikamsk magnesium plant in Permskiy Kray. Rare-earth-bearing residues from the Solikamsk plant are exported for recovery of REEs. The Lovozero operation had the capacity to produce an estimated 3,700 metric tons per year of REOs contained in mineral concentrates. Within a global total of 130 million metric tons, Russia's reserves contributed to the 41 million metric tons of reserves from other counties (Gambogi, 2015).

United States

From 2012 to 2015, the United States was a leading producer of rare-earth minerals outside of China. All mine production of REEs during this period was from Molycorp, Inc.'s Mountain Pass Mine in San Bernardino County, California. Mine production at Mountain Pass began in 1952 but was discontinued from 2002 to 2011 because of low rare-earth prices and environmental permitting issues. In 2012, Molycorp commissioned new mine and processing operations that had an initial planned (but never fully realized) production capacity of 19,000 metric tons per year of REOs. Because of substantial decreases in the market prices of the REEs, however, Molycorp idled operations at the Mountain Pass Mine in 2015. Exploration and development assessment projects in the United States include Bokan Mountain, Alaska; La Paz, Arizona; Diamond Creek, Idaho; Lemhi Pass in Idaho and Montana; Pea Ridge, Missouri; Elk Creek, Nebraska; Thor Mine, Nevada; Round Top, Texas; and Bear Lodge, Wyoming. Domestic reserves of REOs were estimated to be 1.8 million metric tons (Gambogi, 2015).

Conservation, Recycling, and Substitution

Concerns about the availability of rare-earth supplies have stimulated efforts in recycling, substitution, and improving material efficiencies. These efforts are being led by the leading consumers of REEs.

In the United States, the Critical Materials Institute (a partnership of academia, Government, and industry) is working to diversify production, reduce waste, and develop substitutes for rare earths. The collaboration is expected to spend up to $120 million during a period of 5 years to support research focused on ensuring a reliable supply of rare earths and other critical materials (U.S. Department of Energy, 2013).

Belgian-based Umicore Group has developed a battery-recycling program for nickel-metal-hydride (NiMH) batteries at its new recycling plant in Hoboken, Belgium. After the separation of nickel and iron, the company plans to process the REEs into a high-grade concentrate that would be separated into rare-earth materials at Rhodia Rare Earth Systems' plant at La Rochelle, France (Umicore Group, 2011).

In the European Union, a consortium is investigating the extraction of rare-earth metals from permanent magnets in electric vehicle motors. The project is funded by the German Federal Research Ministry, and the consortium is led by Siemens AG (Recycling International, 2011b). German research agency Fraunhofer Institute for Surface Engineering and Thin Films is examining the recycling of rare-earth metals from disused light-metal alloys and from lanthanum from fluid catalytic cracking (FCC) catalysts (Recycling International, 2011a).

In France, Rhodia formed an alliance with Umicore to recycle rare-earth minerals from NiMH rechargeable batteries. Rhodia also planned to recycle rare-earth minerals from low-energy light bulbs and magnets. By yearend 2012, recycling plants in La Rochelle and Saint-Fons, Rhône-Alpes Region, were operational. The company planned to conserve on its consumption of terbium by using reformulated phosphors (Recycling International, 2011b, c).

In Japan, Honda Motor Co., Ltd. has been working with Japan Metals & Chemicals Co. to recapture rare-earth metals from NiMH batteries. Honda expects to recover 80 percent of rare-earth metals contained in the used NiMH batteries and plans to collect the batteries globally (Honda Motor Co., Ltd., 2013). Japan's Hitachi, Ltd. is developing methods to recycle rare-earth magnets from hard disk drives, air conditioners, and other types of compressors. Hitachi Metals also has accelerated development of reduced-dysprosium sintered magnets using a dysprosium vapor-deposition and diffusion technology (Baba and others, 2013, p. 453).

In Vietnam, Japan's Shin-Etsu Chemical Co., Ltd. constructed processing plants for the separation of rare earths and production of rare-earth magnets. The processing plants enable the recycling of rare-earth magnets used in appliances, such as air conditioner compressor motors (Showa Denko K.K., 2010; Shin-Etsu Chemical Co., Ltd., 2014).

Geology

Geochemistry

The REEs are commonly found together in Earth's crust because they share a trivalent charge (REEs^{3+}) and similar ionic radii. Exceptions to the trivalent charge are cerium, which may occur in a Ce^{4+} valence state, and europium, which can exist as Eu^{2+}. The lanthanides (lanthanum to lutetium) (table O1) have a unique property—with each increase in atomic number across the group, an electron is added to an inner incomplete subshell ($4f$) rather than to an outer level. This property of selectively filling inner levels results in a progressive decrease in the ionic radius of the trivalent lanthanide ions from La^{3+} to Lu^{3+} (fig. O2), referred to as "lanthanide contraction." The systematic decrease in ionic radii across the lanthanide group (fig. O2) has two significant consequences: (a) it affects the fractionation of the REEs to a high degree, which allows for their individual separation in geologic environments and in ore processing, and (b) it lends
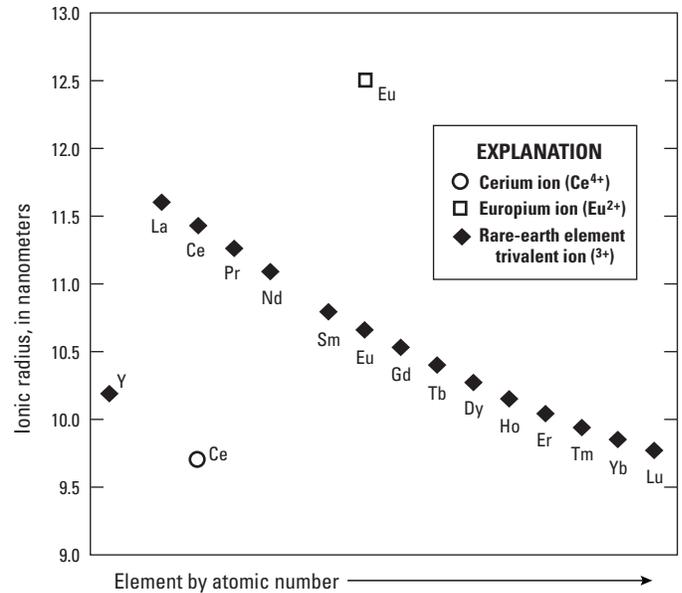
Figure O2.   Graph showing radii (in nanometers) of the trivalent ($^{3+}$) ions of the rare-earth elements (REEs) as well as of cerium in the +4 valence state (Ce^{4+}) and europium in the +2 valence state (Eu^{2+}). The graph illustrates the systematic decrease in the radius of the trivalent REE ions with increasing atomic number. Data plotted are for coordination number VIII. Data are from Shannon (1976). Elements, in order of increasing atomic number: Y, yttrium; La, lanthanum; Ce, cerium; Pr, praseodymium; Nd, neodymium; Sm, samarium; Eu, europium; Gd, gadolinium; Tb, terbium; Dy, dysprosium; Ho, holmium; Er, erbium; Tm, thulium; Yb, ytterbium; Lu, lutetium. Promethium (Pm) is not included in the list because it is extremely rare in nature.

the REEs unusual and useful chemical and physical properties, such as unique magnetic and (or) optical properties.

In magmatic systems, the high-charge of the REE ions impedes the ability of these elements to achieve charge balance and fit into the structure of the common rock-forming minerals, which have coordination sites best suited for valence states of 2 or 1. As a result, when common silicate minerals (such as amphiboles, feldspars, and olivine) crystallize, most of the REEs tend to remain in the coexisting melt. (In contrast, europium is often depleted in magmas because it is incorporated into feldspars owing to its Eu^{2+} valence state.) Successive generations of this process, referred to as crystal fractionation, increase the concentrations of REEs in the remaining melt until individual REE-mineral-rich phases crystallize. In addition to ionic charge (valence state), factors that can affect the partitioning of the REEs between a mineral and the coexisting magma can include temperature, pressure, fluid composition, magmatic convection, and variation in mineral settling velocities (Henderson, 1984; McKay, 1989; Kogarko and others, 2006). Elements, such as the REEs, that do not tend to participate in the early mineral-formation processes are referred to as incompatible elements. In magmatic systems, other incompatible elements may also include hafnium, niobium, phosphorus, tantalum, thorium, titanium, scandium, uranium, and zirconium.

Rare-Earth-Element-Mineral Formation in Carbonatite Magmas

Many of the world's REE deposits are associated with carbonatites, which are igneous rocks derived from carbonate-rich magmas rather than silica-rich magmas. Carbonatites are defined as igneous rocks with greater than 50 modal percent carbonate minerals, usually calcite and dolomite, and, in general, they have the highest REE concentrations of any igneous rocks (Chakhmouradian and Zaitsev, 2012). Carbonatite magmas are derived from the mantle, but the processes responsible for the formation of carbonatite magmas are in debate. Possible processes responsible for carbonatite magma generation include (a) primary mantle melts or (b) evolution from a mantle-derived alkali melt by crystal fractionation. As the carbonatite magma crystalizes, REEs can be concentrated in the primary REE mineral phases or they can become enriched in late-stage magmas or fluids. Late-stage REE-rich magmas can result in ore-grade REE mineralization that contains very large concentrations of LREEs.

Rare-Earth-Element-Mineral Formation in Alkaline Magmas

In addition to carbonatites, the REEs have a strong genetic association with alkaline igneous processes, particularly peralkaline magmatism. Alkaline igneous rocks crystallize from silicate magmas and fluids enriched in alkali elements and precipitate sodium- and potassium-bearing minerals, such as sodium- or potassium-rich amphiboles and pyroxenes. Alkaline igneous rocks are typically undersaturated in silica, and they therefore contain little or no quartz. Peralkaline igneous rocks, which are defined as those in which the molecular proportion of aluminum oxide (Al_2O_3) is less than that of sodium oxide (Na_2O) and potassium oxide (K_2O) combined (that is, $Al_2O_3 < Na_2O + K_2O$), are associated with enrichments in REEs, typically more than most other igneous rocks.

Rare-Earth-Element-Mineral Formation in Parental Magma Sources

The REEs occur in modest concentrations in the upper mantle but by some processes can become highly enriched in carbonate and alkaline magmas that ascend from the mantle to the crust (Arzamastsev and others, 2001). A discussion of what geologic processes separate, enrich, and mobilize REEs in the upper mantle, ultimately forming ore-grade deposits of REE minerals in the crust, is beyond the scope of this chapter. Wyllie and others (1996) provide a comprehensive review and discussion of many studies that focus on the genesis of carbonatite magmas and their REE minerals. An overview of recent research toward REE sources and processes is discussed by Chakhmouradian and Zaitsev (2012).

Rare-Earth-Element-Mineral Formation Through Hydrothermal Processes

The formation of REE minerals in hydrothermal environments is a less investigated aspect of their formation, but is discussed by Gieré (1996). The mobilization of the REEs by hydrothermal processes is summarized by Williams-Jones and others (2012).

Aqueous Geochemistry of Rare-Earth Elements

With the development of inductively coupled plasma-mass spectrometry (ICP–MS), analysis of REEs in aqueous solutions has become routine. As a result, the number of studies that analyze and interpret REEs has increased substantially in the past 15 years. Similar to many trace metals, the REEs occur as cations, which generally become less soluble with increasing pH (Verplanck and others, 2004). The REEs have a charge of +3, but under oxidizing conditions, cerium can have a charge of +4. Under reducing conditions, europium can have a +2 charge, but europium in the +2 oxidation state is generally limited to high-temperature environments.

The behavior of REEs in aqueous solutions can be described as a competition between the formation of stable aqueous complexes and the tendency of REEs to partition to solid phases, either by adsorption or (co)precipitation. The dominant inorganic ligands include carbonate, fluoride, hydroxide, phosphate, and sulfate. Other factors that potentially affect the partitioning between solid and aqueous phases include the composition of solid phases, pH, temperature, and redox conditions. The behavior of REEs in aqueous solutions is particularly relevant to REE ore deposit genesis in both magmatic and surficial environments because the stability of aqueous REE complexes plays an important role in their mobilization, transport, fractionation, and deposition (Williams-Jones and others, 2012).

Mineralogy

The minerals that contain REEs are numerous, diverse, and often complex in composition. Jones and others (1996, appendix A) list 245 individual REE-bearing minerals, which include silicates (in which category the total number of REE-bearing minerals is 85); oxides (59); carbonates, fluoro-carbonates, and hydroxylcarbonates (42); phosphates (26); arsenates, sulfates, and vanadates (19); halides (6); uranyl-carbonates and uranyl-silicates (5); and borates (3). Table O2 lists the REE- and yttrium-bearing minerals that historically have been important ore minerals for these elements.

Bastnaesite (also spelled bastnäsite) may be considered the most important REE mineral because it is the primary ore mineral of the world's two largest REE deposits—the carbonatite deposit at Mountain Pass in California (fig. O3) and the iron-carbonatite deposits of Bayan Obo in China.

Figure O3. Photograph of the Mountain Pass Mine in San Bernardino County, California, which was the only active producer of rare-earth elements (REEs) in the United States in 2013. The orebody is a tabular carbonatite intrusion and is thought to be the largest REE resource in the United States. Molycorp, Inc. (2012), which owns and operates the mine, reported proven and probable reserves totaling 16.7 million metric tons of carbonatite ore at an average grade of 7.98 percent rare-earth oxide (REO) using a cutoff grade of 5 percent REO. The mine was placed on care-and-maintenance status in 2015. Photograph by Bradley S. Van Gosen.

The orebody of the Mountain Pass Mine—the Sulphide Queen carbonatite—contains about 10 to 15 percent bastnaesite and lesser amounts of parisite (Castor and Nason, 2004).

In carbonatites, REE mineral assemblages can be categorized by mineral-forming process into the following three groups (Mariano, 1989; Chakhmouradian and Zaitsev, 2012): (a) primary magmatic mineralization in carbonatites (Mountain Pass, Calif.), (b) hydrothermal-metasomatic mineralization (Bayan Obo, China), and (c) supergene mineralization (Mount Weld in Western Australia, Australia, and Araxá in the State of Minas Gerais, Brazil). The principal REE minerals in carbonatites are fluorocarbonates (bastnaesite, parisite, synchysite), hydrated carbonates (ancylite), and phosphates (monazite). Less abundant REE minerals in carbonatites include REE-bearing britholite, burbankite, and fluorapatite (table O2). Most carbonatites display a multiphase petrogenetic evolution, including hydrothermal overprinting of primary phases; thus, mineralogical and textural characteristics can vary and be complex.

Bastnaesite is typically the most significant source of REEs in carbonatite-related deposits, such as at Mountain Pass (California) and Bear Lodge (Wyoming) in the United States, and Bayan Obo (Nei Mongol Autonomous Region), Maoniuping (Sichuan Province), Daluxiang (Sichuan Province), and Weishan (Anhui Province) in China (fig. O4). Mariano (1989) notes that strong enrichments in the LREEs occur in carbonatite deposits in which the dominant ore mineral is bastnaesite. Mariano (1989) states that bastnaesite of hydrothermal origin typically occurs as fine-grained fibrous

or platy masses in vugs, microfractures, and veinlets, which are commonly associated with, in general order of abundance, quartz, fluorite, strontianite, barite, and hematite. Ancylite is an indicator of secondary carbonate hydrothermal processes; it is found intergrown with strontianite in altered carbonatites (Mariano, 1989). The REE ore minerals in the intensely altered, upper oxidized zones of the Bear Lodge deposit are minerals of the bastnaesite group, plus cerianite (table O2) and locally abundant monazite (Dahlberg, 2014).
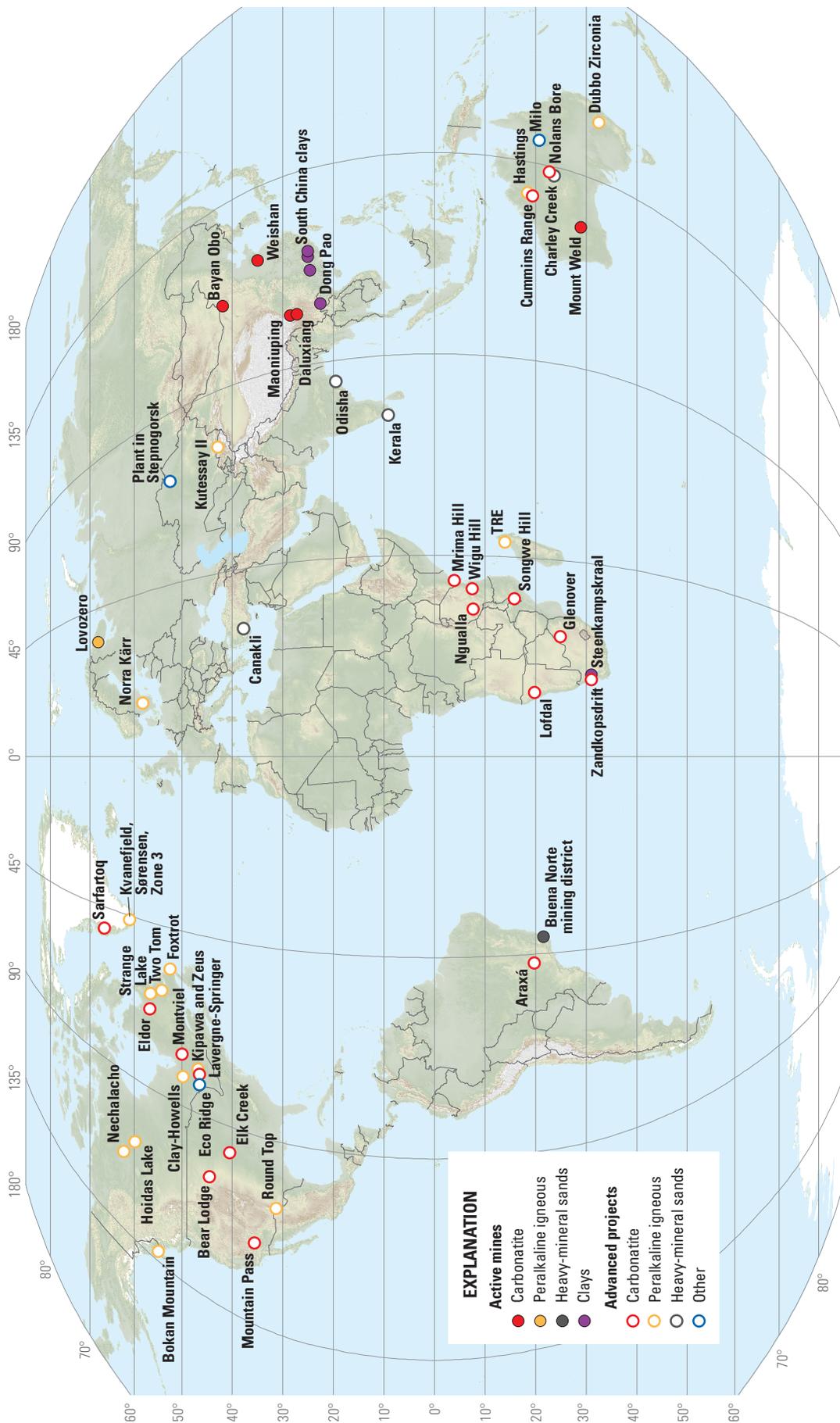
The vast majority of peralkaline REE deposits display complex petrogenetic evolution, which can result in variable mineralogy and intricate textures. Important REE-yttrium-bearing minerals in peralkaline deposits can include, in general order of abundance, fluorapatite (fluorine-rich apatite), eudialyte, loparite, xenotime, monazite, gadolinite, bastnaesite, parisite, synchysite, kainosite, mosandrite, britholite, allanite, brannerite, thalenite, iimoriite, and fergusonite (table O2). In general, REE mineralization in peralkaline intrusions is typically more enriched in the HREEs than is the case with carbonatite-hosted deposits (fig. O5). Complex ore mineralogy with hydrothermal overprinting of primary magmatic phases is typified by the peralkaline dikes at Bokan Mountain on Prince of Wales Island in southeastern Alaska, in which more than 20 REE-yttrium-bearing minerals representing multiple generations have been identified (Barker and Van Gosen, 2012; Dostal and others, 2014). As another example, 45 REE-bearing minerals have been identified in the Khibiny alkaline complex in Murmanskaya Oblast', northwestern Russia (Chakhmouradian and Zaitsev, 2012).

In metamorphic deposits, common REE-yttrium-bearing minerals are the phosphate minerals xenotime and monazite. Examples in gneiss occur in the Music Valley area of the northern part of Joshua Tree National Park in Riverside County, Calif. (Evans, 1964; Long and others, 2010).

The primary REE-rich minerals within magmatic magnetite-hematite deposits are REE-bearing fluorapatite along with xenotime and monazite. Examples of massive magnetite-hematite deposits with REE-bearing fluorapatite, xenotime, and monazite as accessory minerals are the Pea Ridge iron deposit in Washington County, Mo., and iron deposits of the Mineville iron district in Essex County, New York (both districts are summarized in Long and others, 2010).

Nepheline syenite complexes in the Kola Peninsula region of Murmanskaya Oblast' in far northwestern Russia have been mined for their enrichments in niobium and REEs; the REEs occur mainly in loparite (table O2), which is a mineral of the perovskite group. This loparite reportedly contains more than 30 weight percent REO and is strongly enriched in the LREEs compared with the HREEs (Mariano, 1989; Chakhmouradian and Mitchell, 1998).

Deep weathering of REE-bearing alkaline igneous rocks or carbonatite in humid tropical climates with moderate to high rainfall can form thick laterite zones; these laterites can contain economic accumulations of residual REE minerals, depending on the underlying lithology. Examples of REE minerals that occur in the intensely weathered zone (laterite)

Figure 04.   World map showing locations of active or recently active rare-earth-element (REE) mines and ongoing advanced exploration projects. The exploration projects are at the assessment stage, meaning that they are being evaluated to determine if they are economic to develop. REE resource estimates, which are usually based on extensive drilling programs, have been conducted on all the projects. Tables O3 and O4 contain additional information about the deposits shown on this map. Mountain Pass Mine in California (United States) was placed on care-and-maintenace status in 2015.

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

Table O2. List of selected rare-earth-element-bearing and yttrium-bearing ore minerals.

[Source: Jones and others (1996, Appendix A)]

Mineral name[1]	Chemical formula
Allanite	$(REE,Ca,Y)_2(Al,Fe^{3+})_3(SiO_4)_3(OH)$
Ancylite	$Sr(REE)(CO_3)_2(OH) \cdot H_2O$
Bastnaesite	$(REE)(CO_3)F$
Brannerite	$(U,Ca,Y,REE)(Ti,Fe)_2O_6$
Britholite	$(REE,Ca,Th)_5(SiO_4,PO_4)_3(OH,F)$
Burbankite	$(Na,Ca)_3(Sr,Ba,Ce)_3(CO_3)_5$
Cerianite-(Ce)	$(Ce^{4+},Th)O_2$
Eudialyte	$Na_4(Ca,REE)_2(Fe^{2+},Mn,Y)ZrSi_8O_{22}(OH,Cl)_2$
Ferguseonite-(Y)	$YNbO_4$
Florencite	$(REE)Al_3(PO_4)_2(OH)_6$
Fluorapatite	$(Ca,REE,Na)_5(PO_4)_3(F,OH)$
Gadolinite	$(REE,Y)_2Fe^{2+}Be_2Si_2O_{10}$
Gorceixite	$(Ba,REE)Al_3(PO_4)_2(OH_5 \cdot H_2O)$
Goyazite	$(Sr,REE)Al_3(PO_4)_2(OH_5 \cdot H_2O)$
Iimoriite-(Y)	$Y_2SiO_4CO_3$
Kainosite	$Ca_2(Y,REE)_2Si_4O_{12}CO_3 \cdot H_2O$
Loparite-(Ce)	$(Na,Ce,La,Ca,Sr)(Ti,Nb)O_3$
Monazite	$(REE,Th)PO_4$
Mosandrite	$(Ca,Na,REE)_{12}(Ti,Zr)_2Si_7O_{31}H_6F_4$
Parisite	$Ca(REE)_2(CO_3)_3F_2$
Rhapdophane	$(REE)PO_4 \cdot H_2O$
Synchysite	$Ca(REE)(CO_3)_2F$
Thalenite-(Y)	$Y_3Si_3O_{10}OH$
Xenotime	YPO_4

[1]A more-extensive list that includes 245 individual rare-earth-element-bearing minerals is provided in Jones and others (1996, appendix A).

include, in order of abundance, monazite, rhapdophane, crandallite-group minerals (florencite, gorceixite, goyazite), and cerianite; these are secondary rather than primary phases (Mariano, 1989). Examples of thick residual REE deposits (that is, more than 100 meters [m] thick) occur at the Araxá deposit, which overlies the Barreiro carbonatite complex in the State of Minas Gerais, Brazil; the Catalão I carbonatite complex in the State of Goiás, Brazil; and the Mount Weld carbonatite in Western Australia, Australia.

Monazite is the dominant REE mineral in sediments derived from the erosion of igneous or high-grade metamorphic rocks. These sediments are deposited in fluvial (stream and river) environments and coastal areas. Monazite is dense and resistant to chemical and physical weathering. For these reasons, more than any other REE mineral, monazite survives the arduous trip from a bedrock source to its deposition in a stream, river, or shore area. Monazite is the principal REE mineral recovered by placer mining operations, particularly in coastal deposits.

Deposit Types

Deposits of REEs occur in diverse, generally uncommon geologic settings. The discussion that follows does not attempt to encompass all the many subeconomic geologic occurrences in which REEs have been found (such as those described by Mariano and Mariano, 2012). As noted earlier, REEs are quite common, but not often in economic concentrations. The economic or potentially economic REE deposits occur primarily in the following geologic settings:

- Carbonatites
- Peralkaline igneous systems
- Magmatic magnetite-hematite bodies
- Iron oxide-copper-gold (IOCG) deposits
- Xenotime-monazite accumulations in mafic gneiss
- Ion-absorption clay deposits
- Monazite-xenotime-bearing placer deposits

Carbonatites. Carbonatites have been the world's main source for the LREEs since the 1960s. In 2016, REEs were being produced from large carbonatite bodies mined in China (Bayan Obo, Maoniuping, Daluxiang, and Weishan deposits) (table O3; fig. O4). Carbonatite intrusions occur in a variety of forms and carbonate compositions. Forms include stocks, tabular bodies, dikes, irregular-shaped masses, and veins. Carbonatites vary in composition from calcic (calcite-dominant; originally called *soviet*), to dolomitic (dolomite-dominant; called *beforsite)*, to iron-carbonate (rich in ankerite [$Ca(Mg,Fe,^{2+}Mn)(CO_3)_2$] or siderite [$Fe^{2+}CO_3$]). Calcite and dolomite can also occur in roughly equal proportions. Carbonate composition can vary complexly across an individual carbonatite intrusion, such as is displayed in the Sulphide Queen carbonatite at Mountain Pass (Olson and others, 1954; Castor, 2008). Cross-cutting relations, mineralogy, and geochemistry have shown that carbonatite masses and dikes of different mineralogy and chemistry in a single district can represent multiple, discrete episodes of carbonate magma intrusion (Yang and others, 2010).

As noted earlier, in carbonatite deposits, the primary REE ore minerals are bastnaesite, parisite, and synchysite, ancylite, and monazite. Primary gangue (non-ore) minerals are carbonate minerals (calcite, dolomite, ankerite, siderite), which may be accompanied by aegerine-augite, barite, fluorite, fluorapatite, hematite, magnetite, phlogopite, quartz, and (or) strontianite. Accessory minerals—monazite, perovskite, pyrochlore, and thorite—are the most common uranium- and thorium-rich phases.

The geology and mineralogy of the world's largest REE deposit and leading producer of LREEs—the Bayan Obo iron-carbonatite deposit in Nei Mongol Autonomous Region, China—are described by Yuan and others (1992), Xu and others (2010), Yang and others (2010, 2011), Kynicky and others (2012), and Verplanck and others (2014). The Bayan Obo deposit is a complex irregular mass of mixed iron deposits and carbonatite. Two other REE producers in China are hosted by carbonatites—the Maoniuping deposit and the Daluxiang deposit, both in Sichuan Province. Other carbonatites in China are described by Yang and Woolley (2006), Xu and others (2008, 2010), and Kynicky and others (2012).

The largest REE deposit in the United States is the Sulphide Queen carbonatite in Mountain Pass, Calif.; this is the only known carbonatite where the REE ore minerals—bastnaesite and parasite—are interpreted to have crystallized directly from the magma (Mariano, 1989; Castor, 2008). In other carbonatites, the REE-bearing minerals are interpreted to have formed by late-phase hydrothermal processes. Another type of REE enrichment in carbonatite systems—supergene processes—involves deep weathering of a carbonatite in tropical environments, which forms an REE-enriched laterite deposit. Examples of thick laterites with economic accumulations of residual REE minerals are the Araxá deposit that overlies the Barreiro carbonatite complex in Brazil; the Catalão I carbonatite

EXPLANATION

- **Music Valley deposit**—Monazite-xenotime-biotite gneiss
- **Bokan Mountain deposit**—Peralkaline igneous dikes and veins
- **Thor Lake/Nechalacho deposit**—Peralkaline igneous intrusion
- **Foxtrot project deposit**—Mineralized, metamorphosed felsic volcanics
- **Bear Lodge deposit**—Hydrothermally altered carbonatite
- **Mountain Pass deposit**—Magmatic carbonatite
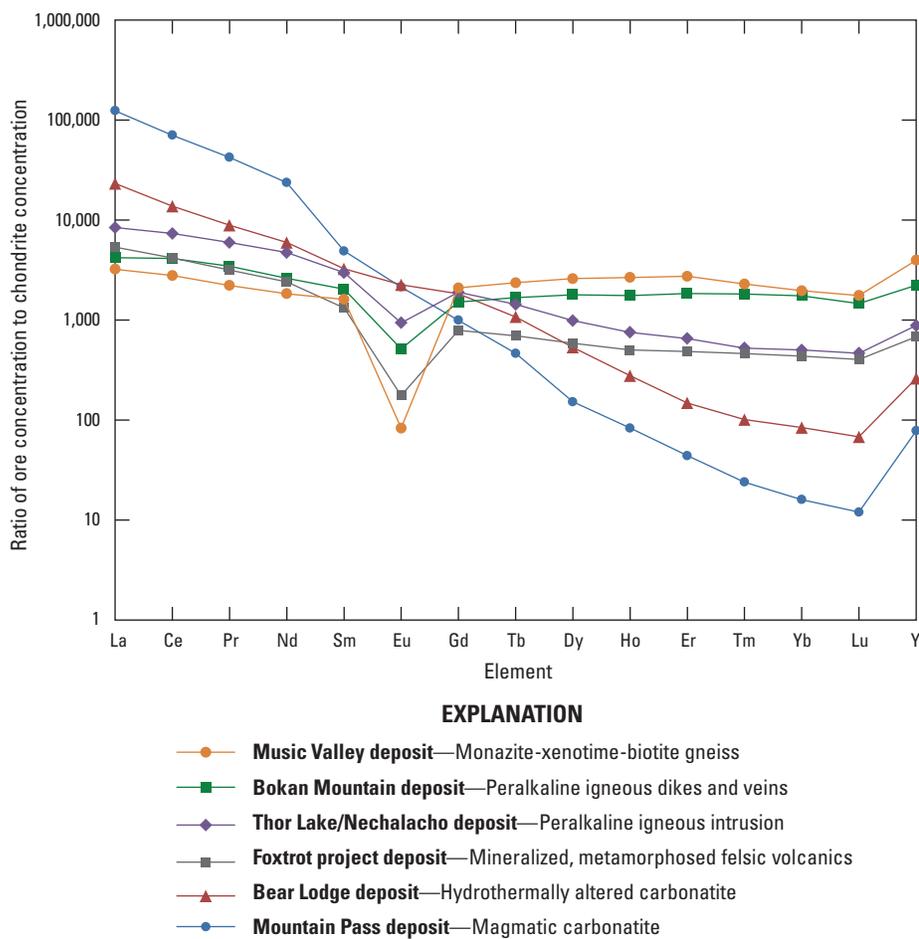
Figure O5. Chondrite-normalized plot showing the rare-earth-element (REE) distribution in six different types of North American REE deposits. The example deposits are located in Music Valley, California; Bokan Mountain, Alaska; Nechalacho (Thor Lake), Northwest Territories, Canada; Foxtrot project, Newfoundland and Labrador, Canada; Bear Lodge, Wyoming; and Mountain Pass, Calif. Notice the higher enrichments in the heavy REEs associated with peralkaline deposits, represented by the Bokan Mountain and Thor Lake deposits. Data for the Bear Lodge, Bokan Mountain, Mountain Pass, and Music Valley deposits are from author samples; Foxtrot project data are from Srivastava and others (2012); Thor Lake data are from Avalon Rare Metals Inc. (2015). Elements: La, lanthanum; Ce, cerium; Pr, praseodymium; Nd, neodymium; Sm, samarium; Eu, europium; Gd, gadolinium; Tb, terbium; Dy, dysprosium; Ho, holmium; Er, erbium; Tm, thulium; Yb, ytterbium; Lu, lutetium; Y, yttrium

Table O3.   Active rare-earth mines, by deposit type.

[Mt, million metric tons; REE, rare-earth element; Y, yttrium; REO, rare-earth oxide; NA, not available; —; none reported]

Deposit	Location	Reported resource (Mt)	Reported grade (total REE+ Y oxide, in weight percent)	Comment	Reference(s)
Carbonatites					
Bayan Obo	Nei Mongol Autonomous Region, China	800	6	Estimated resource in the total deposit, not subdivided	Berger and others (2009)
Daluxiang (Dalucao)	Sichuan, China	15.2	5.0	About 0.76 Mt (estimated) of REOs	Hou and others (2009)
Maoniuping	Sichuan, China	50.2	2.89	REO content of reserves is estimated to be more than 1.45 Mt	Xu and others (2008); Hou and others (2009); Xie and others (2009)
Weishan	Shandong, China	—	—	Tonnage and grade information are not available	NA
Mountain Pass	California, United States	16.7	7.98	Resource represents proven and probable reserves using a cutoff grade of 5 percent REO. Placed on care-and-maintenance status in 2015.	Molycorp, Inc. (2012)
Mount Weld	Western Australia, Australia	23.9	7.9	Tonnage represents the estimated combined total mineral resource as of January 2012 for two deposits at Mount Weld—the Central Lanthanide deposit and the Duncan deposit	Lynas Corporation Ltd. (2012)
Peralkaline igneous					
Karnasurt Mountain, Lovozero deposit	Northern region, Russia	—	—	Loparite concentrate contains 30 to 35 percent REO	Zaitsev and Kogarko (2012)
Heavy-mineral sand deposits					
Buena Norte mining district	East coast of Brazil	—	—	Historic and active producer of REEs from monazite in coastal sands	NA
Ion-adsorption clay deposits					
Dong Pao Mine	Vietnam	—	—	Mine is reportedly in a late stage of development. Laterite clays overlie syenite intrusions	NA
South China clay deposits	Jiangxi, Hunan, Fujian, Guangdong, and Guangxi Provinces, southern China	—	About 0.05 to 0.4	Numerous small mines. Little ore information is available. Best source of data may be Chi and Tian (2008)	Clark and Zheng (1991); Bao and Zhao (2008); Chi and Tian (2008)

complex in Brazil; and the Mount Weld carbonatite in Australia. Laterite-hosted REE deposits are unknown in the United States.

Some carbonatite intrusions are important sources of niobium, which is hosted primarily in the mineral pyrochlore [$(Na,Ca)_2Nb_2O_6(OH,F)$]. More than 90 percent of the world's supply of niobium comes from laterite deposits that are several hundred meters in thickness and that overlie the Barreiro carbonatite complex near Araxá (Papp, 2011). The niobium-rich laterites at Araxá are now being evaluated for the recovery of REEs as a byproduct of niobium production. The largest identified niobium resource in the United States is the buried Elk Creek carbonatite in southeastern Nebraska (table O4; Xu, 1996; Carlson and Treves, 2005).

Peralkaline igneous systems. Peralkaline igneous systems are inherently enriched in REEs, in some instances hosting high-grade deposits. Peralkaline igneous complexes have been targeted by recent exploration (fig. O4) because of their enrichments in the HREEs (fig. O5).

Alkaline igneous rocks make up a large grouping of rock types that are generally deficient in silicon dioxide (SiO_2) relative to Na_2O, K_2O, and calcium oxide (CaO). As noted earlier, peralkaline igneous rocks are a subclass of alkaline rocks, defined as those in which the molecular proportion of $Al_2O_3 < Na_2O + K_2O$.

Peralkaline igneous systems enriched in REEs come in a variety of forms, such as the following:

- Complexes exhibiting vertical and lateral zonation: (a) Kipawa complex, Quebec, Canada (Saucier and others, 2012); (b) Strange Lake complex, Quebec and Labrador, Canada (Quest Rare Minerals Ltd., 2012); (c) Nechalacho (Thor Lake), Northwest Territories, Canada (Avalon Rare Metals Inc., 2015); (d) Kutessay II project, Chuy Oblusu, Kyrgyzstan (Stans Energy Corp., 2015); and (e) Tantalus Rare Earths (TRE) project, northern Madagascar (Tantalus Rare Earths AG, 2013).

- Complexes exhibiting layering: (a) Lovozero complex, Murmanskaya Oblast', Russia (Féménias and others, 2005; Kogarko and others, 2006; Chakhmouradian and Zaitsev, 2012), and (b) Ilimaussaq complex (includes the Kvenfjeld, Sørensen, and Zone 3 deposits), Kommune Kujalleq, Greenland (Greenland Minerals and Energy Ltd., 2012).

- Dikes and veins associated with peralkaline igneous complexes: (a) Bokan Mountain, Alaska (Robinson and others, 2011); (b) Hastings project, Western Australia, Australia (Hastings Rare Metals Ltd., 2015); and (c) Hoidas Lake deposit, Saskatchewan, Canada (Star Minerals Group Ltd., 2014).

- Plutons, stocks, plugs, and other peralkaline intrusions: (a) Norra Kärr deposit, Jönköpings län, Sweden (Tasman Metals Ltd., 2012); (b) Dubbo Zirconia project, New South Wales, Australia (Alkane Resources Ltd., 2015); (c) Two Tom deposit, Labrador, Canada (Daigle, 2012); (d) at Ghurayyah in Tabuk Province, Saudi Arabia; and (e) at Khaldzan-Buregtey in Hovd Aymag, Mongolia.

Peralkaline igneous rock types in REE-bearing systems can vary considerably from deposit to deposit; thus, it is difficult to generalize which peralkaline lithologies are consistently associated with REE deposits. The advanced exploration projects (current as of 2012), which are listed in table O4 and the locations of which are shown in fig. O4, indicate significant REE mineralization of 0.3 to 2.6 percent total REO in alkali granites, nepheline syenite, syenite, and trachyte. Peralkaline igneous rocks are typically more enriched in REEs, especially HREEs, than their silica-rich igneous counterparts. Still, the processes of REE transport and enrichment in peralkaline systems remain poorly understood (Chakhmouradian and Zaitsev, 2012). The recent increase of exploration and drilling into peralkaline systems (table O4) is expected to provide a better characterization of these deposits.

The uncommon mineralogy of peralkaline-related REE deposits is summarized in the Mineralogy section of this chapter and described by Chakhmouradian and Zaitsev (2012). The mineralogies encountered in REE ores in peralkaline igneous systems present challenges in ore processing. Routine metallurgical methods for processing these types of ores do not exist; procedures are developed on a deposit-by-deposit basis. The ore processing must be efficient and economic, employing methods that effectively liberate the diverse REE minerals, then sequentially separate and concentrate the individual REEs. A peralkaline igneous deposit can contain more than 20 REE-bearing minerals. Additionally, the intergrown REE minerals can occur in a variety of compositions, such as carbonates, oxides, phosphates, and silicates.

Magmatic magnetite-hematite bodies. Magmatic magnetite-hematite bodies can contain REE-bearing minerals, with the potential to recover the REEs as a byproduct during iron mining. Examples are deposits in the Pea Ridge iron district in southeastern Missouri and the Mineville iron district in upstate New York (Long and others, 2010).

The Pea Ridge magnetite-hematite orebody is hosted by Mesoproterozoic volcanic rocks of the St. Francois terrane of southeastern Missouri. The magnetite-rich body is interpreted as a high-temperature, magmatic-hydrothermal deposit (Sidder and others, 1993) in ash-flow tuffs and lavas, which may have formed in the root of a volcanic caldera (Nuelle and others, 1991). Four REE-bearing breccia pipes steeply crosscut the magnetite-hematite orebody and the altered rhyolite host rock. Exposed portions of the breccia pipes are as much as 60 m (197 feet [ft]) in length and as much as 15 m (49 ft) in width; the pipes extend below the mined levels to an undetermined depth (Seeger and others, 2001). Identified REE-bearing minerals in the breccia pipes are monazite, xenotime, and minor amounts of bastnaesite and britholite. According to Seeger and others (2001, p. 2), "total REO concentrations of grab samples [of breccia] range from about 2.5 to 19 weight percent." Mine tailings on the surface contain additional lanthanide resources, primarily in fine-grained REE-bearing minerals, chiefly monazite and xenotime, which form inclusions within apatite (Vierrether and Cornell, 1993).

Table O4.   Advanced rare-earth-element (REE) exploration projects and the reported estimates of their REE resources, by deposit type.

[Mt, million metric tons; t, metric ton; %, percent; TREO, total rare-earth oxide. Chemical elements: Ag, silver; Au, gold; Cu, copper; Dy, dysprosium; Mo, molybdenum; Nb, niobium; REE, rare-earth element; U, uranium; Zr, zirconium]

Deposit	Location	Reported resources	Reference(s)
Carbonatites			
Araxá	Minas Gerais, Brazil	Measured and indicated resources=6.34 Mt at 5.01% TREO; inferred resources=21.94 Mt at 3.99% TREO	MBAC Fertilizer Corp. (2012)
Ashram project (formerly Eldor project)	Quebec, Canada	Measured resources=1.59 Mt at 1.77% TREO; indicated resources=27.67 Mt at 1.9% TREO; inferred resources=219.8 Mt at 1.88% TREO	Commerce Resources Corp. (2016)
Bear Lodge	Wyoming, United States	Measured and indicated resources = 16.3 Mt at 3.05% TREO; inferred resources = 28.9 Mt at 2.58% TREO	Dahlberg (2014, p. 1-5, 1-8)
Cummins Range	Western Australia, Australia	Inferred resources=4.9 Mt at 1.74% TREO	Hatch (2015)
Elk Creek	Nebraska, United States	Indicated resources = 80.5 Mt at 0.71% Nb oxide; inferred resources = 99.6 Mt at 0.56% Nb oxide; REE resources exist, but are not estimated	Pittuck and others (2015, p. 150)
Glenover project	South Africa	Indicated resources=16.78 Mt at 1.45% TREO; inferred resources=12.14 Mt at 0.98% TREO	Galileo Resources PLC (2015)
Lavergne-Springer property	Ontario, Canada	Indicated resources=4.2 Mt at 1.14% TREO; inferred resources=12.7 Mt at 1.17% TREO	Hatch (2015)
Lofdal project	Namibia	Indicated resources=0.90 Mt at 0.62% TREO; inferred resources=0.75 Mt at 0.56% TREO	Namibia Rare Earths Inc. (2012)
Montviel project	Quebec, Canada	Indicated resources=82.4 Mt at 1.51% TREO; inferred resources=184.2 Mt at 1.43% TREO	GéoMégA Inc. (2015)
Mrima Hill	Kenya	Measured and indicated resources=48.7 Mt at 4.40% TREO; inferred resources=110.7 Mt at 3.61% TREO	Pacific Wildcat Resources Corp. (2013)
Ngualla	Tanzania	Measured resources=81 Mt at 2.66% TREO; indicated resources=94 Mt at 2.02% TREO; inferred resources=20 Mt at 1.83% TREO	Peak Resources Ltd. (2013)
Nolans Bore	Northern Territory, Australia	Measured resources=4.3 Mt at 3.3% TREO; indicated resources=21 Mt at 2.6% TREO; inferred resources=22 Mt at 2.4% TREO	Arafura Resources Ltd., (2014)
Sarfartoq	Greenland	Indicated resources=5.884 Mt at 1.77% TREO; inferred resources=2.459 Mt at 1.59% TREO	Hudson Resources Inc. (2012)
Songwe Hill	Malawi	Indicated resources=6.2 Mt at 2.05% TREO; inferred resources=5.1 Mt at 1.83% TREO	Mkango Resources Ltd. (2012)
Wigu Hill	Tanzania	Inferred resources=3.3 Mt at 2.6% TREO	Montero Mining & Exploration Ltd. (2011)
Zandkopsdrift	South Africa	Measured resources=23.0 Mt at 2.07% TREO; indicated resources=22.7 Mt at 1.73% TREO; inferred resources=1.1 Mt at 1.52% TREO	Frontier Rare Earths Ltd. (2014)
Peralkaline igneous			
Bokan Mountain	Alaska, United States	Indicated resources for the Dotson Ridge deposit=4.79 Mt at 0.602% TREO; inferred resources=1.05 Mt at 0.603% TREO	Ucore Rare Metals, Inc. (2015)
Clay-Howells project	Ontario, Canada	Inferred resources=8.5 Mt at 0.73% TREO	Hatch (2015)
Dubbo Zirconia project	New South Wales, Australia	Measured resources=35.7 Mt at 0.75% TREO; inferred resources=37.5 Mt at 0.75% TREO	Alkane Resources Ltd. (2015)
Foxtrot project	Newfoundland and Labrador, Canada	Indicated resources=3.41 Mt at 1.07% TREO; inferred resources=5.85 Mt at 0.96% TREO	Srivastava and others (2012)
Hastings project	Western Australia, Australia	Indicated resources=27.0 Mt at 0.2103% TREO; additionally, 0.8913% Zr oxide and 0.3545% Nb oxide; inferred resources=9.1 Mt at 0.21% TREO	Hastings Rare Metals Ltd. (2015)

Table O4.   Advanced rare-earth-element (REE) exploration projects and the reported estimates of their REE resources, by deposit type.
—Continued

[Mt, million metric tons; t, metric ton; %, percent; TREO, total rare-earth oxide. Chemical elements: Ag, silver; Au, gold; Cu, copper; Dy, dysprosium; Mo, molybdenum; Nb, niobium; REE, rare-earth element; U, uranium; Zr, zirconium]

Deposit	Location	Reported resources	Reference(s)
Peralkaline igneous—Continued			
Hoidas Lake deposit	Saskatchewan, Canada	Measured resources=0.9638 Mt at 2.568% TREO; indicated resources=1.6 Mt at 2.349% TREO; inferred resources=0.2866 Mt at 2.139% TREO	Star Minerals Group Ltd. (2014)
Ilimaussaq complex, Kvenfjeld deposit	Greenland	Indicated resources=437 Mt at 1.093% TREO; inferred resources=182 Mt at 0.9763% TREO	Greenland Minerals and Energy Ltd. (2012)
Ilimaussaq complex, Sørensen deposit	Greenland	Inferred resources=242 Mt at 1.1022% TREO	Greenland Minerals and Energy Ltd. (2012)
Ilimaussaq complex, Zone 3 deposit	Greenland	Inferred resources=95 Mt at 1.1609% TREO	Greenland Minerals and Energy Ltd. (2012)
Kipawa	Quebec, Canada	Indicated resources=12.472 Mt at 0.512% TREO; inferred resources=3.842 Mt at 0.463% TREO	Saucier and others (2012, p. 75)
Kutessay II project	Kyrgyzstan	Measured resources=13.548 Mt at 0.27% TREO; indicated resources=2.717 Mt at 0.238% TREO; inferred resources=1.746 Mt at 0.204% TREO	Stans Energy Corp. (2015)
Nechalacho project (Thor Lake)	Northwest Territories, Canada	Measured resources=12.56 Mt at 1.714% TREO; indicated resources=96.54 Mt at 1.57% TREO; inferred resources=160.25 Mt at 1.38% TREO	Avalon Rare Metals Inc. (2015)
Norra Kärr	Southern Sweden	Inferred resources=60.5 Mt at 0.54% TREO	Tasman Metals Ltd. (2012)
Round Top	Texas, United States	Measured and indicated resources = 480 Mt at 0.063% TREO; inferred resources = 342 Mt at 0.063% TREO	Hulse and others (2014, p. 152)
Strange Lake	Quebec, and Newfoundland and Labrador, Canada	Indicated resources=278.12 Mt at 0.93% TREO; inferred resources=214.4 Mt at 0.85% TREO	Quest Rare Minerals Ltd. (2012)
TRE project	Northern Madagascar	Deposits include upper weathered bedrock of peralkaline intrusive complex and overlying argillaceous laterites (saprolite); inferred resources=130 Mt at 0.08% TREO	Tantalus Rare Earths AG (2013)
Two Tom	Newfoundland and Labrador, Canada	Inferred resources=41 Mt at 1.18% TREO	Daigle (2012)
Polymetallic deposits			
Eco Ridge Mine	Ontario, Canada	Indicated resources=22.743 Mt at 0.1606% TREO; inferred resources=36.560 Mt at 0.1554% TREO	Pele Mountain Resources (2013)
Milo project	Queensland, Australia	Inferred resources=187 Mt at 0.06% TREO; deposit contains REEs, Cu, Mo, Au, Ag, and U	GBM Resources Ltd. (2012)
Plant in Stepnogorsk	Northern Kazakhstan	Resources and grade are not reported. Plant is being designed to extract Dy from uranium tailings	Blank (2012)
Steenkampskraal	South Africa	Measured resources=85,000 t at 19.5% TREO; indicated resources=474,000 t at 14.1% TREO; inferred resources=60,000 t at 10.5% TREO	Great Western Minerals Group Ltd. (2014)
Heavy-mineral sand deposits			
Charley Creek deposits	Northern Territory, Australia	Alluvial placers with U resources along with monazite and xenotime; inferred total resources of 805.3 Mt at 0.03% TREO	Hatch (2015); Pancontinental Uranium Corp. (2012)
Canakli deposit	Turkey	Inferred resource=494 Mt at 0.07% TREO	AMR Mineral Metal Inc. (2015)
Kerala deposits	India	Total resources of 1.51 Mt of monazite reported in heavy-mineral sand deposits in the State of Kerala; resource grade is not reported	Government of India, Department of Atomic Energy (2011)

Thorium and REEs reside within apatite in iron bodies once mined in the Mineville iron district, New York, which is located in the northeastern part of the Adirondack Mountains. The orebodies are magnetite deposits that are intricately folded and faulted within a complex suite of Precambrian metamorphic and igneous rocks. The host rocks have both mafic and felsic compositions that include, in general order of abundance, gabbro, diorite, augite syenites, and granite (Staatz and others, 1980). The iron deposits are mainly magnetite, martite, and apatite, with accessory augite, hornblende, albite, quartz, pyrite, and tourmaline (McKeown and Klemic, 1956). Iron deposits in the Mineville–Port Henry area contain apatite and are likewise rich in phosphorous, REEs, and thorium because these elements are concentrated within the apatite grains. In addition, the magnetite (the primary iron ore mineral) is intergrown with 1- to 3-millimeter (0.04- to 0.12-inch)-long rice-shaped grains of apatite. Massive piles of tailings plus unmined parts of magnetite bodies in the Mineville district each contain REE-bearing apatite-rich rock. McKeown and Klemic (1956) reported an average REO content of 11.14 percent in 14 samples of apatite separated from the Old Bed, Joker, and Smith orebodies in this district.

Iron oxide-copper-gold (IOCG) deposits. IOCG deposits are closely related to magmatic iron deposits, described just above, and one could argue that the Pea Ridge and Mineville iron deposits represent variations within the IOCG deposit group. Strictly, IOCG deposits are defined as magmatic-hydrothermal iron deposits that host economic concentrations of copper and gold. This group of deposits was first described and defined after the 1975 discovery of the giant Olympic Dam copper-uranium-gold deposit in South Australia, Australia, which is one of the largest ore deposits in the world. An overview of the IOCG deposit type along with examples of significant IOCG deposits worldwide is provided by Groves and others (2010).The IOCG deposits can be very large and surrounded by alteration zones that can extend for kilometers in width. As at Olympic Dam, IOCG deposits can host REE mineralization, occurring both in iron oxides and in small carbonatites within the intrusive complex. Although an REE resource of substantial size has been identified at Olympic Dam, the mine operator has not yet recovered REEs.

Xenotime-monazite accumulations in mafic gneiss. Xenotime-monazite accumulations in mafic gneiss have not been historically important sources of REEs. Because deposits of this type tend to be preferentially enriched in the HREEs, however, they may be more economic in the future.

Example deposits occur in the Music Valley area of the northern part of Joshua Tree National Park in southern California. Pod-like xenotime deposits of the Music Valley area lie within the Pinto Gneiss of probable Precambrian age. The Pinto Gneiss consists of roughly equal amounts of quartz and plagioclase feldspar, and it averages approximately 35 percent biotite (Evans, 1964). Accessory minerals present in trace amounts in the gneiss include, in general order of abundance, sericite, apatite, magnetite, zircon, and sphene, and locally monazite, actinolite, orthoclase, microcline, perthite,

and muscovite. Biotite-rich zones in the gneiss can contain abundant amounts of orange xenotime grains; xenotime commonly forms 10 to 15 percent of the biotite zones and locally as much as 35 percent (Evans, 1964). Owing to the xenotime and accompanying monazite, the biotite-rich zones can contain more than 8 percent yttrium (Evans, 1964) and elevated percentages of HREEs (fig. O5).

Ion-adsorption clay deposits. Ion-adsorption clay deposits in southern China are the world's primary sources of the HREEs. This deposit type is often informally referred to as "south China clays" (fig. O4). Despite their economic importance, little geologic research has been published that describes the south China clay deposits in detail; a study by Bao and Zhao (2008) is an exception, as well as discussions in Chi and Tian (2008) and Kynicky and others (2012).

Rare-earth-element-bearing ion-adsorption clay deposits form in tropical regions with moderate to high rainfall through the following general processes:

1.   The REEs are leached by groundwater from granites (the bedrock),

2.   Thick zones of laterite soils develop above the granites; this intensely weathered zone contains an abundance of clays, and

3.   The mobilized REEs become weakly fixed (ion-adsorption) onto the clays (kaolinite and halloysite) in the soils.

In deposits of this type in southern China, REE concentrations range from approximately 300 parts per million (ppm) to 2,000 ppm and appear to vary with the parent rocks (Bao and Zhao, 2008). These modest REE concentrations are economic for the south China deposits because (a) the REEs can be easily extracted from the clays with weak acids; (b) the deposits are often enriched in the high-value HREEs; (c) the area has low labor costs; and (d) there has been a localized lack of environmental protection (Liang and Others, 2014).

The highest REE concentrations usually occur in the B horizon (the subsoil) of the weathered zone. In addition to the highest REE content, the B horizon also contains the highest clay content. The overlying A horizon (the uppermost zone) is richest in organic matter, and contains much clay. The underlying C horizon consists of clays and pieces of the weathered granite.

Sanematsu and others (2009) conducted geochemical and sequential leaching experiments of ion-adsorption clays from deposits in Laos. They concluded that "the enrichment of REE[s] is attributed to the occurrence of ion-exchangeable clay minerals and REE phosphates in the weathered crusts and that HREE[s] are [more] selectively adsorbed on the clay minerals than are LREE[s] by weathering" (Sanematsu and others, 2009, p. 527). Laterite clay deposits of the Longnan district in Jiangxi Province in southern China produce HREE-rich material, whereas clay ores from the Xunwu district, also in Jiangxi Province, produce material that is rich in LREEs (O'Driscoll, 2003).

Laterite clay deposits that are generally similar to the deposits in southern China are under development in northern Vietnam at the Dong Pao Mine in Lai Chau Province (fig. O4). In Madagascar, laterite clays formed by tropical weathering above REE-enriched dikes and sills are being explored at the TRE project (table O4; fig. O4; Tantalus Rare Earths AG, 2013).

An announced pilot project in Jamaica is intended to test the recovery of REEs from tailings of red mud produced from bauxite mining. The red mud reportedly contains 0.23 to 0.38 weight percent REEs (Wagh and Pinnock, 1987) and has higher HREE concentrations than do other representative Chinese clay samples (Mariano and Mariano, 2012).

Monazite-xenotime-bearing placer deposits. Monazite-xenotime-bearing placer deposits were important sources of REEs up to the mid-1960s, but they decreased in prominence owing to the discovery of the Mountain Pass deposit in California. Placer deposits may be significant sources of REEs again in the near future. Presently, monazite is extracted from coastal sands at (a) the Buena Norte mining district on the east coast of Brazil (table O3); (b) along the southwestern coast of India in the State of Kerala (table O4); and (c) along the coastline in the State of Odisha in northeastern India (fig. O4; Government of India, Department of Atomic Energy, 2011). The monazite is recovered as a byproduct during the extraction of ilmenite ($FeTiO_3$), leucoxene (altered ilmenite), and rutile (TiO_2) from beach sands. The ilmenite, leucoxene, and rutile—the principal products of value—are chemically processed to remove titanium dioxide, which is used primarily as a pigment in paints.

Two broad settings for monazite-bearing placer deposits are (a) deposits of streams and rivers (fluvial deposits), and (b) coastal and nearshore deposits of sand and silt. In both deposit types, heavy dense minerals (including monazite) are physically sorted and deposited together by the combined actions of water movement and gravity. The resulting deposits of sediments, which are composed of sand and silt with thin layers of heavy minerals, are often referred to as "heavy-mineral sands."

"Heavy minerals" are commonly defined as dense minerals with a specific gravity greater than about 2.9. These minerals are generally resistant to chemical weathering and physical degradation and thus survive well in fluvial environments. Heavy minerals are eroded from bedrock sources, carried by streams or rivers until they are deposited in the stream channel system or into a coastal plain setting. In the stream, the heavy minerals are carried within a slurry mixture of sand and silt. Because of their high density, the heavy minerals can be well sorted by fluvial processes and preferentially deposited into layers through the combined effects of gravity and decreases in stream energy. The Charley Creek deposits in Northern Territory, Australia (table O4; fig. O4) are an example of REE-bearing alluvial placer deposits. At Charley Creek, the REEs occur in the heavy minerals monazite ($(REE,Th)PO_4$) and xenotime (YPO_4).

Carrying heavy minerals, sediments are brought to coastal areas by streams and rivers. These sediments are reworked in nearshore (coastal) areas by the actions of waves and tides, which sort the heavy minerals into discreet layers. In these deposits, dark layers of heavy minerals are often referred to as "black sands." A notable example of such deposits is the detrital monazite deposits in the coastal regions of southern India, which are found in piedmont lakes, shallow seas, sand bars across the mouths of rivers, deltas, beaches, and sand dunes behind the beaches (Bhola and others, 1958).

In addition to modern coastal regions, heavy-mineral deposits occur in ancient coastal plain environments, which are other potential sources of monazite. Carpenter and Carpenter (1991) describe heavy-mineral deposits formed by Pliocene transgressive-regressive events in the Upper Coastal Plain region of eastern North Carolina and eastern Virginia. In 2015, Iluka Resources Ltd. was mining and processing Pliocene-age heavy-mineral sands in the coastal plain of Virginia. Iluka has also worked similar ancient nearshore heavy-mineral deposits in Australia since the 1950s. Iluka's heavy-mineral sands operations target the titanium minerals (ilmenite, leucoxene, rutile) and zircon; they do not recover the monazite.

Heavy minerals in the fluvial and coastal deposit types may include, in order of general abundance, ilmenite, leucoxene, rutile, magnetite, zircon, staurolite, kyanite, sillimanite, tourmaline, garnet, epidote, hornblende, spinel, iron oxides, sulfides, monazite, and xenotime. The typical minerals of value are ilmenite, leucoxene, and rutile for their titanium and titanium dioxide; zircon for its refractory uses (such as specialty ceramics); and in some cases, monazite, for its REEs and thorium. The heavy minerals as a suite typically make up no more than 15 percent of a deposit, and usually much less; quartz and clay minerals form the bulk of the sediment. As an example, in the Pliocene-age Upper Coastal Plain deposits of North Carolina and Virginia, the heavy-mineral suite consists of, on average, about 9 percent of the sediments and monazite occurs in trace amounts (0 to 0.9 weight percent of the heavy minerals) (Berquist, 1987; Carpenter and Carpenter, 1991).

The occurrence of REEs in fluvial placer or nearshore placer deposits depends on the presence of monazite and (or) xenotime in the bedrock sources upstream. Thus, exploration for monazite-bearing placer deposits must consider the mineralogy of the bedrocks that are the source of the sediments.

Resources and Production

Identified Resources

Tables O3 and O4 summarize the estimated REE resources reported for the world's most extensively explored deposits. Exploration for additional REE deposits is ongoing; therefore, the world's identified REE resources very likely will increase. The resource estimates shown in tables O3 and O4 indicate that large resources of REEs exist. If developed, these deposits may supply the world's REE needs for many decades. The process of bringing a particular deposit from the phase of orebody delineation to eventual mining and REE processing is a complex, multistage, multiyear process, however, as explained

in Long and others (2010). The pace or ultimate success of the REE exploration projects in table O4 is difficult to predict.

Berger and others (2009) compiled published tonnage and grade data for 58 REE- and niobium-bearing carbonatite deposits worldwide; the carbonatites included in the dataset are mostly well explored and either partially mined or known to contain these resources. For their carbonatite dataset, they calculated a median tonnage of 49 million metric tons and median grades of 0.61 percent total REO and 0.23 percent niobium oxide.

An earlier inventory of global REE resources (Jackson and Christiansen, 1993) reported that China hosts the largest resources of REEs, followed by Namibia, the United States, Australia, and India. Jackson and Christiansen (1993, p. 43) stated that "Globally, economically recoverable REO ore resources, based on 106 properties, amount to 20.6 billion metric tons, of which 85 percent is in placers and 15 percent is in hard-rock deposits." The REOs in the ore deposits occur dominantly within the hard-rock deposits, however; according to their study, 7 percent of the REOs occur in placers and 93 percent are in hard-rock deposits.

China's Bayan Obo iron-carbonatite deposit in Nei Mongol Autonomous Region has been the world's principal source of LREEs since the mid to late 1980s (Long and others, 2010; U.S. Department of Energy, 2010, 2011). Bayan Obo is thought to be the world's largest REE deposit—it is estimated to contain about 800 million metric tons of ore material at a grade of 6 percent REO content (Berger and others, 2009).

Mining by Molycorp, Inc. in Mountain Pass, Calif., has exploited the Sulphide Queen carbonatite (Olson and others, 1954; Castor, 2008), which is the largest high-grade, LREE deposit in the United States (figs. O3, O4, and O5). This carbonatite reportedly contains 16.7 million metric tons of proven and probable reserves at a grade of 7.98 percent total REO (Molycorp, Inc., 2012).

India reports large resources of REEs, mostly in monazite within coastal sediments along its southern coastlines. According to India's Atomic Mineral Directorate for Exploration & Research, "the reserves of monazite in India is about 10.70 million tonnes which translates to approx. 5 million tonnes of rare earth oxide" (Government of India, Department of Atomic Energy, 2011, p. 2). Also, the Directorate estimates that about 2,000 metric tons of xenotime-bearing heavy-mineral concentrate, which contains about 2 percent xenotime, occurs in riverine placer deposits in the States of Chhattīsgarh and Jharkhand. With national sponsorship, the coastal placers are mined for their titanium minerals (rutile, ilmenite) and monazite. IREL, which is a public sector entity under the Department of Atomic Energy, is constructing a monazite processing plant in the State of Odisha (Government of India, Department of Atomic Energy, 2011).

Undiscovered Resources

The increase in REE prices has led to an increase in exploration activity worldwide; as a result, many more REE resources have been discovered or, in many cases, reinvestigated and better defined. Because REE enrichments can be found in a wide variety of rock types and environments, the probability for the occurrence of substantial undiscovered resources is high. With engineering advances in ore processing, additional deposits may become economic. The following are examples of some of the deposit types that could be potential future sources of REEs.

- Although the ion-adsorption clay deposits of southern China now serve as the world's primary source of the HREEs, these deposits appear not to be unique to southern China. Clay deposits with similar geologic settings and characteristics have been explored elsewhere, although none has yet been brought into production on a significant scale. The Dong Pao deposit in northern Vietnam, for example, is composed of laterite clays that overlie syenite intrusions. The Dong Pao Mine reportedly is in a late stage of development.

- Elevated concentrations of REEs in sea-floor sediments sampled by deepwater drill coring at numerous sites on the floors of the eastern South Pacific Ocean and central North Pacific Ocean were reported by Japanese scientists in 2011 (Kato and others, 2011). The scientists collected more than 2,000 sea-floor sediments, sampled from about 1 m into the sea floor, from 78 sites across the Pacific Ocean. As one example of their results, Kato and others (2011) reported that muds in the eastern South Pacific Ocean had REE contents comparable to or higher than those of the south China ion-adsorption clay deposits; also, that the HREE values were nearly twice as much as the China clays.

- Some modern and ancient coastal deposits can host large undeveloped, poorly studied deposits of monazite. Coastal deposits offer several advantages, such as that (a) these deposits are unconsolidated or weakly consolidated and thus easy to excavate; (b) the deposits are relatively easy to process in order to separate out the heavy minerals; and (c) multiple minerals can be extracted as the primary products of value, such as ilmenite and rutile for titanium and titanium dioxide, zircon for refractories, and garnet for abrasives. As one example, large undeveloped deposits of coastal sediments, ranging from Cretaceous to recent in age, occur from eastern Virginia to Florida in the Southeastern United States. Many sand and silt units in this coastal plain region contain monazite (Staatz and others, 1980; Carpenter and Carpenter, 1991).

Exploration for New Deposits

The search for REEs covers a wide variety of geologic provinces; noteworthy deposits of REE-bearing minerals have been found in alkaline igneous rocks, carbonatites, layers in

mafic metamorphic rocks, laterite clay deposits developed upon weathered granitic plutons, and coastal and fluvial sediments. Some of these types of settings are described briefly below.

Carbonatites and peralkaline igneous complexes. According to Woolley and Kjarsgaard (2008), there are 527 known carbonatites in the world, and about 40 percent are located in the African continent. The majority of the known carbonatites are located in relatively tectonically stable regions within crustal plates, and they are often positioned on deep-seated structural zones of regional extension (intra-continental rift zones). Less commonly, some carbonatites are found near plate margins, and their formation is possibly linked to processes of crustal plate separation or orogeny.

By definition, carbonatites are an igneous rock composed of at least 50 percent carbonate minerals, which sets them apart from other intrusions in igneous terrains. The gangue carbonate minerals, such as calcite and dolomite, can be identified with weak acid, as with any carbonate rock. Most carbonate minerals in carbonatites are generally subdued in outcrop, and the principal REE ore minerals are usually not colorful. In regions with deep, intense weathering, such as laterite weathering of the upper parts of carbonatites in Brazil and Australia, the laterites contain resistate ore minerals (minerals that are resistant to weathering), such as pyrochlore and monazite.

Fenite is a quartz-alkaline feldspar-rich rock that has been altered by alkaline (sodium- and [or] potassium-rich) hydrothermal fluids at the contact of a carbonatite intrusion complex. Fenitization is the alkaline mineralization formed by alkali metasomatism during the emplacement of an alkaline intrusion or carbonatite. This process can form alteration aureoles (fenite) of variable widths and intensity that are developed in the intrusion and the surrounding country rock. The presence of a fenite halo indicates that alkali hydro-thermal processes took place there and is generally a favorable indication of REE enrichment.

Brief descriptions of alkaline provinces and individual alkaline complexes are available for North America and South America (Woolley, 1987), the former Soviet Union (Kogarko and others, 1995), and Africa (Woolley, 2001). These publications are useful references for those conducting REE exploration in these regions.

In an alkaline igneous complex, rock types generally progress from oldest to youngest as ultramafic to mafic lithologies (pyroxenite, biotite-shonkinite, peridotite, and jacupirangite, as examples), to felsic compositions (syenite, alkaline granites, ijolite, trachyte, and phonolite), to carbonatites. Coincidences of these alkaline rock types can indicate evolved alkaline systems. Carbonatite formation is a late (usually last) phase of the alkaline complex, and the carbonatite is often centrally located in the complex. Carbonatite dikes, if present, are also late-phase formations, and they may extend for kilometers outward from the complex. Dikes or veins of carbonatite can indicate that a larger carbonatite mass lies below or in the area.

In peralkaline intrusions, some REE deposits contain relatively rare but useful indicator REEs and alkali minerals, such as acmite (brown/green), alkali amphiboles (blue/black), eudialyte (pink/red), gadolinite (green/brown-black), rinkolite (red brown/yellow brown), and sodalite (dark blue).

Because of the presence of associated thorium-uranium-bearing minerals in alkaline complexes and carbonatites, radioactivity is a common characteristic of REE minerali-zation. Most of the carbonatites and alkaline-intrusion-hosted REE deposits in the United States were discovered by uranium prospectors using handheld radiation detectors, such as Geiger counters and scintillation counters (scintillometers). In most of these deposit types, the radiation is primarily a result of the presence of thorium.

The most diagnostic geochemical elements for carbonatites and peralkaline-hosted REE deposits are the high-field-strength elements, which include hafnium, niobium, REEs+yttrium, scandium, tantalum, thorium, titanium, uranium, and zirconium. Large-ion lithophile elements—barium, cesium, potassium, rubidium, and strontium—are also enriched in carbonatites and alkaline intrusions. Associated elements can include chlorine, fluorine, manganese, and phosphorus.

Geophysical methods can be used to detect and map an ore-bearing mass that may not be exposed. Ground and airborne geophysical techniques have been used to identify and define the size of buried carbonatites and mineralized alkaline intrusions. Geophysical data can be collected and analyzed at a wide range of scales, thereby contributing to exploration at a variety of scales, from regional features to detailed characterization of an individual deposit.

Modern airborne geophysical technologies offer the capability to collect gamma-ray, magnetic, and gravity data concurrently. Electromagnetic data can also be acquired this way. The combination and integration of these methods provides significant insight into a number of physical properties, which, in combination, can significantly enhance an exploration program for intrusion-hosted REE deposits. Airborne geophysical surveys that are flown most often over prospective REE deposits are magnetic, gamma-ray, and, most recently, gravity and gravity gradiometry. The choice of airborne geophysical tool(s) and platform (helicopter or fixed wing) used to explore for an intrusion-hosted REE deposit depends on a number of factors, such as accessibility to the deposit, ruggedness of the terrain, and whether the deposit is entirely or partly exposed or is concealed by rock, glacial deposits, vegetation, or water and (or) ice.

Gravity and magnetic surveying can be especially useful to map partially or entirely concealed carbonatites and alkaline intrusions. Although these methods do not provide direct detection of REE mineralization, they can provide necessary geologic controls on the depth, geometry, and extent of the host intrusion(s). The success of these methods, as with all geophysical mapping tools, depends on there being a physical property contrast (density and magnetization) of the intrusion with the surrounding rocks.

Magmatic magnetite-hematite deposits and iron oxide-copper-gold (IOCG) deposits. As noted earlier, IOCG deposits are typically giant deposits with broad alteration zones that can extend for several kilometers outward from the main deposit (Groves and others, 2010). Iron-dominated deposits, typified by magmatic iron and IOCG deposits, produce substantial magnetic and gravity anomalies, which are usually clearly evident in geophysical surveys at regional and local scales. The techniques traditionally employed in the exploration for precious and base-metal deposits can be likewise used to discover magmatic iron and IOCG deposits.

Xenotime-monazite deposits in metamorphic rocks. High-grade concentrations of xenotime and monazite have been found locally in some mafic gneiss, paragneiss, and migmatites (Mariano and Mariano, 2012). Thus far, none of the discovered occurrences of this type have been deemed large enough to be economic; however, their inherent enrichment in HREEs continues to attract interest.

Local exploration for these deposits can utilize the durability of xenotime and monazite; they are heavy dense minerals that are resistant to mechanical weathering and, as a result, they accumulate with the heavy-mineral suite in stream sediments. Monazite- and xenotime-bearing sediments are typically elevated in the LREEs, yttrium, and thorium.

Radioactivity owing to monazite may be detectable using high-resolution airborne gamma-ray surveys with closely spaced flight lines if the host rocks are exposed at or very near the surface. Ground surveys with a handheld radiation meter can identify monazite-rich zones.

Ion-adsorption clay deposits. On the most basic level, favorable regions for ion-adsorption clay deposits are those where tropical weathering horizons (laterites) formed atop alkaline igneous masses. In southern China, underlying bedrock includes altered "two mica" granites. In addition to the modern tropics, paleo-laterites coincident with alkaline intrusive masses can also be considered.

In many ways, discovery of these types of REE deposits have proven the most elusive thus far, outside of southern China. These clay deposits lack radioactivity (Bao and Zhao, 2008) and have relatively low concentrations of REEs. Sampling studies of prospective laterites typically extract subsurface samples of the weathered zone at selected soil horizons; the samples are analyzed for their REE content and REE leachability.

Monazite-xenotime-bearing fluvial placer deposits. Many of the REEs and associated high-field-strength elements occur in heavy, dense minerals that are resistant to weathering (resistates); thus, heavy-mineral concentrates from stream sediments are a useful sampling technique for these deposit types. Resistate indicator minerals in the heavy concentrate portion of stream sediments can include, in order of general abundance, monazite, pyrochlore, xenotime, allanite, zircon, kainosite, thorite and uranothorianite, and euxenite (Barker and Van Gosen, 2012). Using airborne gamma-ray survey data, radioactivity caused by the presence of thorium (mainly in monazite) may outline fluvial networks that contain monazite.

Monazite-bearing coastal plain deposits. Deposits of sand and silt that contain monazite occur in many coastal environments. These sediments are carried by rivers and streams to coastal settings, including the shore. The sediments originate from the erosion of metamorphic and (or) igneous bedrock located up gradient of the coast. The monazite in these sediments occurs in close association with other heavy minerals, which are most commonly ilmenite, leucoxene, rutile, and zircon. These heavy minerals could thus be considered indicator minerals in these types of deposits. Economic "black sand" deposits in coastal settings (modern or paleo-settings) typically contain 5 percent or greater heavy-mineral content.

Exploration for coastal heavy-mineral sand deposits involves primarily any or all of the following:

- Locating ancient to modern coastal sedimentary deposits that were and (or) are sourced by terrains containing abundant metamorphic rocks and (or) igneous rocks. Favorable target areas are those that experienced transgressive-regressive marine cycles, as well as areas at the intersection of ancient shorelines and major paleorivers.

- Sampling sediments at the surface or (more thoroughly) vertically by using truck-mounted power auger drills.

- Simple panning on site to estimate the approximate heavy-mineral content of a sample. A more-exacting determination of heavy-mineral content is made by using multiple steps, including heavy liquid separation, grain counts of heavy-mineral concentrates, and thorough analyses of heavy-mineral concentrates using spirals, solutions, magnetic separators, and electrostatic separators, as described by Carpenter and Carpenter (1991).

Environmental Considerations

Rare-earth elements are currently produced from just a few mines globally, and, as a result, there are no abandoned REE mines available for study. Previous production from the Mountain Pass Mine in California started before the era of major environmental regulatory oversight; as a result, much of the environmental information associated with new mines is lacking. Further, the Bayan Obo Mine in China, which is the main current source of REEs, also has limited environmental information published. Two advanced exploration projects—the Nechalacho alkaline-intrusion-related deposit (near Thor Lake, Northwest Territories, Canada) and the Bear Lodge carbonatite deposit (Bear Lodge Mountains, northeastern Wyoming)—represent new sources of environmental data as a result of ongoing activities at these sites. At present, however, information regarding the environmental aspects of REE mining is limited. Toxicological data about the effects of REEs on aquatic, animal, or human health are also limited.

Sources and Fate in the Environment

The concentrations of REEs in environmental media are influenced by their normal tendency to occur in diluted concentrations in crustal rocks (rather than in concentrated deposits) and their limited solubility in most groundwaters and surface waters. A significant amount of information is available on their natural abundances and distributions in environmental media, such as seawater (Elderfield and others, 1988), river water (Goldstein and Jacobsen, 1988; Sholkovitz, 1995), groundwater (de Boer and others, 1996), soil, and plants (Tyler, 2004), because of their value in tracing hydrochemical and geochemical processes. The average upper crustal abundance of all REEs combined (lanthanum through lutetium) is 146.4 ppm; the average abundance of yttrium is 22 ppm. The mean REE concentration of soils is similar to the average upper crustal abundance of these elements (Smith and others, 2013; Tyler, 2004). In humid settings with extreme weathering, however, REE concentrations in soil tend to be higher than those in the underlying rock because of leaching of major elements. Plant uptake of REEs is generally low because of the low solubility of REEs, and uptake does correlate with soil acidity (Tyler, 2004). The solubility of REEs in typical surface water or groundwater compositions is low (Wood, 1990). In seawater, the average dissolved concentration of combined REEs is 0.15 part per billion (ppb) (Elderfield and others, 1988). In major rivers, the REE concentrations average 1.6 ppb (Sholkovitz, 1995). Under extreme acid-mine drainage conditions (pH 1.1)—conditions that are not related to REE mining—dissolved REE concentrations can easily reach 2,500 ppb (Seal and others, 2008).

Information on pre-mining environmental concentrations of REEs is limited, in part because of their low concentrations. Data from solid media (rock, soil, and sediment) are more common because REEs are routinely analyzed in solid media. Analysis of REEs in water samples is less common. Environmental baseline studies have been conducted at the Bear Lodge deposit (Dahlberg, 2014) and at the Nechalacho deposit (Avalon Rare Metals Inc., 2011); both are currently advanced exploration projects. Baseline environmental data from all other REE deposit types have not been identified.

At Nechalacho, the surface water sample sites encompass an area that extends up to 6 kilometers from the deposit, but the groundwater samples are from within the deposit as reported by Avalon Rare Metals Inc. (2011). The pH of surface water and groundwater is neutral to slightly alkaline, ranging between 6.9 and 8.6. The cationic species in groundwater and surface water around the deposit are dominated by magnesium, followed by calcium and sodium. Water hardness values range between 71 and 470 ppm calcium carbonate ($CaCO_3$) for both surface water and groundwater. As reflected by alkalinity values that range between 74 and 442 ppm $CaCO_3$, bicarbonate is the most important anionic species, followed by sulfate, chloride, and fluoride. Fluoride concentrations range from 0.06 to 4.4 ppm, which locally exceeds the U.S. Environmental Protection Agency secondary maximum contaminant limit of 2 ppm. Groundwater tends to have higher concentrations of anions than does surface water.

Trace elements are generally low in the vicinity of the Nechalacho deposit but tend to be slightly higher in groundwater compared with surface water. Baseline dissolved iron concentrations in surface water and groundwater are noteworthy and range from less than 30 to more than 10,000 ppb. Baseline dissolved copper concentrations range from 0.2 to 48 ppb. Dissolved aluminum concentrations generally range from 0.5 to 108 ppb, although one outlier sample of groundwater measured 15,300 ppb. Dissolved manganese ranges from 0.2 to 544 ppb. Baseline dissolved nickel and molybdenum concentrations range from 0.25 to 6.6 ppb and from 0.2 to 63 ppb, respectively. Dissolved concentrations of uranium range from less than 0.05 to 20 ppb. Dissolved concentrations of arsenic and antimony are less than 5 and 0.3 ppb, respectively.

Baseline surface water and groundwater chemistry data associated with the Bear Lodge deposit (Dahlberg, 2014), are grossly similar to those from Nechalacho. The pH of waters at the Bear Lodge deposit spans a slightly larger range (6.0 to 8.4). Water hardness ranges from 10 to 380 ppm $CaCO_3$. Bicarbonate is the dominant cation as reflected by the alkalinity values of between 10 and 300 ppm $CaCO_3$, and fluoride is present in concentrations of less than 1 ppm. Trace element concentrations at the Bear Lodge deposit are similar to those at Nechalacho.

Mine Waste Characteristics

The mineralogy of the dominant minerals from carbonatite and alkaline intrusion REE deposits influences the environmental character of their mine waste. The paucity of sulfide minerals, including pyrite, minimizes or eliminates concerns about acid-mine drainage for carbonatite-hosted REE deposits and alkaline-intrusion-related REE deposits. In fact, tailings from metallurgical testing at the Nechalacho deposit contain less than 0.1 weight percent total sulfur (Avalon Rare Metals Inc., 2011). The low acid-generating potential of these deposits is further offset by their high acid-neutralizing potential, particularly for carbonatite deposits, which are dominated by carbonate minerals.

In terms of trace elements, the REE ore minerals factor most prominently in the environmental character of the ores and mine wastes. The main ore minerals currently processed for REEs—bastnaesite ($LnCO_3F$), monazite (($Th,Ln)PO_4$), and xenotime (($Y,Ln)PO_4$) (where "Ln" [for lanthanide] indicates the place of REEs in the mineral formulas)—all contain appreciable amounts of uranium and thorium. Bastnaesite reportedly contains between 0 and 0.3 weight percent thorium dioxide (ThO_2) and 0.09 weight percent uranium dioxide (UO_2); monazite, between zero and 20 weight percent ThO_2 and zero and 16 weight percent UO_2; and xenotime, between zero and 5 weight percent UO_2 (Long and others, 2010). The thorium and uranium contents of the ore minerals and mine

waste represent one of the biggest environmental challenges that must be managed during mining, ore processing, and mine closure. The geochemistry of thorium and uranium influence their interactions with the environment and resulting environmental effects. Thorium is highly insoluble under most conditions. Therefore, for thorium and its radioactive decay products, solid-phase pathways, such as windblown dust from tailings piles and erosion of tailings into water bodies, are of greatest priority for mine planning. Under oxidizing conditions, uranium is highly soluble; therefore, aqueous pathways leading to surface water or groundwater are priority issues for mine planning.

According to the metallurgical testing done, the geochemistry of the tailings at Nechalacho (Avalon Rare Metals Inc., 2011) is anomalous for several elements compared with the guidelines for soil (U.S. Environmental Protection Agency, 2015) and sediment (MacDonald and others, 2000). The chromium concentration of the metallurgical reject material (640 ppm) exceeds the residential soil guideline (280 ppm). Cadmium (6 ppm), chromium (640 ppm), and nickel (330 ppm) concentrations of the reject material exceed sediment guidelines for "probable effects concentrations" for these elements (4.98 ppm, 111 ppm, and 48.6 ppm, respectively). The "probable effects concentration" in sediment is the concentration above which harmful effects on freshwater ecosystems are likely to be observed (MacDonald and others, 2000).

Human Health Concerns

Human health risks associated with mining are typically associated either with contamination of potential sources of drinking water or ingestion of fine particulate mine waste (tailings). The human health effects of REEs have been sparsely studied since the work of Haley (1965). Ingestion and inhalation studies on cerium oxide and cerium compounds indicate minimal effects in laboratory studies on rats (U.S. Environmental Protection Agency, 2009). Exposure to cerium oxides and cerium compounds is unlikely during routine mining, although the potential for exposure is present during ore processing and refining. The United States lacks drinking water standards for the REEs. The limited data on the toxicity of REEs in drinking water has been reviewed by de Boer and others (1996).

For other trace elements, some baseline groundwater and surface waters in the vicinity of the Nechalacho deposit exceed the secondary maximum contaminant limit for fluoride. At the Bear Lodge deposit, a single baseline groundwater sample (13 ppb arsenic) is slightly above the U.S. Environmental Protection Agency drinking water standard for arsenic concentration (10 ppb). Several baseline surface water samples from the Bear Lodge Mountains as well as a single humidity-cell leachate sample from Nechalacho exceed the combined radium radioisotope (^{226}Ra + ^{228}Ra) drinking water standard.

Ecological Health Concerns

The primary pathways for REE mining to affect aquatic ecosystems are through water or sediment contamination. Knowledge regarding the toxicity of REEs to aquatic organisms through either pathway is limited. Environmental guidelines for REEs in surface water and sediment are lacking in the United States. Guidelines for surface water and sediment for both fresh and salt water have been recommended in the Netherlands, however (Sneller and others, 2000). Several studies have documented that the toxicity and biologic uptake of REEs in surface water vary as a function of water hardness and alkalinity (Barry and Meehan, 2000; Moermond and others, 2001). Further, Weltje and others (2004) found that the toxicity of lutetium was proportional to the concentration of the free ion (Lu^{+3}) in microbial bioassay studies. Therefore, REE complexation with carbonate, sulfate, or other ligands in natural systems may significantly influence their toxicity (Wood, 1990). Published aqueous REE data are lacking for the Nechalacho and the Bear Lodge deposits.

Insights into potential ecological risks associated with REE deposits in North America and worldwide are limited to data associated with the baseline environmental characterization of the Nechalacho (Avalon Rare Metals Inc., 2011) and Bear Lodge (Dahlberg, 2014) deposits. Uranium is the only trace element in baseline surface water samples near both deposits. Humidity-cell leachates from Nechalacho exceed the chronic surface water benchmark for uranium (1.87 ppb) but not the acute benchmark (33.5 ppb) (Suter, 1996). Dissolved thorium concentrations are approximately one to two orders of magnitude lower than dissolved uranium concentrations at Nechalacho. Therefore, the risk of mine drainage issues associated with tailings from either alkaline-intrusion-related or carbonatite-hosted deposits is likely minimal.

Accidental release of mill tailings, either during or after closure, can pose a risk to aquatic organisms. This risk can be assessed by the comparison of the geochemical composition of mill tailings with relevant sediment-quality guidelines. In general, most concentrations of trace elements are low. The concentrations of cadmium, chromium, and nickel in a tailings sample from Nechalacho exceeded both the threshold effects concentration and the probable effects concentration (MacDonald and others, 2000). Concentrations of the REEs in the tailings sample exceeded their corresponding negligible concentrations, but not their maximum permissible concentrations (Sneller and others, 2000). Therefore, only a few elements are marginally of concern in the event of accidental release of tailings.

Carbon Footprint

There are several potential links between REEs and greenhouse gas emissions. One of the main ore minerals, bastnaesite ($Ln(CO_3)F$), contains carbonate, which is liberated during ore processing. Because of the low grades of economic

deposits (<10 percent total REOs), however, this carbon flux is not likely to be significant relative to other sources associated with mining. In addition, one of the most important uses of REEs is in permanent magnets used in "green" technologies, such as electric cars, hybrid cars, and wind turbines.

Mine Closure

Mine closure procedures depend on the mining method employed. Mountain Pass in California, Bayan Obo in China, and Mount Weld in Australia are all mined as open pits. At closure, the pits will likely fill with water, depending on the elevation of the local water table. Waste rock piles and mill tailing piles will also remain on site. Both types of piles may be regraded and revegetated. Recent operations at Mountain Pass recycled all water to avoid the need for evaporation ponds (Molycorp, Inc., 2015), which were used during previous mining at the site, to manage process water. Mill tailings disposal included paste disposal, eliminating the need for a tailings dam and its long-term maintenance. (Paste disposal produces tailings that have been significantly dewatered, and, as a result, the tailings do not have a critical flow velocity when pumped into the disposal area.)

Problems and Future Research

The fascinating new era for the REEs involves many challenges that remain to be fully addressed, including those related to economics (supply and demand and price stability issues), technology, and scientific research. In recent years, considerable news coverage and discussion have focused on the global supply and demand concerns for the REEs, underscored by their importance to modern and evolving technologies. In the foreseeable future, will processed REE compounds be readily available and affordable and in adequate supply to meet the needs of technology applications? If not, will suitable substitutes for the REEs be developed? In the fields of geologic research, although REE deposits have been studied for more than a century, many questions remain about their genesis. The questions that follow should be viewed as a partial list of the many issues likely to involve the REEs during the 21st century. These questions also represent opportunities where significant new contributions can be made.

- Will the addition of new LREE mines—such as the Mount Weld Mine (Australia)—prove to be adequate to offset reductions in the exports of REEs from China?

- Do substantial sources of HREEs occur outside of China? Are the ion-adsorption clay deposits of southern China unique? These deposits serve as the world's principal source of the HREEs and, as of 2015, other HREE deposits had not been brought into production. Can other clay deposits similarly enriched in the HREEs be brought into production outside of southern China? Will other types of HREE deposits eventually be brought into production?

- What exploration guidelines and techniques can be applied or developed that lead to discoveries of high-grade deposits of REEs, particularly hidden (concealed) deposits?

- Can advances in ore processing provide an economic advantage to some deposits? For mines that have REEs in the ores that host another primary mineral commodity, can REEs be developed as a byproduct?

- Can REEs be efficiently and economically recovered and recycled from disposed electronics, batteries, and other devices?

- Can REEs be replaced in some current applications by other metals that are less costly and more readily available? If so, will these products perform as well as those that use REEs?

- Can the complex ores of peralkaline deposits be processed by methods that are efficient and economical? This aspect is especially relevant because these deposit types often have a general enrichment in the highly sought HREEs.

- Why do REEs occur only in modest concentrations in Earth's upper mantle, yet they can be highly concentrated in carbonate and alkaline magmas that ascend to the crust, thereby forming ore deposits? The systematic geologic and chemical processes that explain these observations are not well understood, especially in comparison to many other ore-forming systems. Exploration for REEs throughout the world in recent years has provided considerable drilling and other data, which are likely to provide an abundance of materials and information useful for detailed geologic research.

Case histories for the environmental behavior of REE deposits, mines, and their mine wastes are extremely limited because there are so few past and current mines. Further, most past and current mines are located in China, where little environmental information is available. Therefore, insights into future environmental characteristics of REE mine wastes must rely on predictive models.

Little is known about the aquatic toxicity of REEs (Sneller and others, 2000). Although their low solubility likely limits their toxicity, a few studies suggest that their aquatic toxicity varies as a function of water chemistry (Barry and Meehan, 2000; Moermond and others, 2001; Weltje and others, 2004). More study is needed to evaluate the potential environmental risks associated with REEs in hydrologic systems.

References Cited

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

Adams, J.W., and Staatz, M.H., 1973, Rare-earth elements, *in* Brobst, D.A., and Pratt, W.P., eds., United States mineral resources: U.S. Geological Survey Professional Paper 820, p. 547–556. [Also available at http://pubs.er.usgs.gov/ publication/pp820.]

Alkane Resources Ltd., 2015, Projects: Alkane Resources Ltd. Web page, accessed October 9, 2015, at http://www.alkane.com.au/ index.php/projects/current-projects.

American Physical Society Panel on Public Affairs and the Materials Research Society, 2011, Energy critical elements—Securing materials for emerging technologies: Washington, D.C., American Physical Society, 19 p. plus 2 appendixes. [Also available at http://www.aps.org/policy/ reports/popa-reports/upload/elementsreport.pdf.]

AMR Mineral Metal Inc., 2015, Aksu Diamas—Canakli deposit: AMR Mineral Metal Inc. Web page, accessed October 9, 2015, at http://www.amrmineralmetal.com/ aksu_diamas_canakli.asp.

Anderson, D.L., and Patiño-Echeverri, Dalia, advisor, 2009, An evaluation of current and future costs for lithium-ion batteries for use in electrified vehicle powertrains: Raleigh-Durham, N.C., Nicholas School of the Environment, Duke University master's thesis, 44 p., accessed October 9, 2015, at http://dukespace.lib.duke.edu/dspace/bitstream/10161/ 1007/1/Li-Ion_Battery_costs_-_MP_Final.pdf.

Arafura Resources Ltd., 2014, Nolans project—Resources and reserves: Arafura Resources Ltd. Web page, accessed September 18, 2015, at http://www.arafuraresources.com.au/ our-projects/nolans/resources-reserves.html.

Arzamastsev, A.A., Bea, F., Glaznev, V.N., Arzamastseva, L.V., Bea, F., and Montero, P., 2001, Kola alkaline province in the Paleozoic—Evaluation of primary mantle magma composition and magma generation conditions: Russian Journal of Earth Sciences, v. 3, no. 1, 22 p. [Also available at http://dx.doi.org/10.2205/2001ES000054.]

Avalon Rare Metals Inc., 2011, Developer's assessment report, Thor Lake project [Submitted to Mackenzie Valley Environ-mental Impact Review Board]: Avalon Rare Metals Inc., May, accessed January 13, 2015, via http://www.reviewboard.ca/ registry/project.php?project_id=87.

Avalon Rare Metals Inc., 2015, Nechalacho: Avalon Rare Metals Inc. Web page, accessed September 18, 2015, at http://avalonraremetals.com/nechalacho/nechalacho_overview/.

Baba, Kenji, Hiroshige, Yuzo, and Nemoto, Takeshi, 2013, Rare-earth magnet recycling: Hitachi Review, v. 62, no. 8, p. 452–455.

Bao, Zhiwei, and Zhao, Zhenhua, 2008, Geochemistry of mineralization with exchangeable REY in the weathering crusts of granitic rocks in south China: Ore Geology Reviews, v. 33, nos. 3–4, p. 519–535. [Also available at http://dx.doi.org/10.1016/j.oregeorev.2007.03.005.]

Barker, J.C., and Van Gosen, B.S., 2012, Alaska's rare earth deposits and resource potential: Mining Engineering, v. 64, no. 1, p. 20–32.

Barry, M.J., and Meehan, B.J., 2000, The acute and chronic toxicity of lanthanum to *Daphnia carinata*: Chemosphere, v. 41, no. 10, p. 1669–1674. [Also available at http://dx.doi.org/ 10.1016/S0045-6535(00)00091-6.]

Berger, V.I., Singer, D.A., and Orris, G.J., 2009, Carbonatites of the world, explored deposits of Nb and REE—Database and grade and tonnage models: U.S. Geological Survey Open-File Report 2009–1139, 17 p., accessed September 18, 2015, at http://pubs.usgs.gov/of/2009/1139/.

Berquist, C.R., 1987, Minerals in high-level gravel deposits along the Fall Zone of Virginia: Virginia Minerals, v. 33, no. 4, p. 37–40.

Bhola, K.L., Chatterji, B.D., Dar, K.K., Mahadevan, C., Mahadevan, V., Mehta, N.R., Handi, N., Nanhi, H., Narayandas, G.R., Sahasrabudhe, G.H., Shirke, V.G., and Udas, G.R., 1958, A survey of uranium and thorium occurrences in India, session E5 (raw material supplies), *in* Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland, September 1–13, 1958—Volume 2, Survey of raw material resources: Geneva, Switzerland, United Nations, v. 2, P/2516, p. 100–102.

Blank, Stephen, 2012, Kazakhstan completes major uranium and rare earths deals with Japan: Eurasia Daily Monitor, v. 9, no. 144, accessed September 15, 2015, at http://www.jamestown.org/programs/edm/single/ ?tx_ttnews[tt_news]=39705&cHash=4e68ec740b98fe 390061af8ca1769b6c#.Uz16ivldV_5.

Carlson, M.P., and Treves, S.B., 2005, The Elk Creek carbonatite, southeast Nebraska—An overview: Natural Resources Research, v. 14, no. 1, p. 39–45. [Also available at http://dx.doi.org/10.1007/s11053-005-4677-x.]

Carpenter, R.H., and Carpenter, S.F., 1991, Heavy mineral deposits in the upper coastal plain of North Carolina and Virginia: Economic Geology, v. 86, p. 1657–1671. [Also available at http://dx.doi.org/10.2113/gsecongeo.86.8.1657.]

Castor, S.B., 2008, The Mountain Pass rare-earth carbonatite and associated ultrapotassic rocks, California: The Canadian Mineralogist, v. 46, no. 4, p. 779–806. [Also available at http://dx.doi.org/10.3749/canmin.46.4.779.]

Castor, S.B., and Nason, G.W., 2004, Mountain Pass rare earth deposit, California, in Castor, S.B., Papke, K.G., and Meeuwig, R.O., eds., Betting on industrial minerals—Proceedings of the 39th Forum on the Geology of Industrial Minerals, Reno/Sparks, Nevada, May 18–24, 2003: Reno, Nev., Nevada Bureau of Mines and Geology Special Publication 33, p. 68–81.

Chakhmouradian, A.R., and Mitchell, R.H., 1998, Compositional variation of perovskite-group minerals from the Khibina complex, Kola Peninsula, Russia: The Canadian Mineralogist, v. 36, no. 4, p. 953–969.

Chakhmouradian, A.R., and Zaitsev, A.N., 2012, Rare earth mineralization in igneous rocks—Sources and processes: Elements, v. 8, no. 5, p. 347–353. [Also available at http://dx.doi.org/10.2113/gselements.8.5.347.]

Chi, Ruan, and Tian, Jun, 2008, Weathered crust elution-deposited rare earth ores: New York, N.Y., Nova Science Publishers, 286 p.

Clark, A.L., and Zheng, Shuhui, 1991, China's rare earth potential, industry and policy, in Siribumrungsukha, B., Arrykul, S., Sanguansai, P., Pungrassami, T., Sikong, L., and Kooptarnond, K., eds., Proceedings of International Conference on Rare Earth Minerals and Minerals for Electronic Uses, Hat Yai, Thailand, January 23–25, 1991: Hat Yai, Thailand, Prince of Songkla University, v. 70–72, p. 577–602. [Also available at http://dx.doi.org/10.4028/www.scientific.net/MSF.70-72.577.]

Commerce Resources Corp., 2016, Ashram rare earth element deposit [formerly Eldor project]: Commerce Resources Corp. Web page, accessed July 20, 2016, at https://www.commerceresources.com/en/projects/ashram-rare-earth-element-deposit.

Dahlberg, P.S., 2014, Pre-feasibility study report on the reserves and development of the Bull Hill Mine, Wyoming, NI 43–101 technical report, prepared for Rare Element Resources, Ltd.: Sandy, Utah, Roche Engineering, Inc., October 9, 587 p., accessed September 14, 2015, at http://www.rareelementresources.com/bear-lodge-project/project-related-studies-reports.

Daigle, Paul, 2012, Resource estimate and technical report for the Two Tom REE deposit of the Red Wine Complex, Labrador, Canada, NI 43–101 report prepared for Rare Earth Metals Inc.: Toronto, Ontario, Canada, Tetra Tech Wardrop, document no. 1192410100-REP-R0001-01, accessed September 18, 2015, at http://www.canadararearth.com/upload/documents/twotom-43-101.pdf.

de Boer, J.L.M., Verweij, W., van der Velde-Koerts, T., and Mennes, W., 1996, Levels of rare earth elements in Dutch drinking water and its sources—Determination by inductively coupled plasma mass spectrometry and toxicological implications—A pilot study: Water Resources, v. 30, no. 1, p. 190–198. [Also available at http://dx.doi.org/10.1016/0043-1354(95)00120-A.]

Dostal, Jaroslav, Kontak, D.J., and Karl, S.M, 2014, The early Jurrasic Bokan Mountain peralkaline granitic complex (southeastern Alaska)—Geochemistry, petrogenesis and rare-metal mineralization: Lithos, v. 202–203, August, p. 395–412. [Also available at http://dx.doi.org/10.1016/j.lithos.2014.06.005.]

Elderfield, H., Whitfield, M., Burton, J.D., Bacon, M.P., and Liss, P.S., 1988, The oceanic chemistry of the rare-earth elements [and discussion]: Philosophical Transactions of the Royal Society A, v. 325, no. 1583, p. 105–126. [Also available at http://dx.doi.org/10.1098/rsta.1988.0046.]

European Commission, 2014, Critical raw materials for the EU—Report of the ad-hoc Working Group on defining critical raw materials: Brussels, Belgium, and Luxembourg, Luxembourg, European Commission, 41 p., accessed September 18, 2015, at http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical/index_en.htm.

Evans, J.R., 1964, Xenotime mineralization in the southern Music Valley area, Riverside County, California: Sacramento, Calif., California Division of Mines and Geology Special Report 79, 24 p.

Féménias, Oliver, Coussaert, Nicolas, Brassinnes, Stéphane, and Demaiffe, Daniel, 2005, Emplacement processes and cooling history of layered cyclic unit II-7 from the Lovozero alkaline massif (Kola Peninsula, Russia): Lithos, v. 83, nos. 3–4, p. 371–393. [Also available at http://dx.doi.org/10.1016/j.lithos.2005.03.012.]

Frontier Rare Earths Ltd., 2014, Projects: Frontier Rare Earths Ltd. Web page, accessed September 18, 2015, at http://www.frontierrareearths.com/projects/zandkopsdrift-rare-earths-project.

Galileo Resources PLC, 2015, Glenover rare earth project: Galileo Resources PLC Web page, accessed September 18, 2015, at http://www.galileoresources.net/projects.htm.

Gambogi, Joseph, 2015, Rare earths: U.S. Geological Survey Mineral Commodity Summaries 2015, p. 128–129. [Also available at https://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/mcs-2015-raree.pdf .]

Gambogi, Joseph, 2016, Rare earths [advance release], in Metals and minerals: U.S. Geological Survey Minerals Yearbook 2013, v. I, p. 60.1–60.17, accessed May 9, 2016, at https://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/myb1-2013-raree.pdf.

GBM Resources Ltd., 2012, GBM upgrades rare earth resource to over 110,000 tonnes as Milo grows to over a kilometre in length: GBM Resources Ltd. ASX announcement, August 9, accessed October 9, 2015, at http://www.gbmr.com.au/aurora/assets/user_content/Milo%20Resource%20Increased_9thAugust_2012.pdf.

GéoMégA Inc., 2015, Montviel (REE, Nb): GéoMégA Inc. Web page, accessed October 9, 2015, at http://ressourcesgeomega.ca/montviel_page/.

Gieré, Reto, 1996, Formation of rare earth minerals in hydrothermal systems, chap. 5 of Jones, A.P., Wall, Frances, and Williams, C.T., eds., Rare earth minerals—Chemistry, origin and ore deposits (1st ed.): London, Chapman & Hall, Mineralogical Society Series, v. 7, p. 106–150, 6 pls.

Global Times, 2013, China's rare earth industry sees progress, challenges: Global Times [Beijing, China], August 8, accessed June 11, 2015, at http://www.globaltimes.cn/content/802521.shtml.

Goldstein, S.J., and Jacobsen, S.B., 1988, Rare earth elements in river waters: Earth and Planetary Science Letters, v. 89, no. 1, p. 35–47. [Also available at http://dx.doi.org/10.1016/0012-821X(88)90031-3.]

Goonan, T.G., 2011, Rare earth elements—End use and recyclability: U.S. Geological Survey Scientific Investigations Report 2011–5094, 15 p. [Also available at http://pubs.usgs.gov/sir/2011/5094/.]

Government of India, Department of Atomic Energy, 2011, Lok Sabha unstarred question no. 300—Deposits of rare earths: Government of India, Department of Atomic Energy, 2 p., accessed September 18, 2015, at http://www.dae.nic.in/writereaddata/lsus300_231111.pdf.

Great Western Minerals Group Ltd., 2014, Steenkampskraal—Our low-cost, high-grade mining operation in South Africa: Great Western Minerals Group Ltd. Web page, accessed October 9, 2015, at http://www.gwmg.ca/mining-operations/overview.

Greenland Minerals and Energy Ltd., 2012, Ilimaussaq complex—Specialty metals (Kvanefjeld): Greenland Minerals and Energy Ltd. Web page, accessed October 9, 2015, at http://www.ggg.gl/projects/specialty-metals-kvanefjeld/.

Groves, D.I., Bierlein, F.P., Meinert, L.D., and Hitzman, M.W., 2010, Iron oxide copper-gold (IOCG) deposits through Earth history—Implications for origin, lithospheric setting, and distinction from other epigenetic iron oxide deposits: Economic Geology, v. 105, p. 641–654. [Also available at http://dx.doi.org/10.2113/gsecongeo.105.3.641.]

Haley, T.J., 1965, Pharmacology and toxicology of the rare earth elements: Journal of Pharmaceutical Sciences, v. 54, no. 5, p. 663–670. [Also available at http://dx.doi.org/10.1002/jps.2600540502.]

Hastings Rare Metals Ltd., 2015, Brockman project (100%) [Hastings project]: Hastings Rare Metals Ltd. Web page, accessed October 20, 2015, at http://hastingstechmetals.com/index.php/projects/brockman-project/.

Hatch, G.P., 2012a, Dynamics in the global market for rare earths: Elements, v. 8, no. 5, p. 341–346. [Also available at http://dx.doi.org/10.2113/gselements.8.5.341.]

Hatch, Gareth, 2012b, September 2012 updates to the TMR advanced rare-earth projects index: Technology Metals Research, October 12, accessed October 9, 2015, at http://www.techmetalsresearch.com/2012/10/september-2012-updates-to-the-tmr-advanced-rare-earth-projects-index/.

Hatch, Gareth, 2013, The first round of Chinese rare-earth export-quota allocations for 2014: Carpentersville, Ill., Technology Metals Research, LLC, December 13, accessed October 20, 2015, at http://www.techmetalsresearch.com/2013/12/the-first-round-of-chinese-rare-earth-export-quota-allocations-for-2014/.

Hatch, Gareth, 2014, The second round of Chinese rare-earth export-quota allocations for 2014: Carpentersville, Ill., Technology Metals Research, LLC, July 19, accessed October 20, 2015, at http://www.techmetalsresearch.com/2014/07/the-second-round-of-chinese-rare-earth-export-quota-allocations-for-2014/.

Hatch, Gareth, 2015, TMR advanced rare-earth projects index: Technology Metals Research Web page, accessed October 9, 2015, at http://www.techmetalsresearch.com/metrics-indices/tmr-advanced-rare-earth-projects-index/.

Henderson, Paul, 1984, General geochemical properties and abundances of the rare earth elements, chap. 1 of Henderson, Paul, ed., Rare earth element geochemistry: Amsterdam, Netherlands, Elsevier, Developments in Geochemistry series, v. 2, p. 1–32.

Honda Motor Co., Ltd., 2013, Honda established world's first process to reuse rare earth metals extracted from nickel-metal hydride batteries for hybrid vehicles: Tokyo, Japan, Honda Motor Co., Ltd. news release, March 3, accessed October 20, 2015, at http://world.honda.com/news/2013/c130303Reuse-Rare-Earth-Metals/print.html.

Hou, Zengqian, Tian, Shihong, Xie, Yuling, Yang, Zhusen, Yuan, Zhongxin, Yin, Shuping, Yi, Longsheng, Fei, Hongcai, Zou, Tianren, Bai, Ge, and Li, Xiaoyu, 2009, The Himalayan Mianning–Dechang REE belt associated with carbonatite-alkaline complexes, eastern Indo-Asian collision zone, SW China: Ore Geology Reviews, v. 36, nos. 1–3, p. 65–89. [Also available at http://dx.doi.org/10.1016/j.oregeorev.2009.03.001.]

Hudson Resources Inc., 2012, Hudson Resources reports updated mineral resource—Significant grade increases and indicated resources confirmed: Hudson Resources Inc. press release, April 26, 4 p., accessed October 9, 2015, at http://www.hudsonresources.ca/files/NR2012-02.pdf.

Hulse, D.E., Newton, M.C., III, and Malhotra, Deepak, 2014, Amended NI 43–101 preliminary economic assessment, Round Top project, Sierra Blanca, Texas, prepared for Texas Rare Earth Resources: Lakewood, Colo., Gustavson Associates LLC, April 28, 206 p., accessed October 9, 2015, at http://trer.com/_resources/reports/Amended_TRER_ NI43-101_PEA_FINAL_28April2014.pdf.

Indian Bureau of Mines, 2015, Rare earths, in Part III— Mineral reviews (53rd ed.) [advance release]: Nagpur, India, Indian Minerals Yearbook 2014, v. III, p. 43-1–4-9, accessed May 6, 2016, at http://ibm.nic.in/writereaddata/ files/12182015103018IMYB-2014_Rareearths(Adv).pdf.

Jackson, W.D., and Christiansen, Grey, 1993, International strategic minerals inventory summary report—Rare-earth oxides: U.S. Geological Survey Circular 930–N, 68 p. [Also available at http://pubs.usgs.gov/circ/1993/0930n/ report.pdf.]

Jones, A.P., Wall, Frances, and Williams, C.T., eds., 1996, Rare earth minerals—Chemistry, origin and ore deposits (1st ed.): London, United Kingdom, Chapman & Hall, Mineralogical Society series, v. 7, 372 p., 6 pls.

Kato, Yasuhiro, Fujinaga, Koichiro, Nakamura, Kentaro, Takaya, Yutaro, Kitamura, Kenichi, Ohta, Junichiro, Toda, Ryuichi, Nakashima, Takuya, and Iwamori, Hikaru, 2011, Deep-sea mud in the Pacific Ocean as a potential resource for rare-earth elements: Nature Geoscience, v. 4, no. 8, p. 535–539. [Also available at http://dx.doi.org/10.1038/ ngeo1185.]

Kogarko, L.N., Konova, V.A., Orlova, M.P., and Woolley, A.R., 1995, Alkaline rocks and carbonatites of the world—Part two—Former USSR: London, United Kingdom, Chapman & Hall, 226 p.

Kogarko, L.N., Williams, C.T., and Woolley, A.R., 2006, Compositional evolution and cryptic variation in pyroxenes of the peralkaline Lovozero intrusion, Kola Peninsula, Russia: Mineralogical Magazine, v. 70, no. 4, p. 347–359. [Also available at http://dx.doi.org/10.1180/0026461067040340.]

Kopera, J.J.C., 2004, Inside the nickel metal hydride battery: Cobasys LLC Web page, accessed October 9, 2015, at http://www.cobasys.com/pdf/tutorial/InsideNimhBattery/ inside_nimh_battery_technology.html.

Kynicky, Jindrich, Smith, M.P., and Xu, Cheng, 2012, Diversity of rare earth deposits—The key example of China: Elements, v. 8, no. 5, p. 361–367. [Also available at http://dx.doi.org/10.2113/gselements.8.5.361.]

Liang, Tao, Li, Kexin, and Wang, Lingqing, 2014, State of rare earth elements in different environmental components in mining areas of China: Environmental Monitoring and Assessment, v. 186, no. 3, p. 1499–1513. [Also available at http://dx.doi.org/10.1007/s10661-013-3469-8.]

Lide, D.R., ed., 2004, CRC handbook of chemistry and physics (85th ed.): Boca Raton, Fla., CRC Press, 2,712 p.

Long, K.R., 2011, The future of rare earth elements—Will these high-tech industry elements continue in short supply?: U.S. Geological Survey Open-File Report 2011–1189, 41 p. [Also available at http://pubs.usgs.gov/of/2011/1189/.]

Long, K.R., Van Gosen, B.S., Foley, N.K., and Cordier, Daniel, 2010, The principal rare earth elements deposits of the United States—A summary of domestic deposits and a global perspective: U.S. Geological Survey Scientific Investigations Report 2010–5220, 96 p. [Also available at http://pubs.usgs.gov/sir/2010/5220/.]

Lynas Corporation Ltd., 2012, Resource estimates: Lynas Corporation Ltd. Web page, accessed October 9, 2015, at http://www.lynascorp.com/Pages/rare-earths-project.aspx. (Web page no longer available as of October 20, 2015; updated resource estimate issued on October 5, 2015, at https://www.lynascorp.com/PublishingImages/ Pages/Mt-Weld-Resources-and-Reserves/ASX%20 Announcement%20-%20Ore%20Reserves%20and%20 Resources%20FINAL%20051015.pdf.)

MacDonald, D.D., Ingersoll, C.G., and Berger, T.A., 2000, Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems: Archives of Environmental Contamination and Toxicology, v. 39, no. 1, p. 20–31. [Also available at http://dx.doi.org/ 10.1007/s002440010075.]

Mariano, A.N., 1989, Economic geology of rare earth minerals, chap. 11 of Lipin, B.R., and McKay, G.A., eds., Geochemistry and mineralogy of rare earth elements: Washington, D.C., The Mineralogical Society of America Reviews in Mineralogy series, v. 21, p. 309–337.

Mariano, A.N., and Mariano, Anthony, Jr., 2012, Rare earth mining and exploration in North America: Elements, v. 8, no. 5, p. 369–376. [Also available at http://dx.doi.org/ 10.2113/gselements.8.5.369.]

MBAC Fertilizer Corp., 2012, MBAC reports robust preliminary economic assessment for Araxá rare earth oxide/niobium/phosphate deposit—MBAC Fertilizer Corp. press release, September 13 : MBAC Fertilizer Corp. Web page, accessed July 18, 2014, at http://mbacfert.com/news/ news-details/2012/MBAC-Reports-Robust-Preliminary- Economic-Assessment-For-Arax-Rare-Earth-Oxide- Niobium-Phosphate-Deposit-/default.aspx.

McKay, G.A., 1989, Partitioning of rare earth elements between major silicate minerals and basaltic melts, chap. 3 *of* Lipin, B.R., and McKay, G.A., eds., Geochemistry and mineralogy of rare earth elements: Washington, D.C., The Mineralogical Society of America Reviews in Mineralogy series, v. 21, p. 45–77.

McKeown, F.A., and Klemic, Harry, 1956, Rare-earth-bearing apatite at Mineville, Essex County, New York: U.S. Geological Survey Bulletin 1046–B, p. 9–23. [Also available at http://pubs.usgs.gov/bul/1046b/report.pdf.]

Ministry of Commerce, 2010a, 2010 second batch rare earth export quota: Beijing, China, Ministry of Commerce, July 7, 2 p.

Ministry of Commerce, 2010b, 2011 first batch rare earth export quota: Beijing, China, Ministry of Commerce, December 28, 2 p.

Mkango Resources Ltd., 2012, Mkango Resources Ltd.: Mkango Resources Ltd. Web page, accessed September 18, 2015, at http://www.mkango.ca/s/home.asp.

Moermond, C.T.A., Tijink, Jakolien, van Wezel, A.P., and Koelmans, A.A., 2001, Distribution, speciation, and bioavailability of lanthanides in the Rhine-Meuse estuary, the Netherlands: Environmental Toxicology and Chemistry, v. 20, no. 9, p. 1916–1926. [Also available at http://dx.doi.org/10.1002/etc.5620200909.]

Molycorp, Inc., 2012, Molycorp's rare earth reserves at Mountain Pass increase by 36%: Molycorp, Inc. press release, April 10, accessed July 18, 2014, at http://www.molycorp.com/molycorps-rare-earth-reserves-at-mountain-pass-increase-by-36/.

Molycorp, Inc., 2015, Molycorp innovations: Molycorp, Inc. Web page, accessed October 9, 2015, at http://www.molycorp.com/technology/molycorp-innovations.

Montero Mining & Exploration Ltd., 2011, Developing rare earth potential—Wigu Hill, Tanzania: Montero Mining & Exploration Ltd. Web page, accessed October 9, 2015, at http://www.monteromining.com/projects/wigu.html.

Namibia Rare Earths Inc., 2012, Namibia Rare Earths files technical report for initial mineral resource for area 4 of Lofdal project: Namibia Rare Earths Inc. press release, October 30, 8 p., accessed September 18, 2015, at http://www.namibiarareearths.com/upload/08.October_30_2012_NRE_Files_Technical_Report_for_Initial_Mineral_Resource_for_Area_4_of_Lofdal_Project.pdf.

National Research Council, 2008, Minerals, critical minerals, and the U.S. economy—Committee on Critical Mineral Impacts on the U.S. Economy, Committee on Earth Resources, Board on Earth Sciences and Resources, Division on Earth and Life Studies, National Research Council of the National Academies: Washington, D.C., National Academies Press, 245 p. [Also available at http://www.nap.edu/openbook.php?record_id=12034.]

Natural Earth, 2014, Small scale data: Natural Earth map dataset, scale 1:110,000,000, accessed October 9, 2015, at http://www.naturalearthdata.com.

Nuelle, L.M., Kisvarsanyi, E.B., Seeger, C.M., Day, W.C., and Sidder, G.B., 1991, Structural setting and control of the Pea Ridge magnetite deposit, Middle Proterozoic St. Francois terrane, Missouri [abs.]: Geological Society of America Abstracts with Programs, v. 23, no. 5, p. A292 (item no. 28986).

O'Driscoll, Michael, 2003, REgeneration in autocatalysts: Industrial Minerals, no. 424, p. 24–33.

Olson, J.C., Shawe, D.R., Pray, L.C., and Sharp, W.N., 1954, Rare-earth mineral deposits of the Mountain Pass district, San Bernardino County, California: U.S. Geological Survey Professional Paper 261, 75 p. [Also available at http://pubs.er.usgs.gov/publication/pp261.]

Pacific Wildcat Resources Corp., 2013, Mrima Hill project: Pacific Wildcat Resources Corp. Web page, accessed October 9, 2015, at http://www.pacificwildcat.com/mrimahill.html.

Pancontinental Uranium Corp., 2012, Charley Creek REE project scoping/preliminary economic assessment study moves ahead: Pancontinental Uranium Corp. press release, October 25, 3 p., accessed October 9, 2015, at http://www.panconu.com/files/docs_pressrelease/2012/NR Oct 25 12_v001_y151ci.pdf.

Papp, J.F., 2011, Niobium (columbium) and tantalum, *in* Metals and minerals: U.S. Geological Survey Minerals Yearbook 2009, v. I, p. 52.1–52.14, accessed January 13, 2016, at http://minerals.usgs.gov/minerals/pubs/commodity/niobium/myb1-2009-niobi.pdf.

Peak Resources Ltd., 2013, Ngualla rare earth project: Peak Resources Ltd. Web page, accessed October 9, 2015, at http://www.peakresources.com.au/irm/content/ngualla-rare-earth-project.aspx?RID=304.

Pele Mountain Resources, 2013, Eco Ridge Mine overview: Pele Mountain Resources Web page, accessed October 9, 2015, at http://www.pelemountain.com/overview.php.

Pittuck, M.F., Parsons, Benjamin, Ugorets, V.I., Larochelle, Eric, Dorval, Alain, Poeck, Joanna, Osborn, Jeff, Tinucci, John, Balasko, Clara, Willow, Mark, and Obie, Valerie, 2015, Amended NI 43–101 technical report—Updated preliminary economic assessment—Elk Creek niobium project—Nebraska—NI 43–101 technical report, prepared for NioCorp Developments Ltd. [Amended report date: October 16, 2015: Effective date: August 4, 2015]: Denver, Colo., SRK Consulting (U.S.), Inc. and Roche Ltd., Consulting Group, 331 p., accessed June 22, 2017, at http://www.niocorp.com/index.php/30-uncategorised/273-ni-43-101-technical-report-updated-preliminary-economic-assessment-elk-creek-niobium-project-nebraska.

Quest Rare Minerals Ltd., 2012, Strange Lake rare earth project: Quest Rare Minerals Ltd. Web page, accessed October 9, 2015, at http://www.questrareminerals.com/strange_lake.php.

Recycling International, 2011a, Fraunhofer's focus on rare earth metal recycling: Recycling International Web page, November 15, accessed June 9, 2016, at http://www.recyclinginternational.com/recycling-news/4026/research-and-legislation/germany/fraunhofer-s-focus-rare-earth-metal-recycling.

Recycling International, 2011b, Research into rare earths from electric motors: Recycling International Web page, December 9, accessed June 9, 2016, at http://www.recyclinginternational.com/recycling-news/5921/research-and-legislation/germany/research-rare-earths-electric-motors.

Recycling International, 2011c, Rhodia expands rare earth recycling reach: Recycling International Web page, October 12, accessed June 9, 2016, at http://www.recyclinginternational.com/recycling-news/3948/e-waste-and-batteries/france/rhodia-expands-rare-earth-recycling-reach.

Resnick Institute, 2011, Critical materials for sustainable energy applications: Pasadena, Calif., California Institute of Technology, Resnick Institute Report, 46 p. [Also available at http://resnick.caltech.edu/docs/R_Critical.pdf.]

Sanematsu, Kenzo, Murakami, Hiroyasu, Watanabe, Yasushi, Duangsurigna, Sixomxeun, and Vilayhack, Siphandone, 2009, Enrichment of rare earth elements (REE) in granitic rocks and their weathered crusts in central and southern Laos: Bulletin of the Geological Survey of Japan, v. 60, nos. 11–12, p. 527–558. [Also available at http://dx.doi.org/10.9795/bullgsj.60.527.]

Saucier, Guy, Roy, André, Casgrain, Pierre, Côté, Philippe, Thomassin, Yves, Bilodeau, Michel, Cannus, Yann, and Hayden, Alfred, 2012, NI 43–101 report, Preliminary economic assessment study for Kipawa project, NI 43–101 report, prepared for Matamec Explorations Inc. [Effective date January 30, 2012]: Quebec City, Quebec, Canada, Roche Ltd. Consulting-Group and SGS Canada, Inc., ref no. 061623.001 200, 229 p. [Also available at http://www.matamec.com/vns-site/uploads/documents/Rep_Matamec-Fin-PEA-000-20120314-SEDAR-Com.pdf.]

Seal, R.R., II, Hammarstrom, J.M., Johnson, A.N., Piatak, N.M., and Wandless, G.A., 2008, Environmental geochemistry of a Kuroko-type massive sulfide deposit at the abandoned Valzinco Mine, Virginia, USA: Applied Geochemistry, v. 23, no. 2, p. 320–342. [Also available at http://dx.doi.org/10.1016/j.apgeochem.2007.10.001.]

Seeger, C.M., Nuelle, L.M., Day, W.C., Sidder, G.B., Marikos, M.A., and Smith, D.C., 2001, Geologic maps and cross sections of mine levels at the Pea Ridge iron mine, Washington County, Missouri (version 1.0): U.S. Geological Survey Miscellaneous Field Studies Map 2353, 6 p. pamphlet, 5 sheets. [Also available at http://pubs.usgs.gov/mf/2001/mf-2353/.]

Shannon, R.D., 1976, Revised effective ionic radii and systematic studies of interatomic distances in halides and chalcogenides: Acta Crystallographica Section A—Foundations, v. 32, no. 5, p. 751–767. [Also available at http://dx.doi.org/10.1107/s0567739476001551.]

Shin-Etsu Chemical Co., Ltd., 2014, Shin-Etsu Chemical to construct a rare earth magnet manufacturing plant in Hai Phong Province in Vietnam: Tokyo, Japan, Shin-Etsu Chemical Co., Ltd. news release, April 21, accessed October 20, 2015, at http://www.shinetsu.co.jp/en/news/archive.php?id=365.

Sholkovitz, E.R., 1995, The aquatic chemistry of rare earth elements in rivers and estuaries: Aquatic Chemistry, v. 1, no. 1, p. 1–34. [Also available at http://dx.doi.org/10.1007/BF01025229.]

Showa Denko K.K., 2010, SDK subsidiary completes rare earth plant in Vietnam: Tokyo, Japan, Showa Denko K.K. news release, May 11, accessed October 20, 2015, at http://www.sdk.co.jp/english/news/2010/aanw_10_1242.html.

Sidder, G.B., Day, W.C., Nuelle, L.M., Seeger, C.M., and Kisvarsanyi, E.B., 1993, Mineralogic and fluid-inclusion studies of the Pea Ridge iron-rare-earth-element deposit, southeast Missouri, chap. U of Scott, R.W., Jr., Detra, P.S., and Berger, B.R., eds., Advances related to United States and international mineral resources—Developing frameworks and exploration technologies: U.S. Geological Survey Bulletin 2039, p. 205–216. [Also available at http://pubs.usgs.gov/bul/2039/report.pdf.]

Smith, D.S., Cannon, W.F., Woodruff, L.G., Solano, Federico, Kilburn, J.E., and Fey, D.L., 2013, Geochemical and mineralogical data for soils of the conterminous United States: U.S. Geological Survey Data Series 801, 19 p. [Also available at http://pubs.usgs.gov/ds/801/.]

Sneller, F.E.C., Kalf, D.F., Weltje, L., and Van Wezel, A.P., 2000, Maximum permissible concentrations and negligible concentrations for rare earth elements (REEs): Bilthoven, Netherlands, Rijksinstituut Voor Volksgezondheid En Milieu (National Institute of Public Health and the Environment), RIVM Report 601501–011, 66 p., accessed October 9, 2015, at http://rivm.openrepository.com/rivm/bitstream/10029/9551/1/601501011.pdf.

Srivastava, R.M., Gauthier, Jacques, Cox, J.J., and Krutzelmann, Holger, 2012, Technical report on the Foxtrot project in Labrador, Newfoundland & Labrador, Canada, NI 43–101 technical report, prepared for Search Minerals Inc.: Toronto, Ontario, Canada, Roscoe Postle Associates, June 15, accessed October 9, 2015, at http://www.searchminerals.ca/i/pdf/reports/RPA-Foxtrot-July2012.pdf.

Staatz, M.H., Hall, R.B., Macke, D.L., Armbrustmacher, T.J., and Brownfield, I.K., 1980, Thorium resources of selected regions in the United States: U.S. Geological Survey Circular 824, 32 p. [Also available at http://pubs.er.usgs.gov/publication/cir824.]

Stans Energy Corp., 2015, Kutessay II JORC results and REE percentages: Stans Energy Corp. Web page, accessed October 9, 2015, at http://www.stansenergy.com/projects/kutessay-ii/.

Star Minerals Group Ltd., 2014, Hoidas Lake: Star Minerals Group Ltd. Web page, accessed October 9, 2015, at http://www.starminerals.ca/s/Hoidas.asp.

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.]

Tantalus Rare Earths AG, 2013, Tantalus Rare Earths— TRE project: Tantalus Rare Earths AG Web page, accessed October 9, 2015, at http://www.tre-ag.com/operations/tre-project.aspx?sc_lang=en.

Tasman Metals Ltd., 2012, Norra Kärr rare element project: Tasman Metals Ltd. Web page, accessed October 9, 2015, at http://www.tasmanmetals.com/s/Norra-Karr.asp.

Tse, Pui-Kwan, 2011, China's rare-earth industry: U.S. Geological Survey Open-File Report 2011–1042, 11 p., accessed September 14, 2015, at http://pubs.usgs.gov/of/2011/1042/.

Tyler, G., 2004, Rare earth elements in soil and plant systems— A review: Plant and Soil, v. 267, nos. 1–2, p. 191–206. [Also available at http://dx.doi.org/10.1007/s11104-005-4888-2.]

Ucore Rare Metals Inc., 2015, Ucore increases resource at Bokan Dotson-Ridge: Ucore Rare Metals Inc. press release, May 11, accessed June 15, 2017, at http://ucore.com/ucore-increases-resource-at-bokan-dotson-ridge.

Umicore Group, 2011, Umicore and Rhodia develop unique rare earth recycling process for rechargeable batteries: Umicore Group press release CP–2–11–18–R, June 16, accessed October 19, 2015, at http://www.umicore.com/en/media/press/20110616REErecyclingEN/.

U.S. Bureau of Mines, 1961–96, Minerals yearbook 1960–94: U.S. Bureau of Mines, variously paginated. [Also available via http://minerals.usgs.gov/minerals/pubs/commodity/.]

U.S. Department of Energy, 2010, Critical materials strategy: Washington, D.C., U.S. Department of Energy, 166 p., accessed October 9, 2015, at http://energy.gov/sites/prod/files/piprod/documents/cms_dec_17_full_web.pdf.

U.S. Department of Energy, 2011, Critical materials strategy: Washington, D.C., U.S. Department of Energy, DOE/PI–0009, 191 p., accessed October 9, 2015, at http://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf.

U.S. Department of Energy, 2013, U.S. Dept. of Energy, Ames Laboratory mark new era in critical materials research with new Energy Innovation Hub: U.S. Department of Energy press release, September 10, accessed March 24, 2015, at https://www.ameslab.gov/node/8475.

U.S. Environmental Protection Agency, 2009, IRIS toxicological review of cerium oxide and cerium compounds (interagency science discussion draft): Washington, D.C., U.S. Environmental Protection Agency National Center for Environmental Assessment, Report EPA/635/R-08/002, accessed October 9, 2015, at http://cfpub.epa.gov/ncea/iris_drafts/recordisplay.cfm?deid=214572.

U.S. Environmental Protection Agency, 2015, Regional screening levels—Generic tables: U.S. Environmental Protection Agency Web page, accessed October 9, 2015, at http://www.epa.gov/region9/superfund/prg/index.html.

U.S. Geological Survey, 1996, Global 30 arc-second elevation (GTOPO30): Reston, Va., U.S. Geological Survey dataset (digital elevation model), accessed October 9, 2015, 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.]

Verplanck, P.L., Nordstrom, D.K., Taylor, H.E., and Kimball, B.A., 2004, Rare earth element partitioning between hydrous ferric oxides and acid mine water during iron oxidation: Applied Geochemistry, v. 19, no. 8, p. 1339–1354. [Also available at http://dx.doi.org/10.1016/j.apgeochem.2004.01.016.]

Verplanck, P.L., Van Gosen, B.S., Seal, R.R., and McCafferty, A.E., 2014, A deposit model for carbonatite and peralkaline intrusion-related rare earth element deposits: U.S. Geological Survey Scientific Investigations Report 2010–5070–J, 58 p. [Also available at http://pubs.er.usgs.gov/publication/sir20105070J.]

Vierrether, C.W., and Cornell, W.L., 1993, Rare-earth occurrences in the Pea Ridge tailings: U.S. Bureau of Mines Report of Investigations, RI 9453, 10 p. [Also available at http://stacks.cdc.gov/ObjectView?pid=cdc:10215&dsid=DS1&mimeType=application/pdf.]

Wagh, A.S., and Pinnock, W.R., 1987, Occurrence of scandium and rare earth elements in Jamaican bauxite waste: Economic Geology, v. 82, p. 757–761. [Also available at http://dx.doi.org/10.2113/gsecongeo.82.3.757.]

Weltje, L., Verhoof, L.R.C.W., Verweij, W., and Hamers, T., 2004, Lutetium speciation and toxicity in a microbial bioassay—Testing the free-ion model for lanthanides: Environmental Science and Technology, v. 38, no. 24, p. 6597–6604. [Also available at http://dx.doi.org/10.1021/es049916m.]

Williams-Jones, A.E., Migdisov, A.A., and Samson, I.M., 2012, Hydrothermal mobilisation of the rare earth elements—A tale of "Ceria" and "Yttria": Elements, v. 8, no. 5, p. 355–360. [Also available at http://dx.doi.org/10.2113/gselements.8.5.355.]

Wood, S.A., 1990, The aqueous geochemistry of the rare-earth elements and yttrium—1. Review of available low-temperature data for inorganic complexes and the inorganic REE speciation of natural waters: Chemical Geology, v. 82, nos. 1–2, p. 159–186. [Also available at http://dx.doi.org/10.1016/0009-2541(90)90080-Q.]

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., 2001, Alkaline rocks and carbonatites of the world—Part 3—Africa: London, United Kingdom, Geological Society of London, 372 p.

Woolley, A.R., and Kjarsgaard, B.A., 2008, Carbonatite occurrences of the world—Map and database: Geological Survey of Canada Open-File Report 5796, 28 p., 1 CD–ROM, plus 1 map, scale approx. 1:19,000,000. [Also available at http://dx.doi.org/10.4095/225115.]

Wyllie, P.J., Jones, A.P., and Deng, Jinfu, 1996, Rare earth elements in carbonate-rich melts from mantle to crust, chap. 4 of Jones, A.P., Wall, Frances, and Williams, C.T., eds., Rare earth minerals—Chemistry, origin and ore deposits (1st ed.): London, United Kingdom, Chapman & Hall, Mineralogical Society series, v. 7, p. 77–103, 6 pls.

Xie, Yuling, Hou, Zengqian, Yin, Shuping, Dominy, S.C., Xu, Jiuhua, Tian, Shihong, and Xu, Wenyi, 2009, Continuous carbonatitic melt-fluid evolution of a REE mineralization system—Evidence from inclusions in the Maoniuping REE deposit, western Sichuan, China: Ore Geology Reviews, v. 36, nos. 1–3, p. 90–105. [Also available at http://dx.doi.org/10.1016/j.oregeorev.2008.10.006.]

Xu, Anshun, 1996, Mineralogy, petrology, geochemistry and origin of the Elk Creek carbonatite, Nebraska: Lincoln, Neb., University of Nebraska, Ph.D. dissertation, paper AAI9628256, 299 p. [Also available at http://digitalcommons.unl.edu/dissertations/AAI9628256.]

Xu, Cheng, Campbell, I.H., Kynicky, Jindrich, Allen, C.M., Chen, Yanjing, Huang, Zhilong, and Qi, Liang, 2008, Comparison of the Daluxiang and Maoniuping carbonatitic REE deposits with Bayan Obo REE deposit, China: Lithos, v. 106, nos. 1–2, p. 12–24. [Also available at http://dx.doi.org/10.1016/j.lithos.2008.06.005.]

Xu, Cheng, Wang, Linjun, Song, Wenlei, and Wu, Min, 2010, Carbonatites in China—A review for genesis and mineralization: Geoscience Frontiers, v. 1, no. 1, p. 105–114. [Also available at http://dx.doi.org/10.1016/j.gsf.2010.09.001.]

Yang, Kui-feng, Fan, Hong-rui, Hu, Fang-fang, and Wang, Kai-yi, 2010, Intrusion sequence of carbonatite dykes and REE enrichment mechanism in Bayan Obo district, Inner Mongolia: Acta Petrologica Sinica, v. 26, no. 5, p. 1523–1529. [Also available at http://caod.oriprobe.com/articles/26385499/Intrusion_sequence_of_carbonatite_dykes_and_REE_accumulation_mechanism.htm.]

Yang, Kui-Feng, Fan, Hong-Rui, Santosh, M., Hu, Fan-Fang, and Wang, Kai-Yi, 2011, Mesoproterozoic carbonatitic magmatism in the Bayan Obo deposit, Inner Mongolia, north China—Constraints for the mechanism of super accumulation of rare earth elements: Ore Geology Reviews, v. 40, no. 1, p. 122–131. [Also available at http://dx.doi.org/10.1016/j.oregeorev.2011.05.008.]

Yang, Zhuming, and Woolley, Alan, 2006, Carbonatites in China—A review: Journal of Asian Earth Sciences, v. 27, no. 5, p. 559–575. [Also available at http://dx.doi.org/10.1016/j.jseaes.2005.06.009.]

Yap, Chuin-Wei, 2015, China ends rare-earth minerals export quotas: The Wall Street Journal, January 5, accessed October 20, 2015, at http://www.wsj.com/articles/china-ends-rare-earth-minerals-export-quotas-1420441285.

Yuan, Zhongxin, Bai, Ge, Wu, Chenyu, Zhang, Zhongqin, and Ye, Xianjiang, 1992, Geological features and genesis of the Bayan Obo REE ore deposit, Inner Mongolia, China: Applied Geochemistry, v. 7, no. 5, p. 429–442. [Also available at http://dx.doi.org/10.1016/0883-2927(92)90004-M.]

Zaitsev, V., and Kogarko, L., 2012, Sources and perspectives of REE in the Lovozero massif (Kola Peninsula, Russia): European Mineralogical Conference 2012, v. 1, paper EMC2012-290, accessed October 9, 2015, at http://meetingorganizer.copernicus.org/EMC2012/EMC2012-290.pdf.

Van Gosen and others—**Critical Mineral Resources of the United States—Rare-Earth Elements**—Professional Paper 1802–O