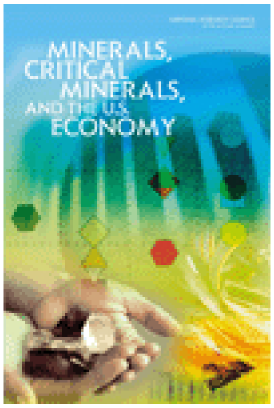

Minerals, Critical Minerals, and the U.S. Economy

Committee on Critical Mineral Impacts of the U.S. Economy, Committee on Earth Resources, National Research Council

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CHAPTER 1

Critical Minerals

INTRODUCTION

Archaeologists and historians describe early civilizations and periods of human history using terms such as the Stone Age, the Copper Age, the Bronze Age, and the Iron Age. Such descriptions reflect the fundamental importance of nonfuel minerals, metals, and materials technology and applications. Early civilizations were built to a significant degree using the seven metals of antiquity (in order of discovery): gold (6000 BC), copper (4200 BC), silver (4000 BC), lead (3500 BC), tin (1750 BC), iron (1500 BC), and mercury (750 BC). Each discovery led to a range of innovations and applications that provided a marked advantage until such time as it was adopted by competing civilizations or overtaken by other innovations. Advances were not limited to military technology but extended to agricultural implements, food storage and preparation, therapeutic and cosmetic applications, and many other aspects of daily life and culture. The much later discovery of arsenic, antimony, zinc, and bismuth in the thirteenth and fourteenth centuries was followed by platinum in the sixteenth century and another 12 metals or metalloids in the eighteenth century, bringing the total number of known metals and metalloids to 24. Most known metals and metalloids were discovered only in the past two centuries.

As our ability has advanced to produce new materials and to characterize, predict, and exploit the chemical and physical properties of minerals, it has become possible to develop new applications that improve the technical performance, durability, and reliability of products; deliver greater value to businesses and consumers; and reduce environmental burdens. In the Information Age, developments in materials science and engineering, mineral exploration, and processing continue to enable and support the development of new technologies. The unique properties of nonfuel minerals, mineral products, metals, and alloys contribute to provision of food, shelter, infrastructure, transportation, communications, health care, and defense. The cellular telephone is one familiar example that illustrates the dependence of a globally important technology on minerals, their chemical and physical properties, and the materials created with them (Box 1.1).

Products depend on essential nonfuel minerals and mineral products the supply of which is sometimes subject to disruption or restriction. In the short or medium term (a few months to a decade), the balance between demand and supply often is fragile and prices may thus be volatile. Over the longer term (more than about 10 years), the availability of nonfuel minerals and mineral products depends heavily on investments in people and technology. Insufficient investment today can lead to restrictions on availability in the future.

This study was undertaken to investigate and highlight both the importance of nonfuel minerals and mineral products in modern U.S. society and the extent to which the availability of these minerals and mineral products is subject to restriction in both the short to medium terms and the long term.

BACKGROUND OF STUDY AND COMMITTEE CHARGE

This study was an outgrowth of meeting discussions and professional exchanges during the past several years conducted by the Committee on Earth Resources (CER) of the National Research Council (NRC) on the topic of nonfuel minerals, their availability and use in domestic applications, and their continued national importance in a global mineral market. The committee was concerned that the impacts of potential restrictions on the supply of nonfuel minerals to different sectors of the U.S. economy were not adequately articulated in the national discussion of natural resource use, and that federal responsibilities to acquire and disseminate information and conduct research on nonfuel minerals were not well defined in a global framework that also accounts for the complete mineral cycle from exploration to recycling (NRC, 2004a, b). Aware of the numerous NRC studies on the topics of nonfuel minerals, federal minerals policy, and federal programs tasked with mineral research and information, the committee suggested that recognition of those minerals that could be considered pivotal, or "critical," for a particular industrial, civilian, or military sector is an important aspect of the nonfuel mineral discussion that had not yet been addressed in an independent NRC report. The committee drafted a prospectus for a study designed to inform public policy on critical mineral impacts on the U.S. economy.

Numerous federal agencies and professional organizations were asked by CER to comment on the committee's study formulation. The U.S. Geological Survey (USGS) and the National Mining Association deemed the issue sufficiently important to bring forward to public discussion in the form of an NRC study. The NRC thus established the Committee on Critical Mineral Impacts on the U.S. Economy to address the issues outlined in the study's statement of task (Box 1.2). The committee consists of nine experts from academia, industry, the federal sector, and Natural Resources Canada. These individuals contributed their professional expertise in areas of mineral exploration and ore deposits, mineral economics, metallurgy, statistics, federal and international standards, regulatory policy, recycling, industrial materials and manufacturing, and mineral processing and engineering, including nanotechnology (Appendix A).

This report constitutes the committee's response to the study charge. This first chapter reviews some of the important issues the study committee has extracted from previous NRC reports on the topic of nonfuel minerals and the mineral life cycle, the committee's interpretation of the term "critical mineral," and the framework in which the committee found it most useful to determine a mineral's criticality.

PREVIOUS AND ONGOING WORK

A number of NRC reports published during the last two decades have analyzed or evaluated a variety of national nonfuel mineral issues. The

BOX 1.1
Cellular Phones, Minerals, and Technology

Cellular phones have become omnipresent in today's society; in 2006, worldwide mobile phone sales exceeded one billion units, an increase of about 21 percent over sales in 2005 (*http://www.gartner.com/it/page.jsp?id=501734*; accessed September 5, 2007). What is not widely recognized is the dependence of cell phone performance, and therefore the communications system, on a wide variety of minerals, many of which can be scarce or expensive to process.

The technological barrier to cellular communication was overcome only in the 1970s with the discovery of barium titanate ceramics. These ceramics possess the requisite dielectric properties to avoid signal broadening and heat buildup, while operating over a wide temperature range at a consistent frequency. Other essential components of the cellular telephone include ceramic magnetic switches that contain rare earth elements (REs) and indium, and the base stations for the cell phone networks that also use the element indium, as well as tantalum. Each of these minerals has specific properties important to the function of the given component for which substitution of other minerals or their derived materials is presently difficult (see figure on facing page).

The commercial picture for cellular communications is complex. The global market for the ceramic (mineral) materials used in the telephone is relatively small ($400 million to $500 million; Vanderah, 2002); however, these materials are essential for the manufacture of the telephone components, the market for which is approximately 10 times larger. The end-user commercial market is the cellular communication systems (including the base station infrastructure) that make use of the components with a market value on the order of 100 times that of the basic materials. This is the reason that most people are offered a free cell phone if they subscribe to a telephone service.

One of the primary issues in material availability is that of obtaining high-quality titanium dioxide (TiO_2), the basic starting material from which the dielectric heart of the phone (as well as numerous critical components in base stations) is produced. In recent years, suppliers in England, Canada, and Germany have shut down because of environmental concerns associated with chloride processing of the materials (T. Negas, personal communication, March 2007).

Markets for many of the specialized minerals or mineral products in the cell phone are small in that the volume of material needed for cell phones is small. As a result, a new or expanding use significantly increases overall demand for the element and prices can increase significantly. Indium is a prime example. Indium tin oxide, an ingredient used in the production of liquid crystal display products for many applications including cell phones, has come under increasing demand during recent years (short term) and indium prices rose from about $200-300 per kilogram in the late 1990s to more than $800 per kilogram in 2006 (USGS, 2007).

Tantalum and REs are subject to similar increases in demand although their prices have not experienced similar recent increases. Tantalum is essential for the dielectric resonators in 2.2 gigahertz cellular base stations. Although some substitutes for tantalum exist, they result in a loss of performance (i.e., more dropped calls) or shorter battery life. REs are needed for ceramic magnetic switches in the cell phone. Since the only U.S. RE mine operated by Molycorp has been closed, manufacturers of components have become dependent primarily on Chinese suppliers for REs. China is the world's largest exporter of REs.

Cellular telecommunications will not be shut down because of mineral supply restrictions. However, supply restrictions for specific minerals, should they occur, will slow the development of better systems that use restricted minerals. At the same time, higher mineral costs could also motivate the development of new technologies that incorporate mineral substitutes yielding the same performance as the restricted mineral.

Cutaway image of a cellular phone showing the interior components, many of which contain and depend on minerals and mineral products to function. SOURCE: CAP-XX Ltd.

BOX 1.2
Statement of Task

Understanding the likelihood of disruptive fluctuation in the supply of critical minerals and mineral products for domestic applications, and making decisions about policies to reduce such disruptions, requires thorough understanding of national and international mineral sources, mineral production technology, the key uses of minerals and mineral products in the United States economy, and potential impediments to the mineral supply.

This study will:

1. Identify the critical minerals and mineral products that are essential for industry and emerging technologies in the domestic economy.
2. Assess the trends in sources and production status of these critical minerals and mineral products worldwide.
3. Examine the actual or potential constraints, including but not limited to geologic, technologic, economic, and political issues, on the availability of these minerals and mineral products for domestic applications.
4. Identify the impacts of disruptions in supply of critical minerals and mineral products on the domestic workforce and economy.
5. Describe and evaluate the current mineral and mineral product databases and other sources of mineral information available for decision making on mineral policy issues.
6. Identify types of information and possible research initiatives that will enhance understanding of critical minerals and mineral products in a global context.

reports have included congressionally mandated studies, as well as those conducted at the direct request of federal agencies. Some of the studies have evaluated existing federal programs—for example, those of the U.S. Bureau of Mines (NRC, 1994, 1995a) and the USGS and its Mineral Resources Program (NRC, 1996a, 2001, 2004a)—or have been broader in scope, covering regulatory issues of hardrock mining on federal lands (NRC, 1999), mineral resources and sustainability (NRC, 1996b), mining technologies (NRC, 2002), material flow analysis (NRC, 2004b), the competitiveness of the U.S. mining and metals industries (NRC, 1990), and mineral supply issues for specific end uses such as gas turbine engines (NRC, 1995b). This study differs from those previous reports. The broad study task asks the committee to determine which minerals could be considered critical to the nation and what, if any, additional information and research might be appropriate for the federal government to collect and conduct to mitigate disruptive fluctuations in the supply of critical minerals to key U.S. economic sectors. The audience for the study thus includes not only federal agencies, industry, and research organizations, but necessarily also the general public and decision makers.

The committee notes that several important conclusions and recommendations repeatedly emerged from the previous NRC reports noted above. The committee concurs with these recommendations and underscores the fact that their repetition is an indication that they have yet to be fully implemented. The following list paraphrases some of the overarching conclusions and recommendations from those reports that the committee found most compelling as related to this study:

- The United States is a major user and producer of mineral commodities, and the U.S. economy could not function without minerals and the products made from them.
- The federal government should lead the development of coordinated efforts among academic, private, and federal sectors related to research and information collection on minerals and metals.
- The federal government has a responsibility to conduct and support research and to gather and disseminate information on minerals and metals.
- Market forces alone are not sufficient to meet challenges of sustainability, so the federal government should help facilitate activities that sustain mineral supplies, including exploration, development, technology, recycling, and appropriate environmental protection.
- The federal government should maintain core competence in the knowledge of mineral deposits and related environmental research, as well as information collection, to respond to future national needs.

- Globalization means that mineral resources have become an issue with importance for national security.

The existence, scope, and size of the National Defense Stockpile (NDS) has also often been part of the national discussion of critical or strategic minerals, particularly as the NDS addresses issues regarding which minerals might be considered critical and strategic for the purpose of national security. The present committee has been fortunate in that a complementary study that assessed the need for an NDS was conducted concurrently by the National Materials Advisory Board of the NRC (NRC, 2007). National defense-related minerals issues are thus incorporated in the present report only briefly as one subset of the broader U.S. economic picture; the interested reader is otherwise referred to the NDS report for detailed discussion of defense-related minerals and materials (NRC, 2007).

THE CYCLE OF MINERALS AND MATERIALS

Fossil fuels, with their geologic origins as organic materials, are consumed when burned to generate usable energy. As such, they are destroyed and not available for use later. Such is not the case for nonfuel minerals, which in principle can be recycled after initial use. Thus, minerals and mineral products are available as primary resources (extracted from Earth's crust) and also as secondary resources (recovered from scrap). In addition, for a country or region—as opposed to the planet as a whole—the importation of metals or metal-containing products serves as an additional ("tertiary") resource. Therefore, the availability of minerals, mineral products, and materials in the United States ought to be viewed and evaluated as a cycle of materials similar to some of the groundwork presented in the NRC (2004b) report *Materials Count: The Case for Material Flow Analysis*.

The importance of considering the entire materials cycle in the analysis of nonfuel minerals and mineral criticality can be appreciated by examining the copper cycle shown in Figure 1.1. Of the 2830×10^3 metric tons (Gg; 1 Gg = 10^3 metric tons) of copper entering use, about 70 percent (1987 Gg, or 2235 Gg ore minus 248 Gg ore entering repositories) was primary copper; 16 percent (450 Gg) was secondary copper; and 14 percent (510 Gg imported minus 117 Gg exported) was tertiary copper. About 570 Gg of copper, or about one-fourth as much as was mined domestically in 1994, was either landfilled or dissipated. It is notable that the copper system is not at steady state. While inventories of copper may increase or decrease in a given year at the production stage and the fabrication and manufacturing stage, the total stock of copper in use tends to increase over time, as does the stock of copper in landfills and other repositories. For example, Figure 1.1 shows that in 1994, of the total flow of copper entering use (2830 Gg), 55 percent (or 1570 Gg) represented net additions to the total stock of copper in use in products.

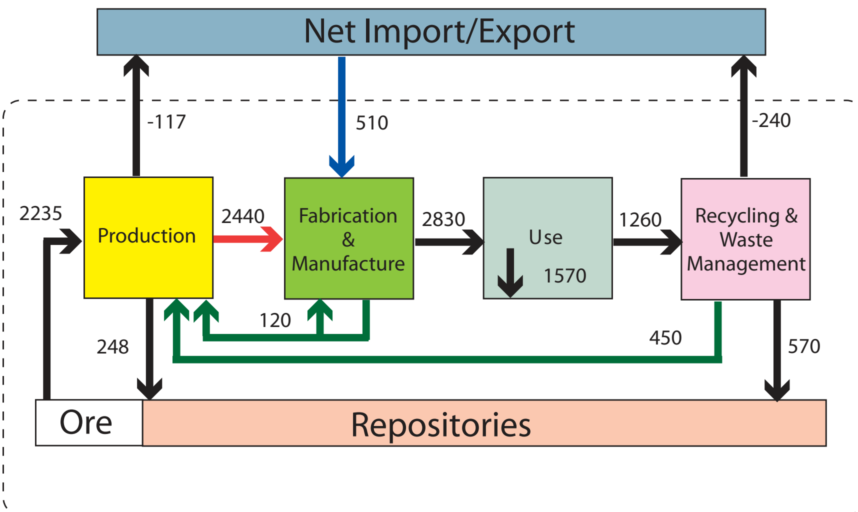

FIGURE 1.1 The U.S. copper cycle in 1994 showing the balance of flows of material for different purposes. The units are thousand metric tons (Gg) of copper. The diagram shows the balance between processing of domestic copper ore (red arrow) plus recycled material (green arrows) and the imported material in semifinished or finished products (blue arrow). Negative numbers and corresponding black arrows represent exports. For many countries, recycled and imported flows are important contributors to the available metal resources. SOURCE: Concept from Graedel et al., 2004.

From this perspective, in-use mineral stock is a future secondary resource and can be regarded with as much interest and analytic rigor as virgin ore bodies. Materials contained in products or applications that reach the ends of their lives in a given time period represent a flow of material that is considered to be available for recycling. On Figure 1.1, for example, about 55 percent of the copper that was removed from service is seen to have been either recycled within the United States (450 Gg) or exported (240 Gg), primarily for scrap processing outside the United States, while 45 percent was discarded to landfills (570 Gg). Material contained in landfills is another secondary resource and could be recovered in the future, but its quality is degraded when mixed with other materials, resulting in a loss of value. The metal content of landfills is difficult to estimate and is highly dependent on the diversion programs in place (e.g., Chandler et al., 1997; Gordon et al., 2006).

Economics and regulations influence the degree to which current needs are met by primary or secondary material (from the global perspective, any tertiary material is fundamentally either primary or secondary). However, a number of other characteristics contribute to the desirability of choosing between different sources for materials, as shown in Table 1.1. In general, primary material benefits from the technological knowledge gained from millennia of discovery and processing, but resource conflicts and other issues can make the exploitation of these stocks problematic. In contrast, secondary or recycled materials possess fewer issues that are potentially problematic, but the collection and reprocessing technologies for those materials are less highly developed. The committee finds it imperative to include the concept of the entire mineral and material cycle in its discussion of mineral criticality.

WHAT IS A CRITICAL MINERAL?

Recognizing that a nonfuel mineral or mineral product can be obtained as either primary or secondary material, what does it mean to say that one of these minerals or mineral products is a *critical mineral*?

In the context of federal communications regarding minerals, the terms

TABLE 1.1 Attributes of Primary and Secondary Materials

	Advantages	Disadvantages
Primary materials	Extensive extraction and processing experience	High energy and water use and air emissions
	Established product specifications and markets	Political disruption a possibility
	Technologies to control impurity levels are well developed	Impacts are "hidden" (often occur in countries other than those in which the material is used)
		Extraction and processing generates high volumes of mine rock, tailings, slags, and residues
Secondary materials	Mostly available in user countries	Collection can be difficult and reprocessing technology is relatively primitive
	Low energy and water use and air emissions	Inappropriate recycling practices pose occupational and environmental health risks in some countries
	Socially and politically acceptable	
	Processing generates low volumes of waste	
	Quality of recycled material is suitable for most applications	Quality of recycled material may not be suitable for some applications

"critical" and "strategic" as mineral or material descriptors have been closely associated, but usually not clearly differentiated. A review of some of these definitions is useful before describing the definition of critical mineral adopted by the committee for this report.

DeYoung et al. (2006) noted that, historically, "strategic materials" in the United States have generally been associated with material availability in times of war or national emergency; the term "critical material" did not enter the federal lexicon until just prior to World War II when it was introduced in the language for the Strategic and Critical Materials Stock Piling Act of 1939 (P.L. 96-41, 1939). The Strategic and Critical Materials Stockpiling Act of 2005 (50 U.S.C. 98 et seq.) defines strategic and critical materials as those that are needed to supply the military, industrial, and essential civilian needs of the United States during a national emergency that are not found or produced in the United States in enough quantities to meet such needs. Specific distinctions between "strategic" and "critical" are not offered in these documents.

The association of the term strategic mineral almost exclusively with national security and military needs or requirements during national emergencies is implicit in the synonyms for "strategic," which include planned, tactical, and calculated. "Critical" in general English usage can refer to something that is vital, important, essential, crucial, or significant. These differences are supported and further refined by definitions in the academic literature suggesting that materials for military uses are strategic, while those for which a threat to supply from abroad could involve harm to the nation's economy are critical (Evans, 1993, in DeYoung et al., 2006). This definition builds on the use of the term critical materials in the context of discussion around the establishment of the National Critical Materials Council in the mid-1980s. Critical materials in this context encompassed any materials—from metals to alloys to composites—on which the economic health and security of the nation resided (Robinson, 1986). A critical material thus has broader connotations than a strategic material, and its definition can be considered to include civilian, industrial, and military applications that could have measured effects on the nation's economy should supply of the material under evaluation become restricted. In accordance with these definitions, a critical material may or may not be strategic, while a strategic mineral will always be critical. This study addresses critical minerals, as opposed to those that may more narrowly be considered strategic, and may differ slightly, for example, from the definition of strategic used by the Industrial College of the Armed Forces (ICAF, 2006).

In the opinion of the committee, a mineral can be regarded as critical only if it performs an essential function for which few or no satisfactory substitutes exist. This dimension of criticality is therefore related to the demand for a mineral that meets very precise specifications required in certain key applications, but it is not simply related to overall demand for all applications. Instead, it reflects economic, social, and other consequences if essential functions cannot be delivered. In addition, a mineral can be regarded as critical only if an assessment also indicates a high probability that its supply may become restricted, leading either to physical unavailability or to significantly higher prices for that mineral in key applications. In turn, the probability of a restriction in the supply of a critical mineral is more likely to be assessed as high if the aggregate demand for key applications represents a relatively large proportion of the overall supply of the mineral that meets the required specifications. Examples presented later in this report also emphasize the distinction between minerals that are *essential* to the economy in certain applications and yet are *not critical*, at least at present, because the risk of supply restriction is low.

In its work, the committee found the concept of a "criticality matrix" to be a useful way to characterize the many variables that influence a mineral's criticality. Determining a mineral's criticality, then, is a means by which decision makers can help alleviate potential impacts of a restriction on the supply of a mineral, or avoid a supply restriction entirely through informed decisions. The matrix concept is developed qualitatively in the next section and in detail in subsequent chapters.

THE CRITICALITY MATRIX

The two important dimensions of criticality are *importance in use* and *availability*. Importance in use embodies the idea that some nonfuel minerals or materials are more important in use than others. Substitution is the key concept here. For example, if substitution of one mineral for another in a product is easy technically, or relatively inexpensive, one can say that its importance is low. In this case, the cost or impact of a restriction in the supply of the mineral would be low. On the other hand, if substitution is technically difficult or is very costly, the importance of the mineral is high, as would be the cost or impact of a restriction in its supply. This concept of importance at a product level significantly includes the net benefits customers receive from using a product—the benefits to human health of nutritional supplements or pollution control equipment, the convenience of cell phones, the durability of an automobile, and so on.

A nonfuel mineral can be important at a scale larger than a product as well as at the product level. A mineral might be important to the commercial success of a company and the company's profitability (importance at a company level). A mineral might be important in military equipment and national defense. Production of a mineral—or products that use the mineral as an input—might be an important source of employment or income for a local community, a state, or the national economy (importance at a community, state, or national level). In all of these cases, the greater the cost or impact of a restriction in supply, which depends importantly on the substitutability of the mineral in question, the more important is the mineral.

Availability is the second dimension of criticality. Fundamentally, society obtains all nonfuel minerals through a process of mining and mineral processing (primary supply). Later, however, in the course of fabrication and manufacturing—and ultimately after products reach the end of their useful lives—society can obtain mineral products through the processing of scrap material (secondary supply). Availability reflects a number of medium- to long-term considerations: geologic (does the mineral exist?), technical (do we know how to extract and process it?), environmental and social (can we extract and process it with a level of environmental damage that society considers acceptable and with effects on local communities and regions that society considers appropriate?), political (how do policies affect its availability both positively and negatively?), and economic (can we produce a mineral or mineral product at costs consumers are willing and able to pay?). In addition, it is important to consider the reliability or risk of supply in the short term. Is the nation vulnerable to unexpected disruptions in availability due to, for example, import dependence, market power in the hands of a small number of powerful producers, thin or small markets that are unable to respond quickly to changing circumstances, or significant changes in public policy that cut off supply or increase costs?

In both dimensions of criticality, time is an important consideration. In the short term (period of a few years or less) or the medium term (less than 10 years), both mineral users and producers generally are less able to respond quickly or effectively to changing market conditions than over longer time periods. Even within a particular period, however, some minerals will be more important in use and more vulnerable to supply disruptions than other minerals. For a given adjustment period (short term to long term), the critical minerals are those that are relatively difficult to substitute and are subject to supply risks.

Figure 1.2 illustrates this concept of criticality and the criticality matrix. The vertical axis embodies the idea of importance in use and represents the impact of supply restriction. The horizontal axis embodies the concept of availability and represents supply risk. One can evaluate a mineral's criticality by evaluating its importance in use and its availability, and locating it on the figure. The degree of criticality increases as we move away from the figure's origin, as shown by the arrow and the increased shading. Mineral A, for example, is more critical than mineral B. In this sense, criticality is appropriately considered a "more-or-less" issue rather than an "either-or" issue. That is, minerals exhibit differing degrees of criticality depending on the circumstances. Some minerals are more critical than others; it is a matter of degree rather than absolutes. To be sure, some mineral users or government officials may want to create a list of critical minerals, implying that minerals not on the list are not critical, for purposes of planning or policy making. The committee has not created a definitive list of critical minerals because it did not have the time or resources to assess all possible critical minerals. Rather, Chapter 4 illustrates how the matrix can be used and suggests several candidate minerals for criticality. The committee used a combination of quantitative measures and expert (qualitative) judgment in implementing the matrix methodology.

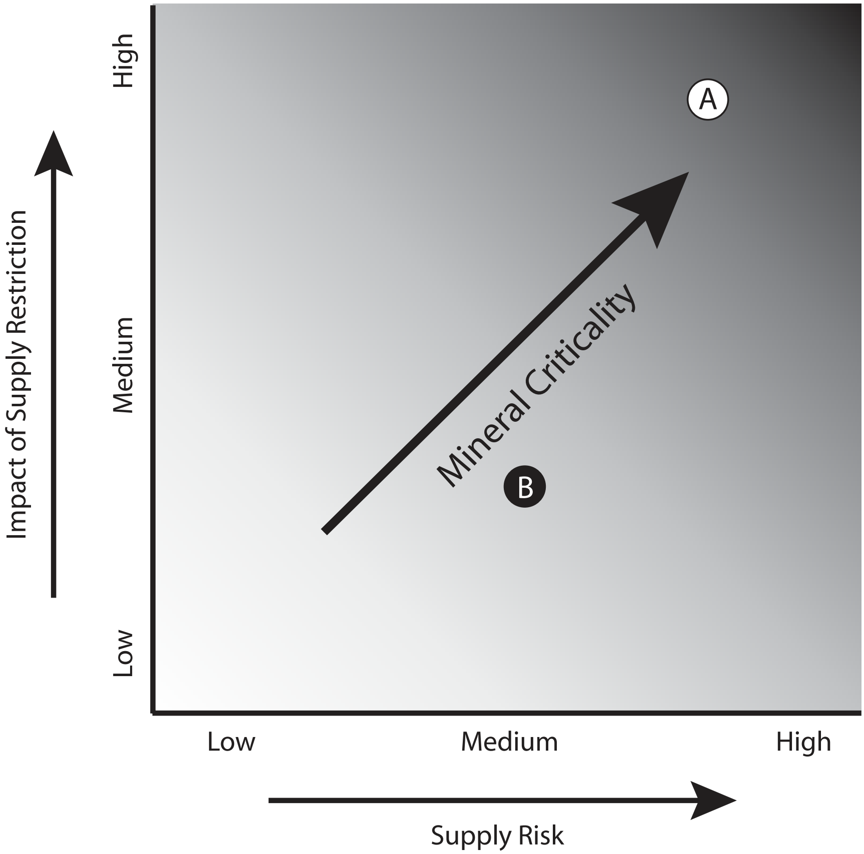

FIGURE 1.2 The criticality matrix, as established in this report, allows evaluation of the criticality of a given mineral. A specific mineral or mineral product can be placed on this figure after assessing the impact of restriction on the mineral's supply should it occur (vertical axis) and the *likelihood* of a supply restriction (horizontal axis). The degree of criticality increases as one moves from the lower-left to the upper-right corner of the figure. In this example, mineral A is more critical than mineral B. More specific descriptions of the parameters used to evaluate mineral supply restrictions and their impacts are presented in Chapters 2-4.

COMMITTEE PROCESS

To address the statement of task and establish report recommendations, the committee reviewed relevant NRC reports; information submitted by and requested from external sources, including two open meetings (see Appendix B); other published reports and literature; and importantly, information from the committee's own experience. The committee held three meetings in Washington, D.C., two of which were at the National Academies' Keck Center and one at the National Academy of Sciences Building (Appendix B). The first meeting in December 2006 included a dialogue with the study's sponsors and other federal agency participants. This meeting also allowed the scope of the concurrent NRC study on the NDS to be discussed, and the two NRC studies have functioned in a complementary and participatory manner during the open sessions of one another's meetings (see also NRC, 2007).

The second meeting of the committee, in March 2007, was the main information-gathering session of the study and consisted of a 2-day open session with four panel discussions. The meeting gathered a spectrum of panelists representing mineral product "users" from the private sector, and individuals who could speak about the sources for minerals and mineral products, the various potential constraints on mineral supply, and the data, research, and information on mineral availability and prices that can be provided to the public. One of the main questions the committee posed to the panelists was with regard to definitions of the term *critical mineral* as might apply to specific manufacturing sectors or consumers and users of mineral-containing products. These definitions weighed into the committee's deliberations to frame the concept of mineral criticality in this report. The final meeting of the committee was a closed session held in May 2007 at which time the recommendations were reviewed. Throughout the study process, the committee also received valuable input through informal interviews with various professionals associated with mineral information, use, and availability and was greatly supported in its work by voluntary contributions from a spectrum of interested individuals from across the country.

REPORT STRUCTURE AND CONCLUDING REMARKS

Having set the stage with this chapter, the committee has organized its analysis in the remainder of the report as follows: Chapter 2 examines the vertical axis of the criticality matrix—the importance of minerals in use—through examples that demonstrate specific applications of minerals and materials in some important U.S. industry sectors and the degree of mineral substitutability in these applications. Chapter 3 examines the horizontal axis of the matrix—the availability and reliability of mineral supply—to describe more completely the numerous factors that can affect mineral supply from short- through long-term periods. Chapter 4 demonstrates application of the matrix to evaluate mineral criticality by examining 11 mineral candidates. The minerals and their applications cross many more industry sectors than the four examined in detail in Chapter 2 and serve to underscore the ubiquitous applications for minerals in everyday life. Chapter 5 presents an overview of the federal data gathering, information, and research efforts appropriate for making informed decisions about minerals, in general, and critical minerals, in particular. Finally, Chapter 6 presents the report's main conclusions and recommendations.

The committee notes that the statement of task refers to "minerals and mineral products"; to streamline the text, the remainder of this document uses the term "minerals" to encompass nonfuel minerals and mineral products and materials, as well as metals. Key terms are otherwise defined in the text and collected together in the glossary (Appendix C). The committee is not consistent in its use of metric or imperial units; instead the report uses the units most commonly applied by the relevant organization or industry in each case and provides conversions where appropriate. While the report focuses on nonfuel minerals, the committee does, in a very limited manner, consider uranium production and use because uranium often occurs in association with other metallic minerals and demonstrates the importance of a range of minerals and mineral-based products without which it would not be possible to maintain or increase nuclear power generation.

Informed planning to maintain and enhance domestic economic growth requires knowledge of potential resource disruptions. Many existing and emerging technologies require nonfuel minerals that are not available in the United States. Thus, although market forces influence some aspects of the balance between supply of and demand for nonfuel minerals and mineral products, various factors including global mineral distribution; mineral discovery, extraction, and processing; and new technologies and applications for minerals also influence the supply of these minerals to manufacturers and their incorporation in consumer goods. This report is designed to give federal agencies, policy makers, industry, academia, and the general public a framework in which to evaluate critical minerals and to indicate which types of data and research are appropriate to help ensure continuing mineral supplies and to develop suitable substitutes.

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