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

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Foreword

From the Stone Age to the present, mineral commodities have been essential ingredients for building and advancing civilization. Products built with materials derived from mineral resources include homes and office buildings; cars and roads; computers, televisions, and smart phones; and jet fighters and other military hardware needed to defend the Nation. In short, minerals are essential to advance and protect modern society.

When the periodic table of elements was first established in the latter half of the 19th century, many of the elements were known to exist in nature, but relatively few were being used by society. Today, discovery of new uses for an increasing number of elements is enabling rapid innovations in technology and materials science. Advances in telecommunications, information technology, health care, energy production, and national defense systems have all been possible through the use of new mineral materials.

As the importance and dependence of specific mineral commodities increase, so does concern about their supply. The United States is currently 100 percent reliant on foreign sources for 20 mineral commodities and imports the majority of its supply of more than 50 mineral commodities. Mineral commodities that have important uses and face potential supply disruption are critical to American economic and national security. However, a mineral commodity's importance and the nature of its supply chain can change with time; a mineral commodity that may not have been considered critical 25 years ago may be critical today, and one considered critical today may not be so in the future.

The U.S. Geological Survey has produced this volume to describe a select group of mineral commodities currently critical to our economy and security. For each mineral commodity covered, the authors provide a comprehensive look at (1) the commodity's use; (2) the geology and global distribution of the mineral deposit types that account for the present and possible future supply of the commodity; (3) the current status of production, reserves, and resources in the United States and globally; and (4) environmental considerations related to the commodity's production from different types of mineral deposits. The volume describes U.S. critical mineral resources in a global context, for no country can be self-sufficient for all its mineral commodity needs, and the United States will always rely on global mineral commodity supply chains. This volume provides the scientific understanding of critical mineral resources required for informed decisionmaking by those responsible for ensuring that the United States has a secure and sustainable supply of mineral commodities.

The Nation was largely built on the products produced from its mineral deposits. The future will also be built on a foundation of minerals, many of which will continue to be discovered and produced from across the country.

Ryan K. Zinke
Secretary of the Interior

Preface

Mineral commodities are vital for economic growth, improving the quality of life, providing for national defense, and the overall functioning of modern society. Minerals are being used in larger quantities than ever before and in an increasingly diverse range of applications—from telecommunications (cell phones and computers), to renewable-energy generation (wind turbines, solar photovoltaics, and fuel cells), to clean forms of transportation (electric and hybrid cars). Until the mid-20th century, only about 15 metallic elements had much practical use. Today, nearly all the natural elements in the periodic table of elements have several significant uses. For example, the manufacture of a modern computer chip requires more than one-half of the elements in the periodic table. Even though many of the elements may be present in only small amounts, each is essential to the function and performance of the chip.

With the increasing demand for a considerably more diverse suite of mineral commodities has come renewed recognition that competition and conflict over mineral resources can pose significant risks to the manufacturing industries that depend on them. In addition, although mineral deposits may occur in many places around the world, production of many mineral commodities has become concentrated in relatively few countries (for example, tungsten, rare-earth elements, and antimony in China; niobium in Brazil; and platinum-group elements in South Africa and Russia), thus increasing the risk for supply disruption owing to political, social, or other factors. At the same time, an increasing awareness and sensitivity to potential environmental and health issues caused by the mining and processing of many mineral commodities may place additional restrictions on mineral supplies. These factors have led a number of Governments, including the Government of the United States, to attempt to identify those mineral commodities that are viewed as most "critical" to the national economy and (or) security if supplies should be curtailed. The lists of critical minerals compiled by Governments and other organizations vary in the number and individual rankings of mineral commodities included on them, but many of the lists include several of the same commodities. Rare-earth elements and platinum-group elements particularly are broadly viewed as critical.

This book presents resource and geologic information on the following 23 mineral commodities currently among those viewed as important to the national economy and national security of the United States: antimony (Sb), barite (barium, Ba), beryllium (Be), cobalt (Co), fluorite or fluorspar (fluorine, F), gallium (Ga), germanium (Ge), graphite (carbon, C), hafnium (Hf), indium (In), lithium (Li), manganese (Mn), niobium (Nb), platinum-group elements (PGE), rare-earth elements (REE), rhenium (Re), selenium (Se), tantalum (Ta), tellurium (Te), tin (Sn), titanium (Ti), vanadium (V), and zirconium (Zr). For a number of these commodities–for example, graphite, manganese, niobium, and tantalum—the United States is currently wholly dependent on imports to meet its needs.

The first two chapters deal with general information pertinent to the study of mineral resources. The introductory chapter (A) discusses the purposes of the volume, the distinctions between reserves and various categories of resources, and issues related to the classification of mineral resource "criticality." The second chapter (B) provides an overview of some of the environmental considerations related to the mining of nonfuel mineral resources, including the modern regulatory framework and development of geoenvironmental mineral-deposit models.

Chapters C through V describe individual mineral commodities and include an overview of current uses of the commodity, identified resources and their distribution nationally and globally, the state of current geologic knowledge, the potential for finding additional deposits nationally and globally, and geoenvironmental issues that may be related to the production and uses of the commodity. These chapters are updates of the commodity chapters published in 1973 in U.S. Geological Survey Professional Paper 820, "United States Mineral Resources." In 1973, many of these commodities were only of minor importance, and resource and geologic information was often very limited and incomplete. In addition, little was generally known about geoenvironmental issues related to their production and use.

We would like to thank our colleagues for their contributions to and cooperation in all phases of the preparation of this book. The descriptions of geology, the origin of mineral deposits, and geoenvironmental chemistry in each chapter necessarily involve some scientific jargon, but much of the discussion is cast in less-technical language. Our hope is that the information provided will be of use to scientists and nonscientists alike.

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Dwight C. Bradley

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Conversion Factors

International System of Units to Inch/Pound

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

International System of Units to Inch/Pound—Continued

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

Inch/Pound to International System of Units

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

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

$$°F = (1.8 \times °C) + 32$$

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

$$K = °C + 273.15$$

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

$$°C = (°F - 32) / 1.8$$

Datum

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

Supplemental Information

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

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

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

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

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

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

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

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

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

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

Equivalencies

part per million (ppm): 1 ppm = 1,000 ppb = 1,000,000 ppt = 0.0001 percent
part per billion (ppb): 0.001 ppm = 1 ppb = 1,000 ppt = 0.0000001 percent
part per trillion (ppt): 0.000001 ppm = 0.001 ppb = 1 ppt = 0.0000000001 percent

Metric system prefixes

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

Abbreviations and Symbols

[This list is intended to help the reader identify the meanings of various abbreviations and symbols used in the text. To avoid unnecessary duplication, not all abbreviations and symbols are included. For example, symbols that are used in only a single table and that are identified in that table's headnote are not included here. Likewise, mineral names and their chemical formulas are not listed here]

α-tin	alpha-tin (also known as gray tin)
ß-tin	beta-tin (also known as white tin)
°C	degree Celsius
δ-MnO_2	delta-manganese dioxide
µCi/mL	microcurie per milliliter
µg Al/L	microgram of aluminum per liter
µg/d	microgram per day
µg/g	microgram per gram
µg/kg	microgram per kilogram
µg/L	microgram per liter
µg/m^3	microgram per cubic meter
µg Mn/L	microgram of manganese per liter
µg Mn/m^3	microgram of manganese per cubic meter
µg V/L	microgram of vanadium per liter
µm	micrometer
3TG	tantalum, tin, tungsten, and (or) gold
Å	angstrom
AC	alternating current
ADTI	Acid Drainage Technology Initiative
AFRG	alkali-feldspar rhyolite-granite
AIDS	acquired immunodeficiency syndrome
AMD	acid mine drainage
AMT	audio magnetotelluric
API	American Petroleum Institute
APS	American Physical Society
ATPC	Association of Tin Producing Countries
ATSDR	Agency for Toxic Substances and Disease Registry
BCMA	beryllium-copper master alloy
Bq/kg	becquerel per kilogram
ca.	circa (about)
CBMM	Companhia Brasileira de Metalurgia e Mineração
CCD	carbonate compensation depth
CCZ	Clarion-Clipperton zone
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act

CIGS	copper-indium-gallium-selenide
cm	centimeter
cm^3	cubic centimeter
CMI	Critical Minerals Index
Congo (Kinshasa)	Democratic Republic of the Congo
CPV	concentrator photovoltaic
CRD	carbonate replacement deposit
DC	direct current
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EA	environmental assessment
EC_{50}	effective concentration 50 (concentration that results in 50 percent exhibiting decreased functionality)
EEZ	Exclusive Economic Zone
Eh	oxidation potential
EIS	environmental impact statement
EMPA	electron microprobe analysis
EPA	U.S. Environmental Protection Agency
FCC	fluid catalytic cracking
FONSI	finding of no significant impact
ft	foot
g	gram
g CO_2-equiv/kWh	gram of CO_2 equivalent per kilowatthour
g/cm^3	gram per cubic centimeter
g/d	gram per day
g/L	gram per liter
g/t	gram per metric ton
Ga	giga-annum
GARD	Global Acid Rock Drainage
GWh	gigawatt-hour
HDC	Hicks Dome Corp.
HFSE	high-field-strength element
HIV	human immunodeficiency virus
HMIS	Hazardous Materials Identification System
HREE	heavy rare-earth element
HSLA	high-strength, low-alloy
IARC	International Agency for Research on Cancer
ICP–MS	inductively coupled plasma-mass spectrometry
IED	improvised explosive device

IMA	International Mineralogical Association
INAP	International Network for Acid Prevention
IOCG	iron oxide-copper-gold
IREL	Indian Rare Earths Ltd.
ISA	International Seabed Authority
ISMI	International Strategic Minerals Inventory
ITO	indium-tin oxide
JORC	Joint Ore Reserves Committee (Australia)
kBq/kg	kilobecquerel per kilogram
kg	kilogram
kg $CaCO_3$ / t	kilogram of calcium carbonate per metric ton
kg/cm^2	kilogram per square centimeter
kg/m^3	kilogram per cubic meter
kg/t	kilogram per metric ton
km	kilometer
km^2	square kilometer
km^3	cubic kilometer
KMML	Kerala Minerals and Metals Ltd.
lb	pound
LC_{50}	lethal concentration 50 (concentration that kills 50 percent of test population within a given timeframe)
LCT	lithium-cesium-tantalum
LED	light-emitting diode
LIP	large igneous province
LOEL	lowest observable effect limit
$_{\log}fO_2$	log of oxygen fugacity
LREE	light rare-earth element
m	meter
M	molarity
m.y.	million years
m^3	cubic meter
Ma	mega-annum
MC–ICP–MS	multiple collector-inductively coupled plasma-mass spectrometry
MDEQ	Michigan Department of Environmental Quality
MEND	Mine Environment Neutral Drainage
mg	milligram
mg Al/kg	milligram of aluminum per kilogram
mg/d	milligram per day
mg/kg	milligram per kilogram

mg/L	milligram per liter
mg/m^3	milligram per cubic meter
Mkg/yr	million kilograms per year
mm	millimeter
MOFCOM	Ministry of Commerce (China)
MRDS	Mineral Resources Data System (USGS)
MRI	magnetic resonance imaging
MRS	Materials Research Society
MSS	monosulfide solution
MTR	Maderia-Tore Rise
MVT	Mississippi Valley-type
NEPA	National Environmental Policy Act
NFPA	National Fire Protection Association
ng/L	nanogram per liter
ng/m^3	nanogram per cubic meter
NI	National Instrument
NiMH	nickel-metal-hydride
NIOSH	National Institute for Occupational Safety and Health
nm	nanometer
NMRI	nuclear magnetic resonance instruments
NPL	National Priorities List (Superfund)
NREL	National Renewable Energy Laboratory
NSTC	National Science and Technology Council
NTP	National Toxicology Program
NYF	niobium-yttrium-fluorine
OPEC	Organization of the Petroleum Exporting Countries
org-Se(-II)	organo-selenide
OSHA	Occupational Safety and Health Administration
PEM	proton exchange membrane
PET	polyethylene terephthalate
pg/L	picogram per liter
pg/m^3	picogram per cubic meter
PGE	platinum-group element
PGM	platinum-group metal
pm	picometer
ppb	part per billion
ppm	part per million
ppt	part per trillion

QSP	quartz-sericite-pyrite
RDA	recommended daily allowance
REE	rare-earth element
REO	rare-earth oxide
RF	radio-frequency
SAF	submerged-arc furnace
SAMREC	South African Code for Reporting Exploration Results
Se(II)	selenide
Se(IV)	selenite
Se(VI)	selenate
SEC	U.S. Securities and Exchange Commission
SEDEX	sedimentary exhalative
SG	specific gravity
SHRIMP	sensitive high-resolution ion microprobe
SSV	sandstone-hosted vanadium
SX–EW	solvent extraction-electrowinning
TBT	tributyltin
TBTCl	tributyltin chloride
TBTO	bis(tri-*n*-butyltin) oxide
Te(II)	telluride
Te(IV)	tellurite
Te(VI)	tellurate
TPT	triphenyltin
TRE	Tantalus Rare Earths
TREO	total rare-earth oxide
TWA	time-weighted average
U.S.C.	U.S. Code
USGS	U.S. Geological Survey
UST	unidirectional solidification texture
VLF	very low frequency
VMS	volcanogenic massive sulfide
VRB	vanadium redox-flow battery
VTM	vanadiferous titanomagnetite
WGS 84	World Geodetic System of 1984
WHO	World Health Organization
wt. %	weight percent