

# **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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## Contents

<b>Foreword</b> .....	iii
<b>Preface</b> .....	v
<b>Chapter A. Critical Mineral Resources of the United States—An Introduction</b> By Klaus J. Schulz, John H. DeYoung, Jr., Dwight C. Bradley, and Robert R. Seal II.....	A1
<b>Chapter B. Environmental Considerations Related to Mining of Nonfuel Minerals</b> By Robert R. Seal II, Nadine M. Piatak, Bryn E. Kimball, and Jane M. Hammarstrom .....	B1
<b>Chapter C. Antimony</b> By Robert R. Seal II, Klaus J. Schulz, and John H. DeYoung, Jr. With contributions from David M. Sutphin, Lawrence J. Drew, James F. Carlin, Jr., and Byron R. Berger .....	C1
<b>Chapter D. Barite (Barium)</b> By Craig A. Johnson, Nadine M. Piatak, and M. Michael Miller .....	D1
<b>Chapter E. Beryllium</b> By Nora K. Foley, Brian W. Jaskula, Nadine M. Piatak, and Ruth F. Schulte .....	E1
<b>Chapter F. Cobalt</b> By John F. Slack, Bryn E. Kimball, and Kim B. Shedd.....	F1
<b>Chapter G. Fluorine</b> By Timothy S. Hayes, M. Michael Miller, Greta J. Orris, and Nadine M. Piatak.....	G1
<b>Chapter H. Gallium</b> By Nora K. Foley, Brian W. Jaskula, Bryn E. Kimball, and Ruth F. Schulte .....	H1
<b>Chapter I. Germanium and Indium</b> By W.C. Pat Shanks III, Bryn E. Kimball, Amy C. Tolcin, and David E. Guberman.....	I1
<b>Chapter J. Graphite</b> By Gilpin R. Robinson, Jr., Jane M. Hammarstrom, and Donald W. Olson .....	J1
<b>Chapter K. Lithium</b> By Dwight C. Bradley, Lisa L. Stillings, Brian W. Jaskula, LeeAnn Munk, and Andrew D. McCauley.....	K1
<b>Chapter L. Manganese</b> By William F. Cannon, Bryn E. Kimball, and Lisa A. Corathers .....	L1
<b>Chapter M. Niobium and Tantalum</b> By Klaus J. Schulz, Nadine M. Piatak, and John F. Papp .....	M1
<b>Chapter N. Platinum-Group Elements</b> By Michael L. Zientek, Patricia J. Loferski, Heather L. Parks, Ruth F. Schulte, and Robert R. Seal II .....	N1
<b>Chapter O. Rare-Earth Elements</b> By Bradley S. Van Gosen, Philip L. Verplanck, Robert R. Seal II, Keith R. Long, and Joseph Gambogi.....	O1
<b>Chapter P. Rhenium</b> By David A. John, Robert R. Seal II, and Désirée E. Polyak.....	P1
<b>Chapter Q. Selenium</b> By Lisa L. Stillings.....	Q1

<b>Chapter R. Tellurium</b>	
By Richard J. Goldfarb, Byron R. Berger, Micheal W. George, and Robert R. Seal II.....	R1
<b>Chapter S. Tin</b>	
By Robert J. Kamilli, Bryn E. Kimball, and James F. Carlin, Jr. ....	S1
<b>Chapter T. Titanium</b>	
By Laurel G. Woodruff, George M. Bedinger, and Nadine M. Piatak.....	T1
<b>Chapter U. Vanadium</b>	
By Karen D. Kelley, Clinton T. Scott, Désirée E. Polyak, and Bryn E. Kimball.....	U1
<b>Chapter V. Zirconium and Hafnium</b>	
By James V. Jones III, Nadine M. Piatak, and George M. Bedinger.....	V1

## Figures

A1. Diagram showing increases in the use of elements over two decades of computer chip technology development.....	A3
A2. Diagram showing the mineral resource classification system used in this volume.....	A5
B1. Graph showing population growth and the change in supporting land area from 3500 B.C. to 2100 A.D., with projections to 2050.....	B3
B2. Graph showing dates associated with all the mine sites on the U.S. Environmental Protection Agency's National Priorities List.....	B10
C1. World map showing locations of selected antimony deposits, mines, and major occurrences.....	C2
C2. Pie chart showing major end uses of antimony as a percentage of antimony consumption in the United States in 2012.....	C3
C3. Graph showing world production, U.S. apparent consumption, and U.S. mine production of antimony from 1900 to 2012.....	C4
C4. Pie charts showing percentages of contained antimony in U.S. imports for the period 2008–11, by source country.....	C5
D1. Graph showing barite world production, U.S. production, and U.S. consumption from 1950 to 2011.....	D2
D2. World map showing locations of selected barite deposits and districts, color-coded by deposit type.....	D4
D3. Pie chart showing average annual barite production for the period 2007–11, by country and amount in thousand metric tons.....	D7
E1. World map showing locations of selected deposits of beryllium by the two major beryllium-bearing mineral types.....	E2
E2. Photographs showing the minerals bertrandite, which can contain up to 42 percent beryllium oxide, and industrial beryl, which can contain up to about 5 percent beryllium.....	E3
E3. Photographs illustrating some of the many uses of beryllium.....	E4
E4. Pie charts showing reported end uses of beryllium consumed in the United States in 2011 for the two main classes of products—performance alloys, and beryllium and composites.....	E6
E5. A generalized cross section showing the geologic setting of and some example deposits for the major types of beryllium resources associated with rare-metal magma systems.....	E12



E6.	Location map and simplified geologic map of the Hellroaring Creek prospect, which is located west of Kimberley, British Columbia, Canada.....	E13
E7.	Generalized geologic cross section showing the setting of volcanogenic beryllium deposits and related deposit types, geologic map of Spor Mountain area in Utah, photograph of beryllium tuff at Spor Mountain, and photograph of nodule from the Spor Mountain tuff.....	E15
E8.	Graph showing general estimates of grade and tonnage for a variety of beryllium deposits, districts, and belts.....	E17
E9.	Graph showing estimated global production of beryllium for 2000–11 .....	E18
F1.	Pie chart showing major end uses of cobalt as a percentage of consumption worldwide in 2011 .....	F2
F2.	Graph showing world cobalt mine and refinery production and apparent consumption from 2007 to 2011 .....	F2
F3.	Graph showing world cobalt mine production from 1950 to 2011 .....	F3
F4.	Pie chart showing percentage of world cobalt mine production in 2011, by country .....	F3
F5.	Pie chart showing percentage of world cobalt mine production in 2011, by deposit type.....	F10
F6.	Grade-tonnage plot for 214 cobalt deposits worldwide .....	F11
F7.	World map showing global distribution of major cobalt-bearing mineral deposits and selected smaller deposits that represent minor types.....	F12
F8.	Pie charts showing proportions of cobalt contained in mineral deposits worldwide, by deposit type .....	F13
G1.	Photograph of a fluorite specimen from the Number 1 (Minerva) Mine, Cave-in-Rock subdistrict, Illinois-Kentucky fluorspar district .....	G3
G2.	Graph showing the solubility of fluorite as a function of temperature for complex Na-Ca-Mg-Cl brines from ambient temperatures to 260 °C.....	G10
G3.	Chart showing eight minerals or mineral groups from which fluorine has been produced or may be produced in the future and a preliminary classification of hydrothermal fluorspar deposits by tectonic and magmatic association.....	G11
G4.	World map showing locations of selected fluorspar deposits according to their tectonic and magmatic class as listed in figure G3B .....	G14
G5.	Map showing the locations of deposits in the Cantabrian salt-related carbonate-hosted mineral district in north-central Spain.....	G19
G6.	Plot of fluorite grade versus tonnage for fluorspar deposits related to strongly differentiated granites, for carbonatite-related fluorspar deposits, and for veins from all classes of fluorspar deposits.....	G24
G7.	Graph showing sources of U.S. fluorspar supply from 1970 to 2011 .....	G29
H1.	Photograph of gallium metal with an inset showing its position on the periodic table of elements .....	H1
H2.	Photographs showing examples of some current uses for gallium.....	H3
H3.	Charts showing U.S. and world gallium production and consumption from 2007 to 2012.....	H4
H4.	World map showing locations of selected mineral deposits, by type; gallium has been produced from these types of deposits.....	H5
H5.	Cross sections showing the general geologic environments for the types of mineral deposits with which gallium is most commonly associated and from which gallium is typically extracted .....	H6

H6.	Plot of the ratio of aluminum to gallium versus gallium content for bauxite deposits, volcanic rocks, and hydrothermally altered rocks of the McDermitt caldera, Nevada .....	H12
H7.	Photographs showing samples of bauxite ore and sphalerite ore, which are the primary mineralogical sources of gallium .....	H14
I1.	Photograph of a concentrator photovoltaic solar power system .....	I3
I2.	Pie charts showing major end uses of germanium and indium as a percentage of world consumption in 2012 .....	I3
I3.	Photographs showing indium-tin oxide, which is a transparent conducting oxide, and examples of flat-panel display screens and touchscreens .....	I4
I4.	Map and schematic cross section showing the geology of the Red Dog mining district in Alaska and the stratigraphy of selected deposits in the district .....	I7
I5.	Map showing the locations and geologic settings of selected volcanogenic massive sulfide, sedimentary exhalative, Mississippi Valley-type, and coal deposits and other types of deposits in southern China .....	I9
I6.	Map showing the location of Kipushi-type deposits (including the Kabwe deposits) and major Neoproterozoic orogenic belts and basins in the Precambrian tectonic framework of southern Africa .....	I10
I7.	Map showing indium-bearing tin-polymetallic ore deposits in Bolivia .....	I12
I8.	Graph showing worldwide production of germanium and indium from 1995 to 2012 .....	I14
J1.	Diagram showing the arrangement of carbon atoms in graphite .....	J6
J2.	World map showing locations of major graphite deposits and districts in the world, by commodity type .....	J14
J3.	Plot of grade and tonnage for some of the amorphous and crystalline graphite deposits listed in table J3, by deposit type .....	J16
J4.	Pie chart showing average annual natural graphite production for the period 2006–10, by country or region and amount .....	J17
K1.	Graph showing world lithium production from 1900 to 2007, by deposit type and year .....	K1
K2.	Pie chart showing major end uses of lithium as a percentage of world consumption in 2013 .....	K2
K3.	Photographs showing some sources and uses of lithium .....	K3
K4.	World map showing locations of selected lithium-cesium-tantalum pegmatites and lithium granites .....	K6
K5.	World map showing locations of selected closed-basin lithium-brine, lithium-enriched oilfield brine, geothermal brine, lithium-clay, and lithium-zeolite deposits .....	K7
K6.	Histograms showing the broad correspondence in the age distributions of lithium-cesium-tantalum pegmatites, detrital zircons from modern river sands, and lithium resources in pegmatites .....	K9
K7.	Schematic cross section showing the concentric arrangement of lithium-cesium-tantalum pegmatites around a parental granite pluton .....	K10
K8.	Conceptual ore-deposit model for lithium brine .....	K11
K9.	Plots of lithium grade and tonnage for selected world deposits .....	K13
L1.	Charts showing world production, apparent consumption, and distribution of production of manganese ore from 2007 to 2011 .....	L3

L2.	Pie charts showing the sources and the annual average amounts of gross weight of U.S. imports of manganese ore, ferromanganese, and silicomanganese for the period 2008–11 .....	L3
L3.	World map showing the location, relative size, and type of the major terrestrial manganese deposits listed in table L2 as well as subeconomic deposits in the United States .....	L7
L4.	Photographs showing examples of contrasting types of manganese ore .....	L8
L5.	Schematic diagram of the oceanic conditions necessary to form sedimentary manganese deposits that are not enriched in iron .....	L8
L6.	Photograph showing a dense carpet of ferromanganese nodules on the seabed off Johnston Island within the United States Exclusive Economic Zone near Hawaii.....	L10
L7.	Photograph showing ferromanganese crust on carbonate rock from the Blake Plateau off the southeastern coast of the United States.....	L11
L8.	Photograph of the Mamatwan open pit mine in South Africa .....	L13
L9.	Graphs showing the cumulative frequency of tonnages and grades of 39 marine sedimentary manganese deposits .....	L14
M1.	Photograph (central view) of the ATLAS detector in the Large Hadron Collider showing its eight superconducting barrel toroid magnets around the calorimeter.....	M3
M2.	Pie charts showing percentage of reported world consumption of niobium and tantalum, by material produced.....	M3
M3.	Criticality matrix for niobium, tantalum, and selected other mineral commodities .....	M4
M4.	Photographs showing centimeter-size pyrochlore crystals from Uganda, and a tantalite crystal .....	M6
M5.	World map showing locations of selected niobium and tantalum mines, deposits, and occurrences, by deposit type .....	M8
M6.	Log-log plots of deposit grades and tonnages of tantalum and niobium, by deposit type .....	M9
M7.	Diagrams showing the subsurface geology of the Saint-Honoré carbonatite complex in southern Quebec, Canada, and a schematic north-south cross-section along line A–A' in A.....	M14
M8.	Schematic cross-section of the Lovozero alkaline intrusion, Kola Peninsula, Russia, showing the relation among the three intrusive phases and the niobium mineralization contained in eudialyte and loparite.....	M17
M9.	Schematic representation of regional lithium-cesium-tantalum rare-metal-bearing pegmatite zoning above a parental granite.....	M18
M10.	Schematic cross-section of a concentrically zoned lithium-cesium-tantalum rare-metal-bearing pegmatite .....	M18
M11.	Bar chart showing niobium resources and reserves in Brazil, Canada, and the United States .....	M20
M12.	Bar chart showing global tantalum resources and reserves .....	M21
M13.	Bar charts showing global mine production of niobium and tantalum, from 2000 to 2011 .....	M23
M14.	Pie charts showing percentage of average annual world production of niobium and tantalum, for the period 2007–11, by country.....	M23

N1.	Graphs showing platinum and palladium consumption, by category of use, from 2000 to 2012 for the world, North America, and China .....	N3
N2.	Photograph of gold mask with platinum highlights, from the period of La Tolita culture, Ecuador .....	N4
N3.	World map showing locations of igneous intrusions and intrusive complexes that contain most of the world's platinum-group-element deposits, as well as the placer deposits that are mentioned in the text .....	N7
N4.	Schematic block diagram showing changes in the form of igneous intrusions with depth and the relative occurrence of conduit-type, contact-type, and reef-type magmatic ore deposits .....	N9
N5.	Map showing the geology of the Siberian flood basalt province in Russia, which is the largest flood basalt province in the world .....	N10
N6.	Map showing the geology of the Noril'sk-Talnakh area and the location of nickel-copper-platinum-group-element deposits .....	N11
N7.	Maps showing nickel-copper-platinum-group-element deposits in the Talnakh area, Russia .....	N13
N8.	Photograph of copper-rich massive sulfide ore exposed in a stope in the Oktyabr'sk Mine in the Talnakh area, Russia .....	N14
N9.	Map showing the Rustenburg Layered Suite of the Bushveld Complex, South Africa, the surface trace of significant orebodies, and cross sections through the central area and northeastern limb .....	N15
N10.	Photograph of the UG2 Chromitite at the Karee Mine in the western part of the Bushveld Complex, South Africa .....	N16
N11.	Photograph of the base of the Merensky cyclic unit, a pegmatoidal pyroxenite, which contains the platinum-group-element-rich Merensky Reef .....	N16
N12.	Geologic map and cross sections of the Great Dyke, Zimbabwe .....	N17
N13.	Geologic map and cross section of the Stillwater Complex, Montana .....	N19
N14.	Photograph of the Stillwater Mine in south-central Montana, looking southeast .....	N20
N15.	Map showing the geology along the western margin of the Duluth Complex, Minnesota, with the surface projection of nickel-copper-platinum-group-element deposits and exploration targets .....	N21
N16.	Maps illustrating the distribution of platinum deposits in the Ural Mountains, Russia .....	N24
N17.	Geology and imagery of the Uralian-type Kondyor Massif, which is located in eastern Siberia, Russia, north of the city of Khabarovsk .....	N25
N18.	Photograph and lithograph showing the morphology of platinum-iron-alloy nuggets derived from Uralian-type intrusions .....	N26
N19.	Maps illustrating platinum-group-element resources in southeastern Alaska .....	N27
N20.	Graph showing world platinum-group-element production, by country and year, from 1960 to 2011 .....	N28
N21.	Pie chart showing world platinum-group-element production from 1960 to 2011, by country and amount, in metric tons .....	N29
N22.	Plot showing the relation between tonnage and grade of remaining resources for conduit-type, reef-type, and other types of deposits enriched in platinum-group elements .....	N30
N23.	Graphs showing the percent of contained metal against percent of deposits for the world's platinum-group-element (PGE) and porphyry copper deposits and for the top 30 percent of the world's PGE deposits .....	N31

N24.	Graph showing contained platinum-group-element (PGE) and gold metal against the ratio of palladium to platinum for the major PGE deposits of the world .....	N32
N25.	Three-dimensional block diagram showing the Merensky Reef interpolated down to 2 kilometers in the southern area of the western limb of the Bushveld Complex, South Africa .....	N33
N26.	Graph illustrating the exposed area and stratigraphic thickness of cumulates in more than 200 intrusions from around the world .....	N34
N27.	Geologic map of the Amphitheater Mountains and south-central Alaska showing the location and names of mafic-ultramafic complexes that are part of the Nikolai large igneous province .....	N36
N28.	Graphs showing platinum-group-element prices for platinum, palladium, rhodium, iridium, ruthenium, and osmium from 1880 to 2013.....	N44
01.	Graph showing world mine production of rare-earth oxides, by country and year, from 1960 to 2012 .....	04
02.	Graph showing radii of the trivalent ions of the rare-earth elements as well as of cerium in the +4 valence state and europium in the +2 valence state .....	06
03.	Photograph of the Mountain Pass Mine in San Bernardino County, California, which was the only active producer of rare-earth elements in the United States in 2013 .....	08
04.	World map showing locations of active or recently active rare-earth-element mines and ongoing advanced exploration projects.....	09
05.	Chondrite-normalized plot showing the rare-earth-element (REE) distribution in six different types of North American REE deposits.....	011
P1.	Photographs of rhenium and rhenium compounds .....	P2
P2.	Pie chart showing major end uses of primary rhenium as a percentage of world consumption in 2012.....	P3
P3.	World map showing locations of major rhenium-bearing deposits listed in table P1 .....	P5
P4.	Plot of rhenium grade versus deposit tonnage for major rhenium-bearing deposits in the world, including those shown in figure P3 .....	P10
P5.	Cross sections illustrating rhenium occurrences in major deposit types from which rhenium is recovered or potentially recoverable.....	P11
P6.	Pie chart showing world rhenium mine production in 2012, by country and percent of world total.....	P18
Q1.	Graph showing relative abundance of the chemical elements in Earth's upper crust.....	Q2
Q2.	Graph showing end uses for selenium in the United States from 1975 to 2012 .....	Q3
Q3.	Graph illustrating a mass balance for selenium in the United States from 1943 to 2015.....	Q5
Q4.	Graph showing average annual prices of commercial-grade selenium from 1970 to 2010.....	Q6
Q5.	Map showing selenium concentrations in coal samples, by region of the United States .....	Q15
Q6.	Maps showing locations of seleniferous sedimentary outcrops and deposits and plant samples with significant selenium content .....	Q18
Q7.	A predictive map of selenium source rocks associated with organic-rich depositional marine basins .....	Q22
Q8.	Maps showing selenium concentrations in soils of the conterminous United States .....	Q24

R1.	World map showing locations of selected tellurium-enriched mineral occurrences discussed in the text, by deposit type .....	R2
R2.	Pie chart showing major end uses of tellurium as a percentage of world consumption in 2010.....	R3
R3.	Phase diagram showing speciation calculations for tellurium in a hydrothermal fluid at 300 degrees Celsius (°C), as a function of pH and oxygen fugacity.....	R4
R4.	Pie chart showing percentage of estimated world tellurium refinery production in 2013, by country or region .....	R13
S1.	Pie chart showing major end uses of tin as a percentage of total consumption in the United States in 2014.....	S4
S2.	Graph showing the average annual prices of tin metal from 1970 to 2010 .....	S5
S3.	Ball-and-stick model of part of the crystal structure of cassiterite.....	S6
S4.	Photograph of cassiterite crystals.....	S6
S5.	Photograph of wood tin cassiterite .....	S6
S6.	Schematic vertical section across a typical hydrothermal mineralized granite cupola showing salient features of a shallow granite-related tin-mineralized system .....	S7
S7.	World map showing locations of major tin deposits and districts in the world, by deposit type .....	S10
S8.	Graph showing grades and resource tonnages of major tin deposits in the world, by deposit type or source.....	S11
S9.	Pie chart showing percentage of world tin reserves in 2016, by country .....	S12
S10.	Pie chart showing estimated world mine production of tin in 2015, by country and amount .....	S12
S11.	Map of Alaska showing the locations of selected tin deposits or occurrences .....	S15
T1.	Chart showing common titanium-bearing oxide minerals and common titanium-bearing silicate minerals with their approximate titanium content .....	T5
T2.	Reflected-light photographs showing lamellae of hematite in ilmenite in hemo-ilmenite from the magmatic Lac Tio hemo-ilmenite deposit; and titaniferous magnetite and ilmenite from the magmatic La Blache iron-titanium-oxide deposit.....	T5
T3.	World map showing global distribution of titanium deposits, by size and type of deposit.....	T7
T4.	Bar chart comparing approximate titanium dioxide content in titanium deposits of different deposit types .....	T8
T5.	Plot of titanium dioxide grade and tonnage for selected igneous, metamorphic, and sedimentary deposits in the world, by deposit type.....	T10
T6.	Pie charts showing percentage of estimated 2012 world mine production of ilmenite and rutile, and percentage of global reserves of ilmenite and rutile, by country .....	T11
U1.	World map showing locations of major vanadium deposits of the world, by deposit type .....	U3
U2.	Pie chart showing percentage of world vanadium production in 2012, by country .....	U9
U3.	Graph showing major end uses of vanadium in the United States from 1970 to 2011 .....	U9
U4.	Photographs showing four examples of vanadium.....	U12
U5.	Plot of grade and tonnage of vanadium deposits for which data were available .....	U19

V1.	Examples of sources and uses of zirconium and hafnium .....	V3
V2.	Graphs showing global zirconium production and U.S. trade information for zirconium ores and concentrates .....	V4
V3.	World map showing locations of selected zirconium and hafnium deposits and regions with modern coastal placer systems .....	V8
V4.	Diagrams showing examples of coastal depositional systems with an emphasis on barrier island location, morphology, and depositional environments .....	V10
V5.	Diagrams showing influences on and locations of placer formation in coastal environments .....	V11

## Tables

A1.	Crustal abundances of mineral commodities (elements) included in this volume .....	A7
B1.	Summary of selected Federal laws relevant to mine permitting .....	B4
B2.	Historical summary of mine sites placed on the U.S. Environmental Protection Agency's National Priorities List. ....	B8
B3.	Selected consortia devoted to identifying and implementing environmental best practices associated with mining .....	B11
C1.	Selected antimony minerals .....	C7
C2.	Estimated world production and reserves of antimony in 2013 .....	C9
C3.	Potential additional sources of antimony ore and concentrate, by country .....	C10
E1.	Selected properties of beryllium, which is a Group 2 alkaline earth metal .....	E5
E2.	Selected beryllium minerals .....	E8
E3.	Global and domestic types of magmatic-related beryllium resources .....	E10
E4.	Location, grade, tonnage, and other data for selected beryllium deposits of the world .....	E22
F1.	Location, grade, tonnage, and other data for selected cobalt deposits of the world .....	F34
F2.	Cobalt concentrations in rocks, soils, waters, and air .....	F6
G1.	Fluorine concentrations in various types of rocks .....	G5
G2.	Concentrations of fluorine and other elements in waters .....	G6
G3.	Selected examples of the chemistry and mineralogy of mine waste generated at fluorspar mines .....	G34
H1.	Selected properties of gallium, a Group 13 post-transition metal .....	H8
H2.	Gallium concentrations in rocks, ore, coal, soils, and natural waters .....	H9
H3.	Selected gallium-bearing minerals—Formula, content, and occurrence .....	H13
H4.	Significant global and domestic deposit types from which gallium is obtained or is potentially extractable .....	H16
I1.	Classification of deposits that host germanium and indium resources .....	I6
I2.	Average estimated annual refinery production of germanium and indium, by area, for 2011 and 2012 .....	I14
I3.	Germanium concentrations in rocks, soils, and waters .....	I16
I4.	Indium concentrations in rocks, soils, waters, and air .....	I17
J1.	Characteristics of graphite commodities, deposits, and uses, by commodity type .....	J2
J2.	Selected physical properties of graphite .....	J3
J3.	Location, grade, tonnage and other data for selected graphite deposits and districts of the world .....	J8

J4.	Estimates of world graphite resources, by country, commodity type, and resource category, in thousand metric tons of recoverable graphite.....	J18
K1.	Commercially and (or) scientifically important lithium-bearing minerals.....	K5
K2.	Lithium concentrations in soils developed on various types of bedrock.....	K15
L1.	Estimated world manganese ore reserves in 2012.....	L3
L2.	Identified resources estimated for major land-based manganese deposits of the world .....	L13
L3.	Grade, tonnage, and quantity of contained manganese for eight manganese deposits and districts in the United States.....	L16
L4.	Background and above-background concentrations of manganese in rocks, soils, waters, and air .....	L19
M1.	Selected properties of niobium and tantalum .....	M2
M2.	Selected niobium and tantalum oxide minerals and their end-member $Nb_2O_5$ and $Ta_2O_5$ contents or compositional range .....	M5
M3.	Major types of niobium and tantalum deposits, with key characteristics and examples .....	M7
M4.	Location, grade, tonnage, and other data for selected niobium-tantalum deposits of the world.....	M10
N1.	Chemical formulas for selected platinum-group minerals as well as other common rock-forming minerals mentioned in this chapter .....	N6
N2.	Examples of rocks and ores with anomalous platinum-group-element concentrations that are not associated with magmatic deposits, by deposit type. ....	N72
N3.	Areas with significant placer platinum production, and estimates of cumulative production and grades.....	N23
N4.	Identified platinum-group-element and gold resources, summarized by deposit type and location .....	N29
N5.	Igneous intrusions and intrusive complexes that contain more than 97 percent of the world's identified platinum-group-element (PGE) and gold resources, in order of total contained PGEs .....	N76
N6.	Areal extent and stratigraphic thickness of layered intrusions with reef-type platinum-group-element deposits and some examples of large intrusions with no known deposits, in order of areal extent.....	N77
N7.	Platinum-group-element concentrations in samples of upper crust, loess, river sediment, and marine pelagic sediment.....	N38
N8.	Trace element geochemistry of waters from selected reef-type, contact-type, and conduit-type deposits.....	N79
N9.	Acid-base accounting for selected reef-type, contact-type, and conduit-type deposits .....	N81
N10.	Grade and tonnage of mineralized rock remaining in platinum-group-element-bearing mineral deposits.....	N82
01.	List of the rare-earth elements found in natural deposits—the “lanthanides” plus yttrium .....	02
02.	List of selected rare-earth-element-bearing and yttrium-bearing ore minerals .....	010
03.	Active rare-earth mines, by deposit type .....	012
04.	Advanced rare-earth-element (REE) exploration projects and the reported estimates of their REE resources, by deposit type. ....	014



P1.	Summary of rhenium, copper, and molybdenum grades, deposit tonnage, and amount of contained rhenium in the rhenium-bearing deposits shown in figure P3 .....	P6
P2.	Rhenium data for selected porphyry copper and porphyry molybdenum deposits of the world.....	P38
P3.	Rhenium concentrations in rocks, soils, biota, waters, and sediments .....	P20
Q1.	Selenium minerals recognized by the International Mineralogical Association.....	Q44
Q2.	A summary of selenium concentrations in various selenides and sulfides from deposits around the world .....	Q49
Q3.	Selenium concentrations in sulfide minerals and other phases, in various deposit types .....	Q10
Q4.	Selenium concentrations in copper-nickel ores in the Sudbury basin, Ontario, Canada .....	Q12
Q5.	Selenium concentrations in selected Earth and lunar materials .....	Q16
Q6.	Estimated world selenium reserves in 2014, in metric tons.....	Q21
Q7.	National Institutes of Health recommended dietary reference intakes (DRIs) for selenium .....	Q31
R1.	Tellurium-bearing minerals, many of which are mentioned in this chapter .....	R5
S1.	List of selected tin-bearing minerals.....	S3
S2.	Location, grade, tonnage, and other data for selected tin deposits of the world with greater than 1,000 metric tons of contained tin.....	S34
S3.	Tin reserves of the world in 2016, in metric tons of contained tin .....	S11
S4.	Tin concentrations in rocks, soils, waters, and air.....	S17
T1.	Classification of selected titanium mineral deposits based on their geologic setting and the processes through which they were formed .....	T3
T2.	Titanium resources of the United States .....	T13
T3.	Titanium mineral resources of the world (excluding the United States) for ilmenite (including titanomagnetite and leucoxene) and rutile (including anatase and brookite). .....	T14
U1.	Location, grade, tonnage, and other data for selected vanadium deposits of the world.....	U4
U2.	Selected vanadium-bearing minerals, by deposit type.....	U11
U3.	Vanadium concentrations in rocks, soils, waters, and air.....	U23

## Conversion Factors

International System of Units to Inch/Pound

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
<b>Length</b>		
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)
<b>Area</b>		
hectare (ha)	2.471	acre
square kilometer (km <sup>2</sup> )	247.1	acre
square meter (m <sup>2</sup> )	10.76	square foot (ft <sup>2</sup> )
square centimeter (cm <sup>2</sup> )	0.1550	square inch (ft <sup>2</sup> )
square kilometer (km <sup>2</sup> )	0.3861	square mile (mi <sup>2</sup> )
<b>Volume</b>		
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 <sup>3</sup> )	264.2	gallon (gal)
cubic centimeter (cm <sup>3</sup> )	0.06102	cubic inch (in <sup>3</sup> )
cubic meter (m <sup>3</sup> )	1.308	cubic yard (yd <sup>3</sup> )
cubic kilometer (km <sup>3</sup> )	0.2399	cubic mile (mi <sup>3</sup> )
<b>Mass</b>		
microgram (µg)	0.0000003527	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]
<b>Deposit grade</b>		
gram per metric ton (g/t)	0.0291667	ounce per short ton (2,000 lb) (oz/T)
<b>Pressure</b>		
megapascal (MPa)	10	bar
gigapascal (GPa)	10,000	bar
<b>Density</b>		
gram per cubic centimeter (g/cm <sup>3</sup> )	62.4220	pound per cubic foot (lb/ft <sup>3</sup> )
milligram per cubic meter (mg/m <sup>3</sup> )	0.0000006243	pound per cubic foot (lb/ft <sup>3</sup> )
<b>Energy</b>		
joule (J)	0.0000002	kilowatthour (kWh)
joule (J)	$6.241 \times 10^{18}$	electronvolt (eV)
joule (J)	0.2388	calorie (cal)
kilojoule (kJ)	0.0002388	kilocalorie (kcal)

## International System of Units to Inch/Pound—Continued

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
<b>Radioactivity</b>		
becquerel (Bq)	0.00002703	microcurie ( $\mu\text{Ci}$ )
kilobecquerel (kBq)	0.02703	microcurie ( $\mu\text{Ci}$ )
<b>Electrical resistivity</b>		
ohm meter ( $\Omega\text{-m}$ )	39.37	ohm inch ( $\Omega\text{-in.}$ )
ohm-centimeter ( $\Omega\text{-cm}$ )	0.3937	ohm inch ( $\Omega\text{-in.}$ )
<b>Thermal conductivity</b>		
watt per centimeter per degree Celsius (watt/cm $^{\circ}\text{C}$ )	693.1798	International British thermal unit inch per hour per square foot per degree Fahrenheit (Btu in/h ft <sup>2</sup> $^{\circ}\text{F}$ )
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 <sup>2</sup> $^{\circ}\text{F}$ )

## Inch/Pound to International System of Units

<b>Length</b>		
mil	25.4	micrometer ( $\mu\text{m}$ ) [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)
<b>Volume</b>		
ounce, fluid (fl. oz)	29.57	milliliter (mL)
ounce, fluid (fl. oz)	0.02957	liter (L)
<b>Mass</b>		
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)
<b>Deposit grade</b>		
ounce per short ton (2,000 lb) (oz/T)	34.285714	gram per metric ton (g/t)
<b>Energy</b>		
kilowatthour (kWh)	3,600,000	joule (J)
electronvolt (eV)	$1.602 \times 10^{-19}$	joule (J)
<b>Radioactivity</b>		
microcurie ( $\mu\text{Ci}$ )	37,000	becquerel (Bq)
microcurie ( $\mu\text{Ci}$ )	37	kilobecquerel (kBq)

Temperature in degrees Celsius ( $^{\circ}\text{C}$ ) may be converted to degrees Fahrenheit ( $^{\circ}\text{F}$ ) as follows:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

Temperature in degrees Celsius ( $^{\circ}\text{C}$ ) may be converted to kelvin (K) as follows:

$$\text{K} = ^{\circ}\text{C} + 273.15$$

Temperature in degrees Fahrenheit ( $^{\circ}\text{F}$ ) may be converted to degrees Celsius ( $^{\circ}\text{C}$ ) as follows:

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8$$

## 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 ( $\mu\text{S}/\text{cm}$  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 ( $\mu\text{g}/\text{L}$ ), nanograms 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 ( $\mu\text{g}/\text{g}$ ), 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 ( $\mu\text{Ci}/\text{mL}$ ).

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 ( $\mu\text{g}/\text{g}$ )	part per million
microgram per kilogram ( $\mu\text{g}/\text{kg}$ )	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 = 0.000000001 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- ( $\mu$ -)	$10^{-6}$	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]

$\alpha$ -tin	alpha-tin (also known as gray tin)
$\beta$ -tin	beta-tin (also known as white tin)
$^{\circ}\text{C}$	degree Celsius
$\delta$ - $\text{MnO}_2$	delta-manganese dioxide
$\mu\text{Ci/mL}$	microcurie per milliliter
$\mu\text{g Al/L}$	microgram of aluminum per liter
$\mu\text{g/d}$	microgram per day
$\mu\text{g/g}$	microgram per gram
$\mu\text{g/kg}$	microgram per kilogram
$\mu\text{g/L}$	microgram per liter
$\mu\text{g/m}^3$	microgram per cubic meter
$\mu\text{g Mn/L}$	microgram of manganese per liter
$\mu\text{g Mn/m}^3$	microgram of manganese per cubic meter
$\mu\text{g V/L}$	microgram of vanadium per liter
$\mu\text{m}$	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 <sup>3</sup>	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 <sub>50</sub>	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 <sub>2</sub> -equiv/kWh	gram of CO <sub>2</sub> equivalent per kilowatthour
g/cm <sup>3</sup>	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 <sub>3</sub> / t	kilogram of calcium carbonate per metric ton
kg/cm <sup>2</sup>	kilogram per square centimeter
kg/m <sup>3</sup>	kilogram per cubic meter
kg/t	kilogram per metric ton
km	kilometer
km <sup>2</sup>	square kilometer
km <sup>3</sup>	cubic kilometer
KMML	Kerala Minerals and Metals Ltd.
lb	pound
LC <sub>50</sub>	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 <sup>3</sup>	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 <sup>3</sup>	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 <sup>3</sup>	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 <sup>3</sup>	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- <i>n</i> -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

