# 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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John H. DeYoung, Jr.
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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) | $6.241 \times 10^{18}$ | electronvolt (eV) |
| joule (J) | 0.2388 | calorie (cal) |
| kilojoule (kJ) | 0.0002388 | kilocalorie (kcal) |

International System of Units to Inch/Pound—Continued

| 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) | $1.602 \times 10^{-19}$ | 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 |