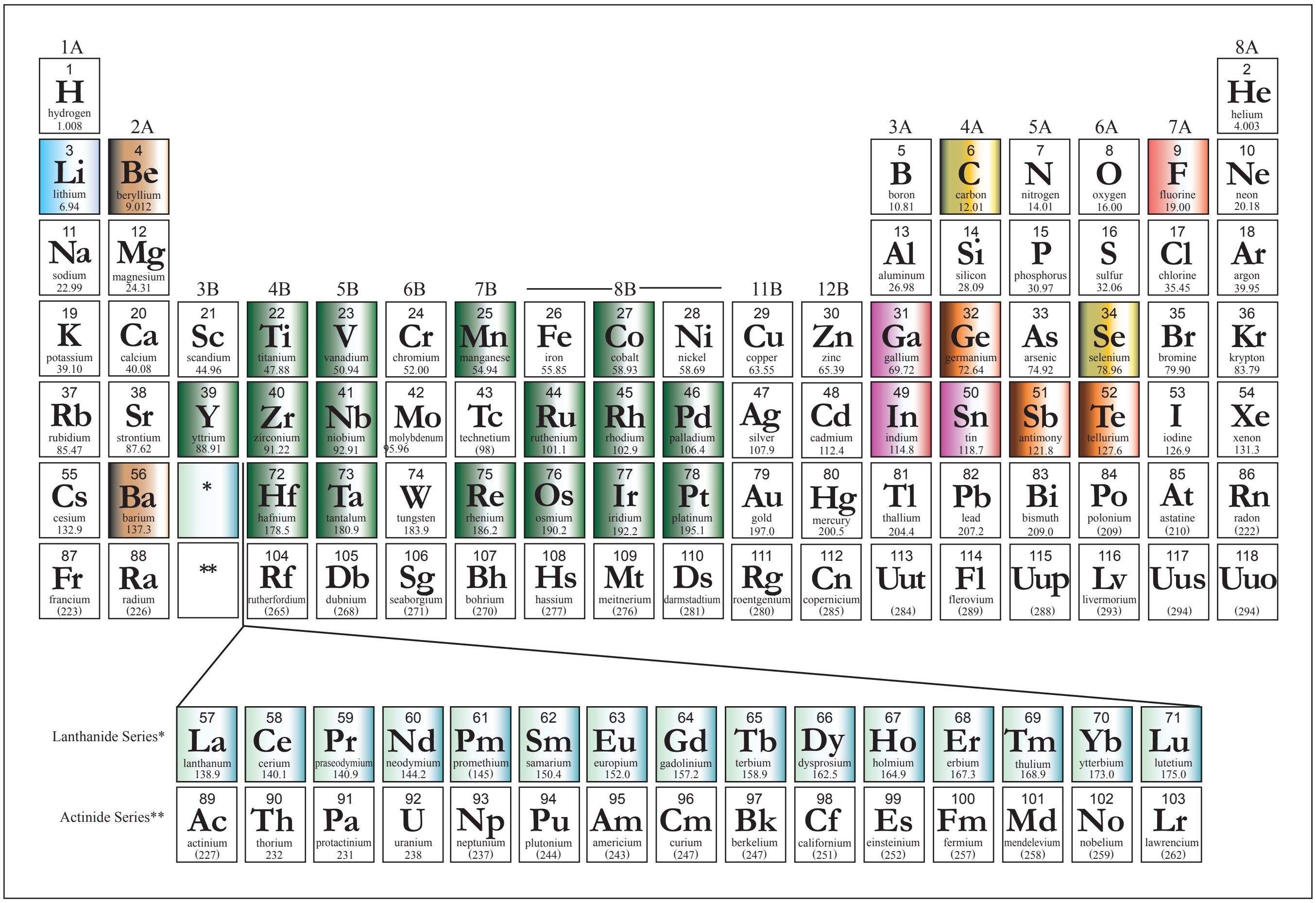
science for a changing world

Critical Mineral Resources of the United States—An Introduction

Chapter A of

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



1A	2A	3B	4B	5B	6B	7B	8B	8B	8B	11B	12B	3A	4A	5A	6A	7A	8A
1 H hydrogen 1.008																	2 He helium 4.003
3 Li lithium 6.94	4 Be beryllium 9.012											5 B boron 10.81	6 C carbon 12.01	7 N nitrogen 14.01	8 O oxygen 16.00	9 F fluorine 19.00	10 Ne neon 20.18
11 Na sodium 22.99	12 Mg magnesium 24.31											13 Al aluminum 26.98	14 Si silicon 28.09	15 P phosphorus 30.97	16 S sulfur 32.06	17 Cl chlorine 35.45	18 Ar argon 39.95
19 K potassium 39.10	20 Ca calcium 40.08	21 Sc scandium 44.96	22 Ti titanium 47.88	23 V vanadium 50.94	24 Cr chromium 52.00	25 Mn manganese 54.94	26 Fe iron 55.85	27 Co cobalt 58.93	28 Ni nickel 58.69	29 Cu copper 63.55	30 Zn zinc 65.39	31 Ga gallium 69.72	32 Ge germanium 72.64	33 As arsenic 74.92	34 Se selenium 78.96	35 Br bromine 79.90	36 Kr krypton 83.79
37 Rb rubidium 85.47	38 Sr strontium 87.62	39 Y yttrium 88.91	40 Zr zirconium 91.22	41 Nb niobium 92.91	42 Mo molybdenum 95.96	43 Tc technetium (98)	44 Ru ruthenium 101.1	45 Rh rhodium 102.9	46 Pd palladium 106.4	47 Ag silver 107.9	48 Cd cadmium 112.4	49 In indium 114.8	50 Sn tin 118.7	51 Sb antimony 121.8	52 Te tellurium 127.6	53 I iodine 126.9	54 Xe xenon 131.3
55 Cs cesium 132.9	56 Ba barium 137.3	*	72 Hf hafnium 178.5	73 Ta tantalum 180.9	74 W tungsten 183.9	75 Re rhenium 186.2	76 Os osmium 190.2	77 Ir iridium 192.2	78 Pt platinum 195.1	79 Au gold 197.0	80 Hg mercury 200.5	81 Tl thallium 204.4	82 Pb lead 207.2	83 Bi bismuth 209.0	84 Po polonium (209)	85 At astatine (210)	86 Rn radon (222)
87 Fr francium (223)	88 Ra radium (226)	**	104 Rf rutherfordium (265)	105 Db dubnium (268)	106 Sg seaborgium (271)	107 Bh bohrium (270)	108 Hs hassium (277)	109 Mt meitnerium (276)	110 Ds darmstadtium (281)	111 Rg roentgenium (280)	112 Cn copernicium (285)	113 Uut (284)	114 Fl flerovium (289)	115 Uup (288)	116 Lv livermorium (293)	117 Uus (294)	118 Uuo (294)

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

Professional Paper 1802–A

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Cover. Periodic table of elements. The elements discussed in this volume are highlighted. Modified from Los Alamos National Laboratory Chemistry Division; available at http://periodic.lanl.gov/images/periodictable.pdf.

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U.S. Department of the Interior
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U.S. Geological Survey, Reston, Virginia: 2017

Suggested citation:
Schulz, K.J., DeYoung, J.H., Jr., Bradley, D.C., and Seal, R.R., II, 2017, Critical mineral resources of the United States—An introduction, chap. A *of* Schulz, K.J., DeYoung, J.H., Jr., Seal, R.R., II, and Bradley, D.C., eds., Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply: U.S. Geological Survey Professional Paper 1802, p. A1–A14, https://doi.org/10.3133/pp1802A.

ISSN 2330-7102 (online)

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Abbreviations and Symbols

CMI	Critical Minerals Index
NSTC	National Science and Technology Council
ppm	part per million
U.S.C.	U.S. Code
USGS	U.S. Geological Survey

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Abstract

Many changes have taken place in the mineral resource sector since the publication by the U.S. Geological Survey of Professional Paper 820, “United States Mineral Resources” (Brobst and Pratt, 1973), which is a review of the long-term United States resource position for 65 mineral commodities or commodity groups. For example, since 1973, the United States has continued to become increasingly dependent on imports to meet its demands for an increasing number of mineral commodities. The global demand for mineral commodities is at an alltime high and is expected to continue to increase, and the development of new technologies and products has led to the use of a greater number of mineral commodities in increasing quantities to the point that, today, essentially all naturally occurring elements have several significant industrial uses. Although most mineral commodities are present in sufficient amounts in the earth to provide adequate supplies for many years to come, their availability can be affected by such factors as social constraints, politics, laws, environmental regulations, land-use restrictions, economics, and infrastructure.

This volume presents updated reviews of 23 mineral commodities and commodity groups viewed as critical to a broad range of existing and emerging technologies, renewable energy, and national security. The commodities or commodity groups included are antimony, barite, beryllium, cobalt, fluorine, gallium, germanium, graphite, hafnium, indium, lithium, manganese, niobium, platinum-group elements, rare-earth elements, rhenium, selenium, tantalum, tellurium, tin, titanium, vanadium, and zirconium. All these commodities have been listed as critical and (or) strategic in one or more of the recent studies based on assessed likelihood of supply interruption and the possible cost of such a disruption to the assessor. For some of the minerals, current production is limited to only one or a few countries. For many, the United States currently has no mine production or any significant identified resources and is largely dependent on imports to meet its needs. As a result, the emphasis in this volume is on the global distribution and availability of each mineral commodity. The environmental issues related to production of each mineral commodity, including current mitigation and remediation approaches to deal with these challenges, are also addressed.

This introductory chapter provides an overview of the mineral resource classifications, terms, and definitions used in this volume. A review of the history of the use and meaning of the term “critical” minerals (or materials) is included as an appendix to the chapter.

Background

In 1973, the U.S. Geological Survey (USGS) produced Professional Paper 820, “United States Mineral Resources” (Brobst and Pratt, 1973), a review of the long-term United States resource position for 65 mineral commodities or commodity groups. A main purpose of that volume was to provide nonspecialists with easily understandable factual information on the resources of the many mineral commodities that are important to the national economy, national security, and the everyday lives of U.S. citizens. More specifically, that volume addressed three basic questions about each mineral commodity:

> “(1) How important is it to our present industrial civilization and standard of living? (2) how much of it do we have and to what extent is it economically and technologically available? and (3) how and where can we find more?” (Brobst and Pratt, 1973, p. 1).

The emphasis was on domestic mineral resources, but many chapters also include information on resources in other countries.

The economy and the national security of the United States are based directly or indirectly on minerals and, in the early 1970s, there was increasing recognition of and concern about the fact that the United States did not have adequate domestic supplies of many of the nonfuel minerals needed to sustain its economy (U.S. Geological Survey, 1975). In an analysis of the principal developments in U.S. mineral history and world mineral history since 1939, Cameron (1973) concluded that:

> “(1) United States mineral production has greatly increased but has not kept pace with consumption. Self-sufficiency in minerals has declined, both overall and in numbers of minerals involved.

> (2) Since 1945, world mineral production has increased far more rapidly than United States production. The relative importance of the United States as a supplier of world minerals, raw and manufactured, has rapidly declined.
>
> (3) World mineral consumption has increased far more rapidly than United States consumption. The United States is no longer the world's principal market for mineral raw materials, and it faces increasing competition for the world's mineral supplies." (Cameron, 1973, p. 25).

The volume "United States Mineral Resources" was produced to provide factual information on the Nation's mineral resources at the time and to inform policymakers and the public in efforts to frame national mineral policy.

U.S. Mineral Supply Situation

The conclusions reached by Cameron (1973) about the United States mineral position at that time are even more pertinent now, more than 40 years later. In 1980, the United States was more than 50 percent dependent on imports to meet its annual requirements for more than 20 major nonfuel mineral commodities; in 2014, that number had increased to more than 40 commodities (Fortier and others, 2015; U.S. Geological Survey, 2015b, p. 6). The United States was the world's leading producer of copper for much of the 20th century, but Chile became the leading copper-producing country in 1982 and has remained so. In 2014, China accounted for 20 percent or more of the world's mine production of more than 40 mineral commodities; these included the rare-earth elements, of which China accounted for 85 percent of world production; tungsten, 82 percent; antimony, 76 percent; germanium, 73 percent; mercury, 68 percent; graphite, 66 percent; fluorspar, 59 percent; and bismuth, 56 percent (U.S. Geological Survey, 2016).

As world population increases and the average standard of living improves, the global demand for mineral commodities is at an all-time high and is expected to continue to increase. Much of this demand is the result of industrialization in large developing countries, such as Brazil, China, and India.

In addition, the development of new technologies and products has led to the use of a greater number of mineral commodities in increasing quantities. In 1932, uranium and rare-earth elements had only minor uses, and the production or uses of such elements as gallium, germanium, rhenium, and several others were not even tracked. As of the first decades of the 21st century, essentially all the naturally occurring elements have several significant industrial uses (Price, 2013). By way of example, in the 1980s, 12 elements were used in the manufacture of computer chips. A decade later, 16 elements were employed, and by 2006, as many as 60 elements were used in the manufacture of high-speed, high-capacity integrated circuits (fig. A1; National Research Council, 2008, p. 56–58).

In the 1970s, concerns regarding the adequacy of future supplies of minerals were raised owing to a perceived lack of world resources. Based on their finite occurrence, "limits to supply" of nonrenewable resources, such as minerals, was most famously predicted in a report by the Club of Rome (Meadows and others, 1972). The concerns raised in that report were based partly on results of previous studies. For example, the time-series analysis of metal production in mining districts of Europe by Hewett (1929) demonstrated cyclical patterns that were subsequently applied to the production histories of other nonfuel minerals and energy minerals (Lasky, 1951, 1955; Hubbert, 1956; Pazik, 1976). This type of analysis formed the basis of numerous studies that predicted that the highest level of production of some mineral commodities may soon be reached and that production is likely to decline from then on. This approach to studying future resource availability is often termed "peak minerals." Many of these studies, however, used estimates of mineral *reserves* (the economically extractable portion of resources at the time of determination) as a proxy for the Earth's *resources*, including those that have been discovered (identified resources), which, in turn, include those that are economic to produce (reserves) (Meadows and others, 1972; Cohen, 2007). This approach is flawed, because estimates of mineral reserves are a function of economic factors, such as metal prices and costs of recovery, which can vary considerably over time. New geologic knowledge can result in changes to estimates of identified resources, including those identified resources that are economic (reserves) changing as well (Rustad, 2012; Gold, 2014; Meinert and others, 2016). Likewise, both the development of new extractive technologies and increased metal prices have resulted in mineral deposits previously considered subeconomic or marginally economic becoming viable sources for mineral production. In addition, improved methodologies for estimating undiscovered mineral resources, the discovery of new mineral deposit types, improved recycling technologies, higher processing efficiency, and longer product life have all helped allay fears that we are near peak supply of most mineral commodities. Today, therefore, it is generally recognized that, although mineral commodities are mostly nonrenewable on human time scales and are inherently finite, fears of resource depletion for most mineral commodities anytime soon are unwarranted.

Nonetheless, although most mineral commodities may be present in sufficient amounts in the earth to provide adequate supplies for some years to come, they are generally found concentrated only in small volumes in the crust and are not distributed evenly across the planet. As a result, no country today can be fully self-sufficient in meeting all its mineral resource needs. In addition, the availability of mineral commodities is not just a function of geologic accessibility but of such factors as social constraints, politics, laws, environmental regulations, land restrictions, economics, and infrastructure. Large deposits of a particular mineral commodity tend to account for the bulk of production, but these deposits

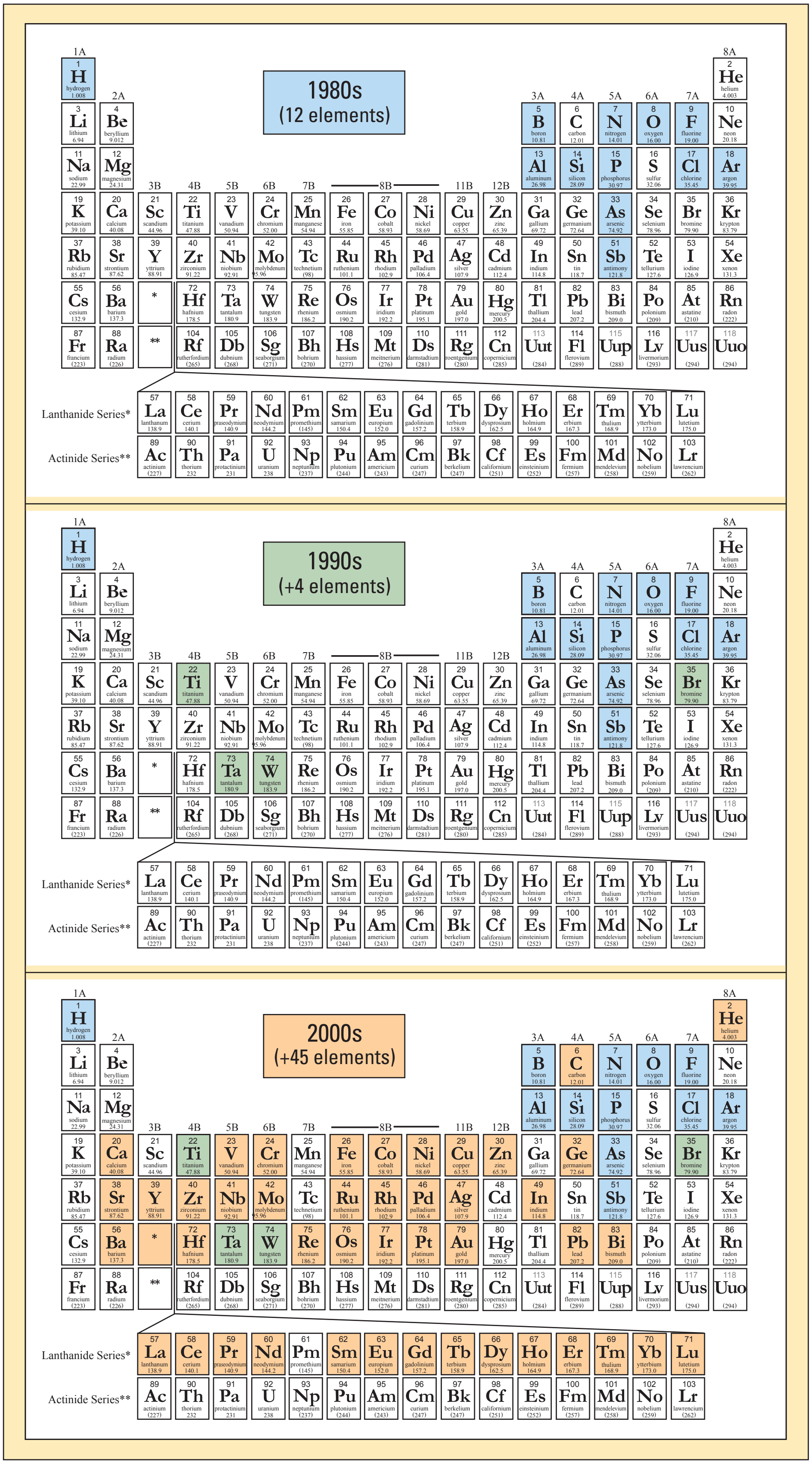

Figure A1. Diagram showing increases in the use of elements over two decades of computer chip technology development. High-speed, high-capacity integrated circuits have gone from being made with *A*, 12 minerals or their elemental components in the 1980s to *B*, 16 in the 1990s to *C*, more than 60 by the 2000s. Modified from National Research Council (2008, fig. 2.2).

are few in number and geographically restricted. As a result, there is potential for local social and environmental issues or political manipulation to restrict or deny access to supply.

The sometimes-tenuous nature of the mineral supply chain received world attention in 2010 when China suddenly drastically cut its export quota for the rare-earth elements. The move highlighted the fact that China had a virtual monopoly on the short-term supply of rare-earth elements—elements that are essential to the renewable energy sector and many other high-tech applications globally. The rest of the world was left scrambling to find alternative and secure supplies. China is also the world's major producer of a number of other mineral commodities that are essential in high-tech applications, renewable energy, and national security, including antimony, bismuth, fluorspar, germanium, graphite, and indium (Price, 2013). These and other mineral commodities that are largely controlled by one country, such as cobalt (Democratic Republic of the Congo), niobium (Brazil), and platinum (South Africa), are also considered to be at high risk of supply disruption and would have high impact if supply restrictions should take place (McGroarty and Wirtz, 2012).

Mineral Resource Classifications, Terms, and Definitions Used in This Volume

Through the years, a variety of terms have been used to describe and classify mineral resources. Although some terms have gained wide use and acceptance, they are not always used with precisely the same meaning. Some basic terms and definitions are listed below. No attempt has been made to include a detailed listing of all mineral-resource-related terms and definitions; rather, emphasis is on those basic terms that are essential to proper understanding of the chapters in this volume. This terminology is intended to represent standard definitions and usage by the mineral industry and resource assessment community today. A more comprehensive discussion of mineral resource terms and definitions is presented in U.S. Bureau of Mines and U.S. Geological Survey (1980); Cox and others (1986); and U.S. Geological Survey National Mineral Resource Assessment Team (2000).

Mineral resources are classified based on a number of factors, such as their geologic and physical and (or) chemical characteristics (such as grade, mineralogy, tonnage, thickness, and depth) of the material in place; the economic viability of production based on costs of extracting, processing, and marketing the material at a given time; the level of certainty of estimates of physical and economic factors; and environmental and legal constraints on resource development. The mineral resource classification system used in this volume is shown in figure A2 (U.S. Bureau of Mines and U.S. Geological Survey, 1980).

When used in this volume, the terms listed below have the following meanings:

mineral occurrence. A mineral concentration that is considered valuable by someone somewhere, or that is of scientific or technical interest.

mineral deposit. A mineral concentration of sufficient size and grade that it might, under the most favorable of circumstances, be considered to have potential for economic development.

> **undiscovered mineral deposit**. A mineral deposit believed to exist 1 kilometer or less below the surface of the ground, or an incompletely explored mineral occurrence or prospect that could have sufficient size and grade to be classified as a deposit.
>
> **ore deposit**. A mineral deposit that has been tested and is known to be of sufficient size, grade, and accessibility to be producible to yield a profit.

resource. A mineral concentration of sufficient size and grade and in such a form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.

> **identified resources**. Resources whose location, grade, quality, and quantity are known or estimatable from specific geologic evidence.
>
>> **reserves**. Identified resources that meet specified minimum physical and chemical criteria related to current mining and production practices and that can be economically extracted or produced at the time of determination.
>
> **undiscovered resources**. Resources in undiscovered mineral deposits whose existence is postulated on the basis of indirect geologic evidence.

economic. Profitable extraction or production under defined investment assumptions has been established, analytically demonstrated, or assumed with reasonable certainty.

A mineral occurrence becomes a mineral resource only if there is a demand to use it—that is, inherent in the definition of a mineral resource is the necessity for there to be present or expected future demand for a mineral commodity in order for an occurrence of that mineral to be considered a resource. Note also that the quantity of the resource within each category is a stock variable (a measurement at a specific point in time), as contrasted with a flow variable, such as production (a measurement that covers a period of time). The quantity of resources (including reserves) is not static, and the assignment of the resource to a given category often changes over time.

The development of mineral resources into the category of reserves requires the creation of facilities to extract the ore, process it into a mineral product, and transport that product to the user. Although the quantity of production is a flow measure (amount per unit time—for example, tons per month or tons per year), the estimates of the amount available in each resource category (a stock variable) also changes over time as

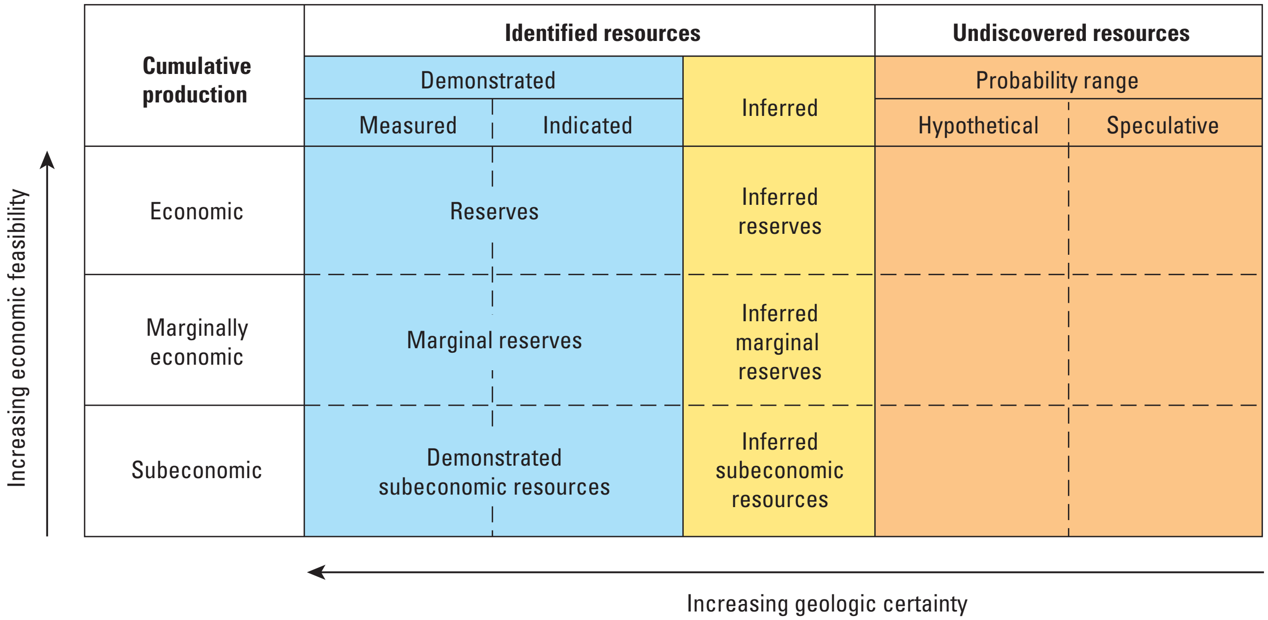

Figure A2. Diagram showing the mineral resource classification system used in this volume. Modified from U.S. Bureau of Mines and U.S. Geological Survey (1980).

production removes part of the resource; additional exploration results in the discovery of new deposits and provides new information about previously discovered deposits; advances in technology affect the costs and methods of mining, processing, and use; and changes in market conditions affect the economic viability of production. For example, in 1973, world reserves of cobalt were estimated to be 2.5 million metric tons of contained cobalt (U.S. Bureau of Mines, 1973, p. 39). Since then, more than 2.0 million metric tons of cobalt has been mined worldwide, yet world reserves of cobalt in 2015 were estimated to be 7.2 million metric tons of cobalt, which is almost triple the amount estimated in 1973, despite the depletion by mining of an amount equivalent to 80 percent of the 1973 reserve estimate (Shedd, 2015, 2016; U.S. Geological Survey, 2015a).

E.W. Zimmermann saw resources as a function of human wants and abilities. In the revised edition of his 1933 book, "World Resources and Industries—A Functional Appraisal of the Availability of Agricultural and Industrial Resources," he discussed the debate between "the static school who insists that 'resources are'," and "the dynamic, functional, operational school who insists that 'resources become'" (Zimmermann, 1951, p. 11). He succinctly stated the relation between demand and resources as "Resources are not, they become."

Joint Products, Byproducts, and Coproducts

Many of the mineral commodities included in this volume are not produced as independent (also called individual, primary, or main) products; rather, they are produced (mined and [or] processed) along with other minerals. The terms used to describe the mineral commodities produced at a particular site can give an indication of their relative economic importance at that site. The terms, however, are not always used consistently across the industry.

The term "byproduct," for example, has been used to characterize any mineral commodity produced along with another as a "secondary product" (Kesler, 1994, p. 371) and (or) as a "secondary or additional product" (Thrush and others, 1968, p. 157). Landsberg and others (1963, p. 479–483) used the terms "byproduct" and "coproduct" interchangeably in a detailed study of the future availability of natural resources to meet projected material use. Brooks (1965, p. 25–31), who was a senior contributor to that study, later described a "joint product" relationship when he developed his classification system for minor metals.

Brooks defined an individual product as one that is produced alone or with other minerals that are "of comparatively insignificant value." Joint products are called "byproducts" or "coproducts" depending upon their effect on the economic viability of the production process. If the joint product is needed to make the operation viable, it is a coproduct; if not, it is a byproduct. Changes in market conditions (prices and costs of production processes) and in applicable mining and processing technologies can change the status of joint products. With this caveat, the uses of the terms joint product, byproduct, and coproduct in this volume follow the definitions established by Brooks (1965). The revised version of the 1968 U.S. Bureau of Mines dictionary of mining and mineral terms published by the American Geological Institute in 1997 added a definition of "coproduct" that is cross-referenced to the definition of "byproduct" that is generally consistent with the classification developed by Brooks (American Geological Institute, 1997, p. 76, 124).

Scarcity and Rarity

Analysis of mineral resources is linked to concerns about scarcity because resources are defined as physical quantities that can be extracted at a cost that is commensurate with current or potential profitable marketability. Brooks (1965, p. 22) explained the important distinction between physical rarity and economic scarcity; that is, rarity is determined by "…an element's relative physical abundance in some specified portion of the earth" and scarcity is determined by the "…cost of acquisition under given conditions of time and place." The concepts of rarity and scarcity derive from different origins—rarity from the differentiation of the universe, over which humans have no control, and scarcity from many causes, of which human activity is often the sole determinant, such as monopolistic or oligopolistic market forces (Brooks, 1965, p. 22).

Three reasons why an element or mineral commodity may be scarce are rooted in geochemistry. First, rarity may result in scarcity; however, elements that have similar rarity as measured by average crustal abundance, such as cobalt and scandium, may have quite different scarcity as measured by market price. For example, in 2012, the price of cobalt was about 2.9 cents per gram ($13 per pound), whereas the price of scandium was $169 per gram for metal ingots (Gambogi, 2014; Shedd, 2014). Because of market prices, cobalt was rare but not scarce, whereas scandium was both rare and scarce.

A second factor affecting the scarcity of an element is the concentration of the element above its average crustal abundance that is required to create an ore deposit (where the mineral can be extracted at a profit). The concentration above average crustal abundance needed to enable profitable mining is also dependent upon the byproducts and coproducts present in the deposit, ore mineralogy, grain size, consolidation of the material to be mined, and deposit depth and location. These characteristics are not accounted for in a ratio of the grade of an element in a deposit to its average crustal abundance. The necessary concentration with respect to average crustal abundance to make mining profitable varies considerably. Brooks (1976, p. 149) credited former USGS Director V.E. McKelvey with pointing out that titanium has been mined from deposits having grades *below* its average crustal abundance, whereas, for antimony, the concentration has needed to be as high as more than 300,000 times its crustal abundance for mining to be economic.

Finally, a mineral commodity may be scarce because of the lack of technology needed to effectively and economically mine and process ore material into a usable (and marketable) product. The need for such technology is dictated by the intended use. If a mineral commodity can be used effectively while containing some impurities, then the absence of processing technology to separate impurities is not a factor that contributes to scarcity. If removal of impurities is necessary, then the absence of such technology increases scarcity (Brooks, 1965, p. 23–24).

In "United States Mineral Resources," Erickson (1973) estimated the resource base—that is, the total amount of a mineral or metal in the earth (Lusty and Gunn, 2015, p. 266)—by using estimates of elemental concentrations in Earth's crust. In the present volume, the mineral commodities included have crustal abundances that range from 5,650 parts per million (ppm) (titanium) to 0.0007 ppm (rhenium). The crustal abundance of the mineral commodities (elements) discussed in this volume are listed in table A1.

Some of the chapters in this volume give different elemental abundances than those presented in table A1. This reflects that different sources were used for the information and, in some cases, abundances were for the upper continental crust versus the total crust. Rudnick and Gao (2003) reviewed current estimates of the composition of continental crust and discussed the methods employed to derive the estimates.

Mineral Commodities Selected for Inclusion in This Volume

The use of terms such as "critical," deficient," "essential," and "strategic" to identify minerals or lists of minerals that are considered important by some observer(s) has a long and complicated history (appendix A1). In addition to implying a general level of importance, the word "critical" has been used to describe minerals or materials whose "criticality," as quantified by various analytical approaches, has been determined to exceed some specified limit. Some of the numerous studies that have been conducted to quantify or rank the criticality of selected mineral commodities have focused on the broad resource needs of current and emerging technologies (National Research Council, 2008; European Commission, 2010), whereas others have focused on certain sectors only, such as the energy sector (Massachusetts Institute of Technology, 2010; U.S. Department of Energy, 2011) or the national security sector (McGroarty and Wirtz, 2012). As a result, the mineral commodities classified as critical by each of these studies differ, although many of the findings include some of the same mineral commodities, such as some or all of the rare-earth elements and platinum-group elements.

The 23 mineral commodities or commodity groups selected for coverage in this volume (antimony, barite, beryllium, cobalt, fluorite, gallium, germanium, graphite, hafnium, indium, lithium, manganese, niobium, platinum-group elements, rare-earth elements, rhenium, selenium, tantalum, tellurium, tin, titanium, vanadium, and zirconium) have been listed as critical and (or) strategic in one or more of the recent studies based on assessed risks to their supply and (or)

Table A1. Crustal abundances of mineral commodities (elements) included in this volume.

[Source: Jefferson Science Associates, LLC (2014). ppm, part per million]

Element	Symbol	Crustal abundance (ppm)
Titanium	Ti	5,650
Manganese	Mn	950
Fluorine	F	585
Barium	Ba	425
Carbon	C	200
Zirconium	Zr	165
Vanadium	V	120
Cerium	Ce	66.5
Neodymium	Nd	41.5
Lanthanum	La	39
Yttrium	Y	33
Cobalt	Co	25
Scandium	Sc	22
Lithium	Li	20
Niobium	Nb	20
Gallium	Ga	19
Praseodymium	Pr	9.2
Samarium	Sm	7.05
Gadolinium	Gd	6.2
Dysprosium	Dy	5.2
Erbium	Er	3.5
Ytterbium	Yb	3.2
Hafnium	Hf	3
Beryllium	Be	2.8
Tin	Sn	2.3
Europium	Eu	2
Tantalum	Ta	2
Germanium	Ge	1.5
Holmium	Ho	1.3
Terbium	Tb	1.2
Lutetium	Lu	0.8
Thulium	Tm	0.52
Indium	In	0.25
Antimony	Sb	0.2
Selenium	Se	0.05
Palladium	Pd	0.015
Platinum	Pt	0.005
Osmium	Os	0.0015
Iridium	Ir	0.001
Rhodium	Rh	0.001
Ruthenium	Ru	0.001
Tellurium	Te	0.001
Rhenium	Re	0.0007

impact of potential supply restrictions. They are viewed as critical to a broad range of existing and emerging technologies, renewable energy, and national security (National Research Council, 2008; Massachusetts Institute of Technology, 2010; U.S. Department of Energy, 2011). They all have specialized and important applications in high-tech industrial, energy, defense, and (or) medical sectors, often with no effective substitutes. For some, current production is largely limited to only one or a few countries (for example, cobalt, niobium, rare-earth elements, and platinum-group elements), making their supply vulnerable to potential influence and disruption by such factors as civil unrest, political changes, natural disasters, environmental issues, and market manipulation. For many, the United States currently has neither mine production nor significant identified deposits and is largely dependent on imports to meet its resource needs.

This volume does not cover all 65 mineral commodities and commodity groups presented in “United States Mineral Resources” because the global resource picture for many of the major base, ferrous, and precious metals is already relatively well understood and documented, and the information on future sources of supply has not changed significantly in the past 40 years. Many of the commodities or commodity groups covered in the present volume, on the other hand, were considered less significant in the early 1970s because of their limited uses, and the documentation on them was sparse. In this volume, greater emphasis is placed on the global distribution of resources of these minerals than was the case in “United States Mineral Resources.” In addition, for each mineral commodity, the text includes a discussion of the environmental issues related to its production, including current mitigation and remediation approaches to deal with these challenges.

Work on this volume began in 2013, and the writing and technical reviews of the chapters were completed between 2014 and 2016. As a result, there are some differences between chapters, particularly with respect to the most recent information regarding identified resources, reserves, and production.

Changes Since the Mid-1970s

The status of global mineral resources and mining has changed significantly since the publication of “United States Mineral Resources.” The annual world production of most mineral commodities has increased markedly—in the case of the minerals covered in the chapters of this volume, the changes from 1973 to 2015 range from a modest 21 percent increase in annual tin production to a 2,800-percent increase (more than 29 times as much production!) for gallium. In light of this increased demand, concerns about possible weak links in the supply chains for mineral commodities have highlighted the need for reliable, regularly updated minerals information that is both broad in the scope of the mineral commodities covered and expansive in geographic reach. In addition, there is need for reliable assessments of the global distribution of mineral resources, their potential for supply disruption, and the environmental consequences of their production and use (Herrington, 2013).

Geologic knowledge and research technologies have also changed significantly since the publication of “United States Mineral Resources.” During the 1960s, the theory of plate tectonics had been formulated and most geologists had embraced it, but as of the early 1970s, the implications for ore-deposit geology were still only dimly perceived. Today, several plate-tectonic processes are seen to control the genesis of most mineral-deposit types, and such other factors as paleoclimate and time in Earth history are also recognized as important.

Geologic maps remain the main prerequisite in the exploration for ore deposits, and the past four decades have seen huge strides in the amount and quality of geologic map coverage of the world, especially in the less developed countries. New software developments have made it possible for all geologists to use the once-specialized toolkit of satellite remote sensing. Methods of isotopic analysis have vastly improved, and it is now possible to date many ore deposits accurately and precisely, so that their origins can be understood in terms of the regional geologic and tectonic history. It is also possible to analyze a tiny sample of rock or ore chemically for virtually any element in the periodic table, including those elements that are the focus of this volume. All these scientific advances have helped to bring down the cost of mineral exploration and raise the probability of success. Despite these advances, however, continued research is essential for future geologists to find, and engineers to develop, mine, and process, increasing amounts of mineral resources to meet future needs.

Furthermore, as discussed by Seal and others (this volume, chap. B), people, governments, and corporations are much more aware than before of the environmental impacts of mineral resource extraction and use. Environmental challenges for the future remain, such as increased mine-waste and water management issues, including those caused by the effects of climate change, and the aspect of more energy-intensive mining operations.

Back to the Future

Despite the many changes in the status of global mineral resources and mining and the advances in geologic knowledge during the past 40 years, much of the previous analysis—and cautions—about mineral supplies and knowledge of them remains relevant. Cameron’s (1973) statements about the U.S. mineral position, based on his analysis of U.S. mineral history and world mineral history since 1939, are perhaps even more pertinent today. McDivitt and Manners (1974, p. 10–11) wrote that in spite of the inescapable facts “that the total amount of each and every mineral is fixed and that use diminishes this given stock, …the availability of minerals is expanded steadily by a growing knowledge of the world’s geology, by the falling real costs of transport that allow minerals to be moved over ever-increasing distances, and by the development of techniques that permit the processing of different types of ore, often without more costly effort.” They tempered expectations that these factors would keep major problems of inadequate mineral supplies at bay with cautions about how far into the future these expectations could be extended. At some point, increases in real costs for some minerals might result in changes in consumption, including the use of substitute materials.

Tilton (2003, p. 101–102) concluded that “depletion raises the specter of a world where resources are too costly to use rather than a world with no resources,” but that “the past is not necessarily a good guide to the future,” especially to the more distant future. He added that “More geologic information on the incidence and nature of mineral deposits, particularly subeconomic mineral deposits, could go a long way toward resolving this critical issue by providing useful insights on the nature and shape of cumulative supply curves” but that this information is not likely to become available soon because of the lack of economic incentives to gather information on deposits that are not currently profitable to develop (Tilton, 2003, p. 103).

Former mining industry executive Simon Strauss drew on his 1986 book, “Trouble in the Third Kingdom,” when he delivered a presentation titled “The Appetite for Minerals” at a seminar at the USGS National Center on April 18, 1989. Mr. Strauss concluded that continued success in addressing mineral supply problems could be expected by stimulation of domestic production; increases in recycling, conservation, and substitution; and the use of stockpiles. When asked if that view might indicate a lack of need for further research on the geology of mineral deposits and on mining and mineral processing technology, such as that done by the USGS and the U.S. Bureau of Mines, Mr. Strauss replied that the contributions of those institutions were an important reason for his optimistic outlook, but that the role of those institutions in helping ensure adequate past and future mineral supplies was widely appreciated and that they would continue to perform those roles. The closure of the U.S. Bureau of Mines in 1996 indicates that the appreciation of the value of scientific research that provides the foundation for solving future resource problems should not be taken for granted.

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Appendix A1. What is Meant by "Critical" Minerals (or Materials)?

Problems resulting from the lack of domestic production of certain mineral commodities became apparent in World War I when "Minerals that were essential to the war effort … could not be produced in adequate amounts from domestic sources…" (Cameron, 1986, p. 254). These became known as "strategic minerals." Charles Kenneth Leith has been credited with compiling the first of many lists of "strategic and critical minerals" when he was serving as a mineral adviser to the War Industries Board in 1917—this "unofficial" list was industrial in character, rather than defense oriented (Roush, 1939, p. 10). The first "official" list was prepared under the auspices of the Supply Division of the General Staff on January 20, 1921 (Pehrson, 1944, p. 339). The plethora of lists that followed seems to bear out an observation of a university administrator that ranking (and listing) things is "a part of the DNA of America" (Pope, 2013, p. 31). Roush (1939, p. 2–10) documented 15 different lists of strategic and critical minerals and materials created from 1917 through 1939; there were both official lists and unofficial lists that categorized minerals as strategic (from the standpoints of industrial needs, defense needs, or both), critical ("those minerals which might be expected to develop a shortage with increased demand, but which, with careful control of consumption and proper stimulation of production, might be maintained on a self-supporting basis"), essential ("essential materials neither strategic nor critical"), and deficient ("in a major degree" and "to a lesser degree"). In addition, there were several changes in the stated meaning of the terms and differences in their application over time, depending upon the perspective of the person or groups of persons compiling the lists (Roush, 1939, p. 3).

Pehrson (1944, p. 339–340) attempted to set the record straight in this regard by defining strategic materials as those that were essential for defense and for which the United States relied on foreign supply sources, and critical materials as those that were essential to defense but less difficult to obtain because they were less essential or had domestic supply sources. In 1944, the Army and Navy Munitions Board approved a new definition of "strategic and critical materials" (with no distinction between the two adjectives) as "…those materials required for essential uses in a war emergency, the procurement of which in adequate quantities, quality, and time is sufficiently uncertain for any reason to require prior provision for the supply thereof." In the Strategic and Critical Materials Stock Piling Act (50 U.S.C. §98), "The term 'strategic and critical materials' means materials that (A) would be needed to supply the military, industrial, and essential civilian needs of the United States during a national emergency, and (B) are not found or produced in the United States in sufficient quantities to meet such need." Pehrson (1944, p. 341) documented the changes as to which minerals were classified as strategic, critical, essential, or strategic and critical in several lists since the first official list was compiled in January 1921. McKinstry (1948, p. xvii–xix) attributed the increased attention concerning strategic minerals in the 1940s to "geological economists" and observed that, in time of war, "almost all useful minerals become strategic" and information about where minerals occur and how soon and for how long they can be produced is "critical."

The American Geological Institute "Dictionary of Geological Terms" (1962, p. 113, 475) defined critical [materials] and strategic [materials] separately. The Commerce Department representative on the staff of the 1978–79 Presidential Review of Nonfuel Minerals Policy succinctly summarized the two-definition concept by saying, "Critical means you need it; strategic means you don't have it!" (William J. Kaestner, U.S. Department of Commerce, oral commun., 1978). In contrast, Evans (1993, p. 10) stated, "A material needed for military purposes is considered strategic and a material is termed critical if future events involving its supply from abroad threaten to inflict serious harm on a nation's economy" (DeYoung and others, 2006, p. 486).

The number of minerals classified as strategic, critical, vital, deficient, or strategic and critical (with frequent changes in definitions of the terms and as viewed from the perspectives of various stakeholders) increased from 4 in World War I, to 9 in 1939, to 52 later in World War II (Hewett, 1959, p. 191). In 1974, the President's Council on International Economic Policy reported on a list of 19 critical materials, but did not provide a definition of critical (Council on International Economic Policy, Executive Office of the President, 1974). A 1982 National Indicators System report on the domestic supply of critical minerals explained that classification of minerals as strategic or as critical changes over time across countries, industries, and users and that the determination of which minerals were "strategic and critical" was made by the executive branch of the Government. For the purposes of that report, the 15 "critical" minerals chosen were based on one or more of several considerations, including the large amounts used and resulting importance to the economy, strategic importance to national defense, special properties not readily found in other materials, reliance on imports for domestic consumption, and alloying properties (U.S. Bureau of Mines, 1982, p. 2–3). In advocating a national geochemical census and increased support for basic research, Yoder (1982, p. 229) stated that all the minerals for which the United States was more than 50 percent import reliant in 1979 were critical to the economy and that they could be classified as "strategic" if they met one or more of four criteria describing their geologic availability, technology necessary to bring them to market in a timely fashion, the "possibility that unforeseen essential uses may develop," and the reliability of foreign sources. When the National Critical Materials Council was established in 1984, the enabling legislation (30 U.S.C. §§1801–1811) specified a definition for "materials," but not for "critical." Some lists that use "critical" as a modifier explicitly restrict the definition of critical to that applied to a particular end use, such as "energy-critical" minerals (American Physical Society and the Materials Research Society, 2011; U.S. Department of Energy, 2011).

Conflicting uses of terms to describe critical and (or) strategic minerals led Archer (1980, p. 2) to question whether the cobalt in the turbine blades of a jet engine was more strategic or critical than the petroleum-based fuel or the materials used in constructing the runway. He concluded that the term "strategic" was used by some as an impressive synonym for "important" and that "criticality" as measured by the part that a mineral plays in everyday life, industry, and defense, is not related to its source of supply.

When they addressed their question, "How critical are critical materials?", Clark and Field (1985, p. 38–40) did not present a way to measure criticality but concluded, after examining statistics on net import reliance, that mechanisms to address short-term and long-term problems that might result from disruptions in mineral supplies were already in place (stockpiles, conservation, recycling, and development of alternative materials). Scientists in the Department of the Interior's Office of Minerals Policy and Research Analysis had already begun to develop a new measure, the Critical Minerals Index (CMI). They recognized that the "imports market share" measure ignored the two primary determinants of mineral criticality—supply risk and economic importance—and was thus of little use to policymakers in focusing attention on supply problems for specific minerals (Adams and others, 1979, p. 1–2). Two CMI components were identified for each mineral commodity—a Mineral Disruption Index (the likelihood of disruption of U.S. imports during the time period of consideration) and a Mineral Cost Index (the annual cost imposed by the import disruption; Adams and others, 1979, p. 4–5).

In 2008, these two components were used by the National Research Council's Committee on Critical Mineral Impacts on the U.S. Economy to develop a two-dimensional graphical approach to define and measure criticality, the "criticality matrix," which was applied to several nonfuel mineral commodities (National Research Council, 2008). Subsequent studies have added a third dimension (environmental implications) to the matrix, considered the implications of specifying a time dimension, added net present value calculations to the economic value (cost) dimension, and incorporated the determinants of risk into the vulnerability dimension (Erdmann and Graedel, 2011; Graedel and others, 2012; Glöser and others, 2015; Graedel and Reck, 2015; Mayer and Gleich, 2015). Studies that have applied these approaches to produce quantitative measures of criticality have incorporated existing data series as surrogates for the components; for example, Silberglitt and others (2013, p. 4) used the Herfindahl-Hirschman Index (a measure of the concentration of market power and international trade) as a measure of the geographic concentration of mineral production and the World Bank's Worldwide Governance Indicators (a measure of the quality of governance in six dimensions) as a measure of supply risk where reliability of supply might be affected by political instability, government control of mineral production, or restrictive trade policies.

In 2016, the National Science and Technology Council (NSTC) issued a report that provided and applied a systematic methodology to screen for potentially critical minerals. The report summarized an interagency effort to develop a screening process to assess "potential criticality" based on three fundamental indicators: supply risk, production growth, and market dynamics. The screening was applied to 78 minerals or mineral commodities for each year from 1996 through 2013. This study defined critical minerals to be "those that have a supply chain that is vulnerable to disruption, and that serve an essential function in the manufacture of a product, the absence of which would cause significant economic or security consequence," and strategic minerals as "a subset of critical minerals and are those that are essential for national security applications" (National Science and Technology Council, 2016, p. ix).

In wrestling over the question of "Which materials are 'critical' and which are 'strategic'?", Simandl and others (2015, p. 59) concluded that "misunderstanding, miscommunications and potentially misrepresentations" can result from the lack of consistency in use of the terms "critical" and "strategic" and that "Which materials are considered critical depends to a large extent on the priorities and objectives of the organization or country that commissions the study." This observation about the necessarily subjective nature of determining criticality—depending upon who commissions a study about critical minerals, makes a list of critical minerals, or devises a process to define and measure criticality of minerals—has been stated explicitly in many studies and is implicit in all the rest. The economic concept of utility, how useful or satisfying a good, service, or action is to an individual, underlies the formation of priorities and objectives. In fact, as noted by Sears (2011), "it is impossible to compare utility levels of different people" and thus "modern utility theory does not allow the economist to combine individual utilities into one number for all society." Recognition of the role of perspective in determining what is "critical" or important and the attendant limitations of such determinations is a critical element in understanding what is meant by "critical" minerals.

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Prepared by the USGS Science Publishing Network
Reston Publishing Service Center
Edited by J.C. Ishee
Illustrations by Caryl J. Wipperfurth
Layout by Caryl J. Wipperfurth and Cathy Y. Knutson
Posting by Angela E. Hall

Schulz and others—**Critical Mineral Resources of the United States—An Introduction**—Professional Paper 1802–A

ISSN 2330-7102 (online)
https://doi.org/10.3133/pp1802A