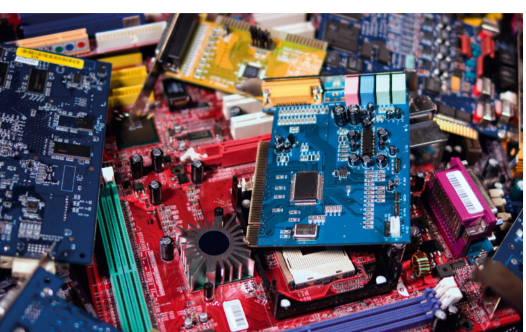
# CRITICAL METALS HANDBOOK

Edited by Gus Gunn



British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

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Keyworth
Nottingham
UK

*Published in collaboration with the British Geological Survey*

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Gus Gunn

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# 1. Metal resources, use and criticality

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## The geology and technology of metals

### *Key concepts*

In a book such as this, which is intended for a broad audience, it is important to discuss some key concepts and terminology relating to minerals and metals which, although widely used, are seldom defined. In some cases the meaning may be obvious, while in others they are anything but obvious. To avoid confusion and misuse, and to minimise the risks of misunderstanding, we define in the first part of this chapter certain fundamental terms that will provide a foundation for the chapters which follow.

Minerals are essential for economic development, for the functioning of society, and for maintaining our quality of life. Everything we have or use is ultimately derived from the Earth, produced either by agricultural activities or by the extraction of minerals from the crust. Unlike crops, which are grown for the essential purpose of maintaining life by providing the nutrients we need to survive, mankind does not generally need the minerals themselves. Rather, minerals are extracted for the particular physical and chemical properties their constituents possess and which are utilised for specific purposes in a huge range of goods and products. Following some form of processing and purification, a mineral, often in combination with certain other minerals, is incorporated into a component which is used in a product. It is the need or desire for the products that generates a demand for minerals, rather than demand for the mineral itself. As a result, there is always the possibility of finding an alternative material to provide the required functionality. The only exceptions to this possibility are nitrogen, phosphate and potash, which are essential to life itself and cannot be substituted.

The term 'mineral' is used to describe any naturally occurring, but non-living, material found in, or on, the Earth's crust for which a use can be found.[1] Four principal groups of minerals may be distinguished according to their main uses:

1. Construction minerals – these comprise bulk minerals such as sand and gravel, crushed rock and clay, which are used for making concrete and bricks to provide foundations and strength in buildings, roads and other infrastructure. They are produced in large quantities at low cost from extensive deposits that are widely distributed at shallow depths in the Earth's crust.
2. Industrial minerals – these are non-metallic minerals that, by virtue of specific chemical or physical properties, are used for particular applications in a wide range of industrial and consumer products. There are numerous industrial minerals

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but the most widely used include salt, gypsum, fluorspar, and kaolin. They tend to occur in large quantities but only at relatively few locations. They generally require specialist processing in their production and consequently they are relatively expensive.

3. Energy minerals – these are minerals such as oil, gas and coal that are used to generate energy that is captured when they are burned. They are used in the production of electricity, in fuels for transportation and heating, and also in the manufacture of plastics. Coal is relatively easy to find and cheap to extract; in contrast, oil and gas are generally difficult to find and extract and, therefore, command high prices.

4. Metals – metals are distinguished by distinctive chemical and physical properties, such as high electrical and thermal conductivity, malleability, ductility and the ability to form alloys. They are exploited for a multitude of purposes and some, such as iron, aluminium and copper, are used in huge quantities. Other metals with fewer or more specialised applications, such as platinum, indium and cobalt, are used in much smaller quantities, ranging from tens to hundreds or thousands of tonnes per year. Economic deposits of metals are rare and difficult to locate. The metal-bearing ores are expensive to mine and to process, and consequently metals command a high price.

Another term in common usage is 'mineral commodity' which is used to refer to any mineral raw material that can currently be extracted from the Earth for a profit.

The abundance of individual metals in the Earth's crust varies greatly (Figure 1.1) and influences the costs involved in locating, mining and preparing the metals for use. Some of the major industrial metals, like iron, aluminium and calcium, have crustal abundances similar to the main rock-forming elements, such as oxygen, silicon and calcium, and are several orders of magnitude more abundant than many of the widely used base metals such as copper, lead and zinc. Many others, such as the precious metals gold and platinum, are considerably rarer. However, crustal abundance is only one factor that influences production costs. Some metals that are common in the crust, such as magnesium, aluminium and titanium, occur in forms that need a high input of energy to separate them from their ores, thus making them relatively expensive. It is also important to note that the localised concentrations of metals that can be exploited economically result from unusual geological processes. Consequently, the distribution of economic deposits in the Earth's crust is highly dispersed, with some regions richly endowed in metals and others largely devoid of them. Furthermore, our knowledge of the processes that lead to the concentration of particular metals in the Earth's crust varies widely. For metals that are used in large quantities, such as copper and zinc, we have a reasonably good idea of where and how to locate new deposits. However, for many of the scarcer metals, especially those that have been brought into wide use relatively recently, information on their occurrence, concentration and processing is generally very limited.

It is a complex and expensive process to prove economic viability once an unusual enrichment of a potentially useful mineral or assemblage of minerals, commonly referred to as a 'mineral occurrence', is discovered. This involves determination of the quantity of mineral present and the assessment of the optimum methods for mining and processing the ore. Apart from geological processes that determine the physical availability of a metal there are a host of other factors that influence access to the resources in the ground – cheap labour or cheap power may confer a competitive advantage to a particular country or region while, on the other hand, government regulation, fiscal and administrative requirements, or social and cultural constraints may restrict or prevent access to potentially valuable deposits.

The timescale from discovery of a mineral occurrence to mine production is generally a long one. It commonly takes more than ten years to evaluate the mineral resource in the ground, to raise the funds to build a mine, to acquire the necessary regulatory approvals and to secure the trust and cooperation of the local communities. Once these are in place, and provided that favourable economic conditions prevail, the mine and

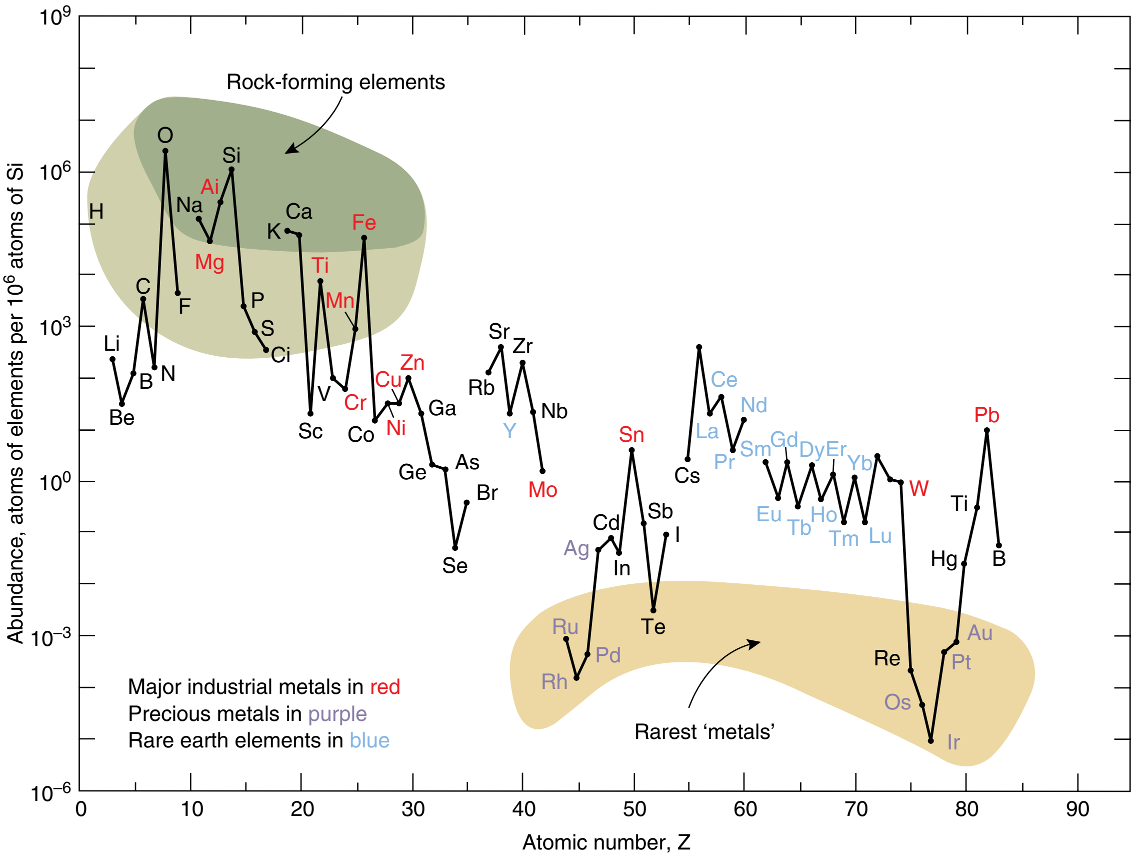



Figure 1.1 The abundance of the chemical elements in the Earth's upper continental crust as a function of atomic number. Many of the elements may be classified into partially overlapping categories. (Modified from USGS, 2002.)

supporting infrastructure can be built and mineral extraction can commence.

### *Definitions and terminology*

The costs involved in bringing a new mine into production today commonly amount to hundreds of millions of dollars or, in the case of a large new mine on a greenfield site, more than a billion dollars. A metal mine typically operates for a minimum period of a decade although, depending on economic and other circumstances, it may continue for more than 100 years. Given the size and duration of these investments it is essential that all parties – the mining company, investors, local communities, governments and regulators – 'speak the same language' and fully understand their obligations and expectations throughout the life of the mine, from construction to operation, closure and site rehabilitation. Without effective communication, based on clear unambiguous terminology, such understanding can never be attained and problems may well arise at some stage.

The first steps in determining the economic viability of a mineral deposit are the exploration and resource assessment stages which involve drilling and detailed sampling to determine the quantity of material present and its quality – or, in the case of a metallic mineral deposit, its grade, which is the percentage of metal that the rock contains. The consistent and correct use of terminology is essential for the reporting and assessment of exploration results and to underpin sound decision making. Without this, discrimination between genuinely economic deposits and those of marginal or unproven economic significance is impossible.

The assessment is, therefore, based on a system of resource classification the main objective of which is to establish the quantities of minerals likely to be available in the future. Many governments now require that resources and reserves are reported according to internationally accepted codes in countries where the company's stock is listed. Adherence to such reporting standards ensures full and transparent disclosure of all material facts and is intended to provide all parties with reliable information on which to base investment decisions. Such codes include the Joint Ore Reserves Committee (JORC) code in Australia and the Canadian Institute of Mining, Metallurgy and Petroleum (CIM) reporting standard which is referred to as National Instrument (NI) 43-101. Following an era of industry self-regulation, these codes were developed in response to scandals in Australia and Canada where many people were misled by speculation and rumour leading to unfounded spectacular rises in share prices and, soon after, rapid falls. In the short term these led to huge financial losses and, in the longer term and more significantly, to a prolonged loss of investor confidence in the mining industry. Accordingly these, and other codes, were developed to set minimum standards of reporting of exploration results, mineral resources and ore reserves. They provide a mandatory system of classification of tonnage and grade estimates according to geological confidence and technical/economic considerations. They require public reports to be prepared by appropriately qualified persons and provide guidance on the criteria to be used when preparing reports on exploration results, mineral resources and ore reserves.

### *Resources and reserves*

The key elements of the reporting codes are the terms 'resources' and 'reserves', which are frequently confused and/or used incorrectly. They are, in fact, fundamental to the distinction between a mineral deposit that is currently economic (reserves) and another which may become economic in the future (resources).

A mineral 'resource' is a natural concentration of minerals or a body of rock that is, or may become, of potential economic interest as a basis for the extraction of a commodity. A resource has physical and/or chemical properties that makes it suitable for specific uses and is present in sufficient quantities to be of intrinsic economic interest. To provide more information about the level of assurance, resources are divided into different categories which, in the JORC code, are referred to as measured, indicated and inferred resources, reflecting decreasing level of geological knowledge and hence decreasing confidence in their existence.

It is important to note that identified resources do not represent all the mineral resources present in the Earth, a quantity that is sometimes referred to as the 'resource base.' In addition to identified resources, there are resources that are undiscovered or unidentified (Figure 1.2). Undiscovered resources may be divided into hypothetical and speculative categories. Hypothetical resources are those which may reasonably be expected to occur in deposits similar to those known in a particular area under similar geological conditions. Speculative resources are those which may be present either in known deposit types in areas with favourable geological settings but where no discoveries have yet been made or in new types of deposit whose economic potential has not yet been recognised.

A mineral 'reserve' is that part of a mineral resource that has been fully geologically evaluated and is commercially and legally mineable. Mineral reserves are divided in order of increasing confidence into probable and proved categories.

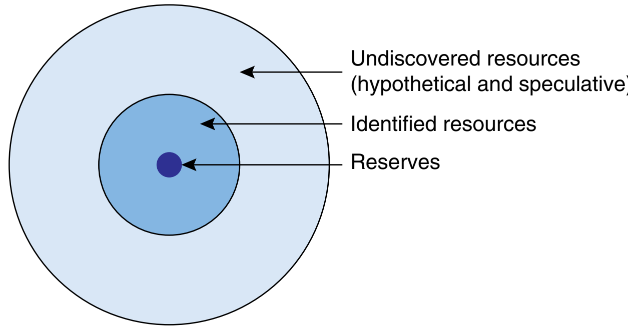



**Figure 1.2** Schematic representation of the relative size of the quantities represented by the terms resources and reserves. Reserves generally represent only a tiny fraction of resources.

The ultimate fate of a mineral reserve is either to be physically worked out or to be made non-viable, either temporarily or permanently, by a change in circumstances (most often economic, regulatory or social). So-called 'modifying factors' (economic, mining, metallurgical, marketing, social, environmental, legal and governmental) contribute to the viability of a mineral deposit and determine whether or not it will be exploited.

Figure 1.2 is a simple graphical depiction of the relative sizes of the quantities represented by the terms undiscovered and identified resources and reserves. If this figure were drawn to scale the circle representing the reserves would be very small relative to the resources because reserves are only a tiny fraction of the resources of any mineral.

The term 'reserve base' was also formerly used when discussing mineral resources and mineral availability. This term, introduced by the United States Geological Survey (USGS) and the United States Bureau of Mines (USBM) in 1980, was used as an estimate of the size of the mineral reserve and those parts of the resources that had reasonable potential for becoming economic within planning horizons beyond those that assume proven technology and current economics. However, the reserve base estimates were generally based on expert opinion rather than on data and were not readily defensible, especially at times of rapid growth in mineral demand and consequent massive increases in exploration expenditure, as happened during much of the first decade of the 21st century. Consequently, the USGS abandoned use of the reserve base category in 2010 (USGS, 2010).

## Will we run out of minerals?

We are using minerals and metals in greater quantities than ever before. Since 1900 the mine production of many metals has grown by one, two, or even three orders of magnitude (Graedel and Erdmann, 2012). For some metals, especially those used in high-tech applications, the rate of use has increased particularly strongly in recent decades, with more than 80 per cent of the total global cumulative production of platinum-group metals (PGM), indium, gallium and rare earth elements (REE) having taken place since 1980 (Hagelüken et al., 2012). We are also using a greater variety of metals than ever before. For example, turbine blade alloys and coatings make use of more than a dozen metals and high-level technological products, such as those used in medicine, incorporate more than 70 metals. In the quest for improved performance, microchips now use about 60 metals, whereas in the 1980s and 1990s only about 20 were commonly incorporated into these devices.

The main reasons for these changes are increased global population and the spread of prosperity across the world. New technologies, such as those needed for modern communication and computing and to produce clean energy, also require considerable quantities of numerous metals. In the light of these trends it has become important to ask if we can continue to provide the minerals required to meet this demand, and also to question whether our resources will ultimately be exhausted.

## *Geological assessment*

In general, our knowledge of the geology and industrial uses of those metals used in greatest amounts, such as iron, aluminium and copper, is extensive. There is a reasonably good idea of the geological processes responsible for the formation of economic deposits of these metals, and consequently how to identify the best places to look for additional resources. Experience over many decades and centuries has taught geologists and mining engineers how to find, extract and process these metals to provide the goods and services we need. As a result it has been possible to find new deposits to replace those that are worked out, and economic development has not been constrained by metal scarcity.

However, reliable estimates of the total amount of any metal that may be available in the Earth's crust are not in place. Various authors have calculated the maximum quantities present based on estimates of mean elemental crustal concentrations and have concluded that the amounts potentially available are huge (e.g. Cathles, 2010). Although these estimates provide upper limits to availability, they have little real practical value because they take no account of the costs, economic, environmental or social, that would be involved in extracting metals from these sources. Some researchers have adopted a different, 'bottom up' approach based on probabilistic estimates of the crustal endowment of particular metals in specific deposit types. Perhaps the best known and largest study of this type is the United States Geological Survey's Global Mineral Resource Assessment Project, which is being undertaken to assess the world's undiscovered non-fuel mineral resources. One of the first studies completed was a quantitative mineral resource assessment of copper, molybdenum, gold and silver in undiscovered porphyry deposits of the Andean mountain belt in South America (Cunningham et al., 2008). This study concluded that there may be a huge amount of copper to be discovered to a depth of one kilometre below the Earth's surface in the Andes, equivalent to 1.3 times as much as has already been found in porphyry copper deposits in this region. Estimates derived in this way are very useful, not only to mining companies but also to planners, economists, governments and regulators. The approach also has real practical value because it assesses the availability of resources of a type that are well known and can be mined and processed economically with current technology. However, this method is dependent on the availability of high-quality geological data and on a sound understanding of the target mineral deposit class. Unfortunately, such geological information is not generally available and knowledge of many mineral deposit classes that may contribute to global metal production is poor. Consequently, this approach is not likely to yield reliable estimates of global metal availability in the near future; rather, its application will be restricted to a particular deposit type within specific areas. Of course, rather than having accurate estimates of what might ultimately be available to us, what really matters is how can we be sure that we have enough metal to meet our needs and that we will not run out in the future as demand grows.

## *Considerations of supply and demand*

Much of the recent debate has focused on the adequacy of mineral deposits to meet future demand rather than on the political and economic barriers. Several authors have concluded that mineral scarcity and, ultimately, depletion are unavoidable (Ragnarsdottir, 2008; Cohen, 2007). Some have made alarmist forecasts that suggest that for some minerals and metals depletion may occur over relatively short timescales of a few decades or even years. However, these predictions are based on 'static lifetimes' derived from existing known resources or reserves divided by current or projected future demand (Cohen, 2007; Gilbert, 2009; Sverdrup et al., 2009). These forecasts fail to recognise that resources

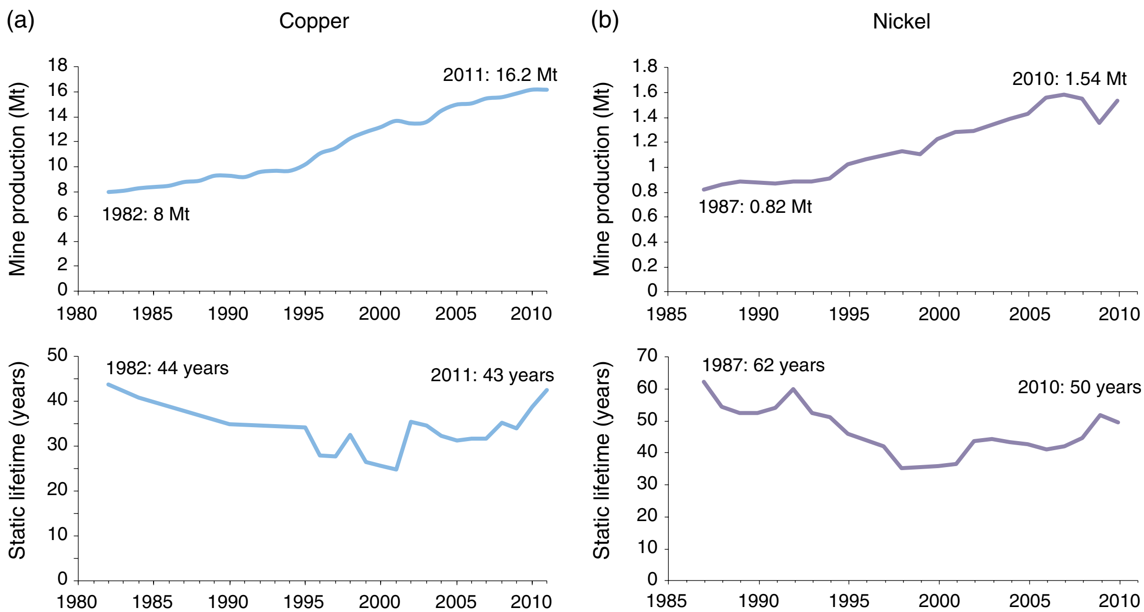



Figure 1.3 Despite escalating global production of metals, reserves have continually been replenished. These graphs show that static lifetimes (number of years' supply remaining equals reserves divided by annual production), in this case of (a) copper and (b) nickel, are extended ahead of production (Mt, million tonnes, metal content). (Mine production data from BGS World Mineral Statistics Database; reserve data from USGS Mineral Commodity Summaries, 2012 and earlier editions.)

and reserves are neither well known nor fixed. Reserves are economic entities that depend on scientific knowledge of minerals and on the price of the target metal or mineral. As our scientific understanding has improved, reserves have continually been replenished through new discoveries, by improved mining and processing technology, and by improved access to deposits. Furthermore, market mechanisms help to overcome supply shortages for major metals – if prices rise, then reserves will extend to include lower-grade ore; if prices fall then they will contract to include higher-grade material. High prices will also stimulate increased substitution, recycling and resource efficiency and thus will contribute to improved security of supply.

Crowson (2011) has discussed changes in reserve levels of some major industrial metals since 1930. He showed that, despite escalating production, reserve levels have actually grown over time and outpaced production. For example, global copper reserves in the early 1930s were reported to be about 100 million tonnes, thought at the time to be sufficient for about 80 years. However, in 2010 the USGS reported copper reserves of 540 million tonnes (USGS, 2010) and in 2011 the estimate was again revised upwards to 630 million tonnes, an increase of more than 16 per cent in a single year (USGS, 2011). Similar trends can be seen in the global reserve levels for some minor metals. For example, tungsten reserves grew by more than 50 per cent between 2000 and 2011, while reserves of REE grew by 25 per cent between 2008 and 2011. It is clear, therefore, that reserve estimates are unreliable indicators of the long-term availability of metals as their definition depends on current science, technology and economics (Figure 1.3).

A type of scarcity referred to as 'technical scarcity' or 'structural scarcity' presents a particular challenge and may be difficult and expensive to

Table 1.1 By-product metals derived from the production of selected major industrial metals (top row, bold). Those metals shown in italics may also be produced from their own ores. (PGM, platinum-group metals; REE, rare earth elements.)

| **Copper** | **Zinc** | **Tin** | **Nickel** | **Platinum** | **Aluminium** | **Iron** | **Lead** |
|---|---|---|---|---|---|---|---|
| *Cobalt* | Indium | *Niobium* | *Cobalt* | Palladium | Gallium | *REE* | *Antimony* |
| *Molybdenum* | Germanium | *Tantalum* | *PGM* | Rhodium | | *Niobium* | Bismuth |
| *PGM* | Cadmium | Indium | Scandium | Ruthenium | | Vanadium | Thallium |
| Rhenium | | | | Osmium | | | |
| Tellurium | | | | Iridium | | | |
| Selenium | | | | | | | |
| Arsenic | | | | | | | |

alleviate. Technical scarcity applies chiefly to a range of rare metals used mostly in high-tech applications. Many of these are not mined on their own; rather they are by-products of the mining of the ores of the more common and widely used metals, such as aluminium, copper, lead and zinc (Table 1.1). These by-product or companion metals are present as trace constituents in the ores of the host metals and, under favourable economic conditions, they may be extracted from these ores, or from concentrates and slags derived from them. For example, indium and germanium are chiefly by-products from zinc production, while tellurium is mainly a by-product of copper mining. However, the low concentration of the companion metal in the host ores means that there is little economic incentive to increase production at times of shortage. For example, only about 25–30 per cent of the 1000 tonnes of indium that is potentially available globally each year from mining indium-rich zinc ores is actually recovered. The rest ends up in wastes because it is not economic to install the additional indium extraction capacity at zinc refineries or because the efficiency of the indium recovery is poor (Mikolajczak and Harrower, 2012). It is therefore difficult to predict the capacity of the supply chain to meet increased demand for the by-product. If the high level of by-product demand is expected to be sustained, for example because of a particular well-established technological requirement such as indium in flat-panel displays and portable electronic devices, then a good economic case for increased indium production can be made.

In some situations certain elements which are normally mined as by-products may also be mined in their own right if their concentrations and mode of occurrence allow it. For example, cobalt is generally a by-product of copper mining, but, exceptionally, it can be mined on its own. Similarly, the PGM are commonly by-products of nickel mining but most production is from PGM-only mines in South Africa.

In some instances groups of metals have to be produced together as coupled elements because they are chemically very similar and cannot be easily separated from the minerals in which they occur. The best examples of coupled elements are the platinum-group metals (PGM: rhodium, ruthenium, palladium, osmium, iridium and platinum) and the rare earth elements (REE comprising 15 lanthanides, scandium, and yttrium). In these cases there is no major carrier metal, but normally one or two of the group determines production levels and the economic viability of the extractive operations. In the case of the PGM, platinum is commonly the main driver for production, with palladium, iridium and ruthenium derived as by-products.

The petroleum industry's debate about 'peak oil' has been extended to the non-fuel minerals industry. The peak concept was developed from the work of oil geologist Hubbert in the 1950s who predicted, on the basis of the existence of a well-known 'ultimately recoverable reserve', that oil production in the USA would peak about 1970 and then enter a terminal decline (Hubbert, 1956). Others extended this approach to predict that global oil production would peak in 2000. These predictions proved largely correct, although global oil production peaked a few years later than forecast. Hubbert's model is based on symmetrical (bell-shaped) curves, with the production peak occurring when approximately half of the extractable resource has been extracted. More recently various authors have advocated 'peak metals' as a tool for understanding future trends in the production of metals (Bardi and Pagani, 2007; Giurco et al., 2010). Bardi and Pagani (2007) examined global production data for 57 minerals and concluded that 11 of these had clearly peaked and several others were approaching peak production.

The application of the peak concept to metals production has been criticised by various authors who have questioned both the validity of the assumptions underlying the model when applied to metals and also the failure to address the real causes of variations in production and consumption in the mineral markets (Crowson, 2011; Ericsson and Söderholm, 2012). Records from the last 200 years show that the prices of major metals are cyclical, with intermittent peaks and troughs closely linked to economic cycles. Declining production is generally driven by falling demand rather than by declining resources or lack of resource discovery. At times of increasing scarcity the price of minerals will increase, which, in turn, will tend to stimulate increased substitution and recycling and encourage investments in new capacity and more exploration. High prices may also lead to more focus on improving current exploration and production technologies. Historically, technological innovation has often succeeded in developing new lower-cost methods for finding and extracting mineral commodities.

It is concluded, therefore, that the peak concept is not valid for modelling mineral resource depletion and cannot provide a reliable guide to future metal production trends. Furthermore, estimates of reserves and resources, and the static lifetime of mineral raw materials calculated from them, should not be used in the assessment of future mineral availability as they are highly likely to give rise to erroneous conclusions with potentially serious implications for policy making and investment decisions.

## Recycling and reuse of metals

Modern technology is largely designed around the use of virgin materials extracted from geological sources. It is increasingly apparent, however, that materials that have been incorporated into products no longer in use (secondary materials, scrap) can provide a valuable supplement to virgin stocks. This reuse will generally require that the secondary materials are comparable in quality to those generated from the virgin stocks.

Primary metals are produced through a sequence of actions following their discovery and evaluation: mining the ore, milling it (crushing the rock and separating the metal-containing minerals from the waste material), smelting (to transform the metal oxides and sulfides into impure metal), and refining (to purify the smelted material). None of these processes is perfect, so metal is lost at each stage. The sequence for secondary metals has some of the same characteristics. It begins with collection of the discards, separation of the metals in the discards, sorting of the separated metals, and smelting or similar metallurgical processes to transform the results of the previous processes into metals pure enough for reuse. As with primary processes, metal is lost at each stage.

In a world of increasing resource use, secondary supplies of metals will, however, be insufficient to meet overall demand. Even if all the metals incorporated into products were collected and recycled with 100 per cent efficiency at the end of their useful life, there would inevitably be a shortfall in supply which would have to be filled through production from primary resources (Figure 1.4).

Nonetheless, secondary supplies provide a resource supplement that generally requires less energy than primary metals (often much less), and has generally lower environmental impacts. Through recycling activities, most metals have the potential for reuse over and over again, but only if product designers enable recycling by judicious choice of metal combinations and assembly

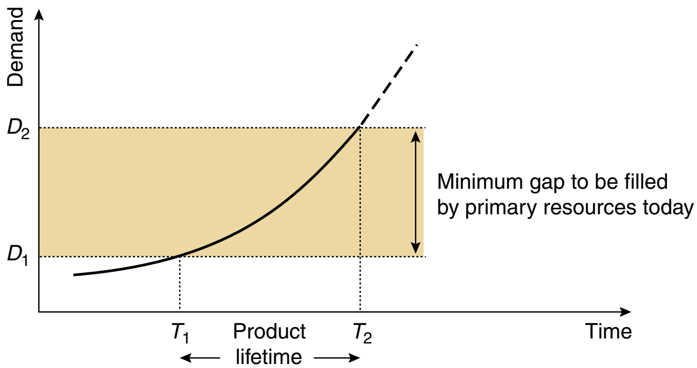



Figure 1.4 When demand for a commodity increases over time recycling alone cannot meet the higher demand. At the beginning of the lifetime of a product, $T_1$, demand is at a level $D_1$. At the end of its lifetime, $T_2$, demand has risen to $D_2$ but the amount potentially available from recycling will be $D_1$. The gap in supply ($D_2$–$D_1$) can only be met from primary resources.

practices, if governments and individuals optimise product collection at end of life, and if recycling technology is able to produce secondary material whose quality is sufficiently high to enable reuse without downgrading. Certain elements in specific applications are used in a highly dispersed state and cannot be recovered. For example, potassium, phosphate and nitrogen in fertilisers are dissipated in use, as are metals like zinc and magnesium, which are also used for agricultural purposes. Other unrecoverable losses of metals include titanium in paint pigments, and platinum and ruthenium used in very thin layers in hard-disc drives. A wide range of other metals is also lost due to wear and corrosion in use.

Recycling of metals and minerals and the challenges associated with improving its uptake and efficiency are discussed in more detail in Chapter 3 of this book.

## The concept of criticality

Without minerals we would not enjoy the lifestyle that we enjoy in the West and to which many others aspire. Without the continued development in the twentieth century of technology for mineral exploration, processing and manufacturing we would not benefit from cheap and reliable products ranging from aeroplanes and cars, to computers, mobile phones and a panoply of other portable personal electronic products that are currently proliferating, such as tablet computers.

This book deals with certain metals that have become increasingly important in recent years for a variety of purposes and for which demand is rapidly increasing. For example, as technology has progressed so new markets for metals, which were previously little used, have arisen or, in some instances, greatly expanded in response to society's needs. Of particular importance are so-called 'green' technologies, especially as the major world economies attempt to shift from carbon-based energy systems.

What is meant by the 'criticality' of metals? Dictionary definitions (e.g. "the quality, state, or degree of being of highest importance") suggest that the term relates to 'essential' or nearly so. In the first few years of the 21st century the label was applied to metals, and particularly to the possibility that some metals might become scarce enough to cease being routinely available to technology. This is more than an idle concern: there have been a number of instances in the past few decades when war, technological change or geopolitical decisions have resulted in temporary shortages. We ask a more fundamental question here, however: might some metals be particularly susceptible to long-term scarcity regardless of the reason or reasons? If we entertain this possibility, could we forecast this situation far enough in advance to mitigate some of its most challenging implications? Or, to simplify, can we determine a metal's criticality and turn that knowledge to use?

The first complexity to point out is that criticality is a matter of degree, not of state. Figure 1.5 makes this point graphically: criticality is not the

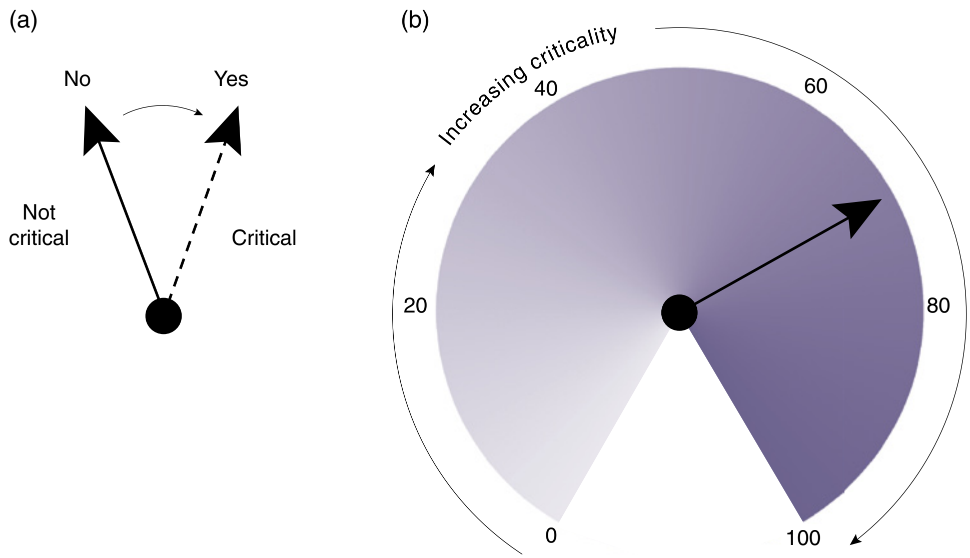



Figure 1.5 Criticality is not simply a designation of 'critical' or 'not critical' as indicated in (a); rather it is a matter of degree, as indicated in (b) where an arbitrary 'criticality level' (here 70) is defined.

position of a switch, such that a metal is either critical or non-critical (Figure 1.5a), but rather a position on a dial where any position above a certain level could arbitrarily be designated as the dividing line between critical or not. The next complexity concerns the metric itself: what is the dial measuring? As we will see, methodologies for determining degrees of criticality can be very complex and are generally multi-dimensional, so the arrow in Figure 1.5b points to a location in two-dimensional or three-dimensional space. This reflects the fact that scarcity may be a consequence of geological factors, economic factors, technology evolution, potential for substitutes, environmental impacts, and many more. This complexity has spawned a variety of analytical approaches and, unfortunately for those wishing to employ the information from those studies, a variety of results.

It is also important to point out that criticality is not a property whose determination is identical to all potential users. For a company whose business is making electrical cables, copper is essential. For a maker of fine jewellery, gold is essential. However, the cable-maker's business does not utilise gold, nor the jeweller's copper (i.e. for those users, either gold or copper cannot be deemed a critical metal). In sum, the degree of criticality of a metal is related to the physical and chemical properties of the metal itself, to a number of factors influencing supply and demand, and to the questioners themselves.

## *Assessments of criticality*

As mentioned earlier in this chapter, concerns about the possible scarcity of natural resources are a recurring theme in history. The main focus has been on the potential impacts of supply disruptions to the economy, especially where it is dependent on imported materials. In the minerals industry finding rapid solutions is particularly challenging because of the high costs and long lead times required to make new mineral supplies available. Buijs and Sievers (2012) noted that the criticality studies conducted in the USA and EU in the 1970s and 1980s adopted basically similar approaches to those used today to identify critical raw materials. Nevertheless, the critical minerals

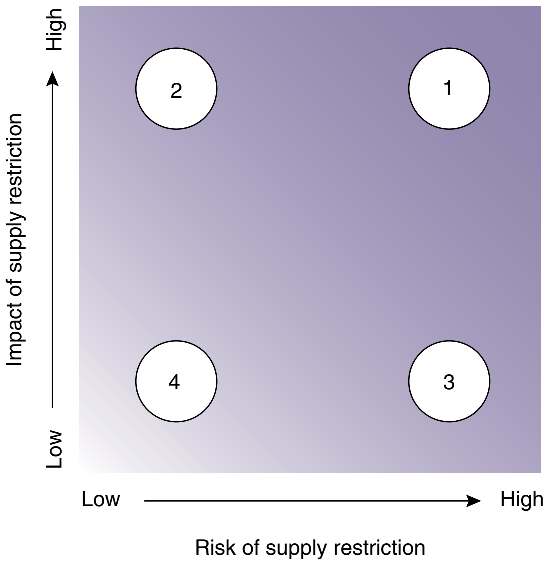


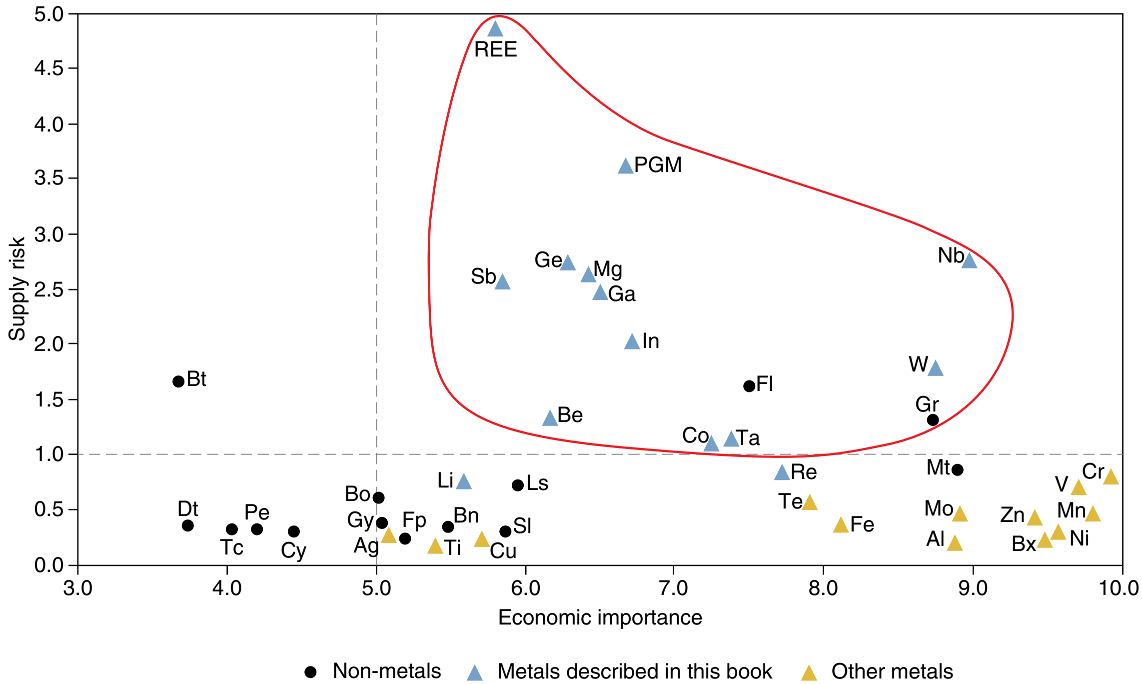

Figure 1.6 The criticality matrix originated by the U.S. National Research Council (2008), as revised by Graedel and Allenby (2010). Metals falling in sector 1 are more critical than those falling in sectors 2 or 3, and much more critical than those falling in sector 4.

identified in those earlier assessments differ from those now classified as critical, thus highlighting that such studies provide only a 'snapshot' of a dynamic system and have little predictive value. However, Buijs and Sievers also observe that the analysis conducted in the earlier studies and the solutions proposed at that time are similar to those of today. Then, as now, it was concluded that, although geological scarcity was highly unlikely, the main supply risks were companion/host relationships, import dependence, the concentration of production in a small number of politically unstable countries, and increased resource nationalism in various forms as the governments in producing countries seek to derive greater benefits from the exploitation of indigenous resources. The measures proposed to alleviate future supply shortages include stockpiling of raw materials, establishment of long-term supply contracts and exploitation of indigenous resources.

The first recent attempt to define metal criticality and suggest metrics that might be employed to assess it was that of a committee of the US National Research Council (2008). The committee proposed that criticality was a two-parameter variable, one parameter being supply risk and the other the impact of supply disruption. Figure 1.6 shows the concept, in which an element falling in the area 1 quadrant was deemed more critical than those in other areas of the diagram. Further, each of those parameters in turn was regarded as some sort of aggregation of a number of contributory metrics: the committee suggested geological availability, political factors, technological capacity and other factors for Supply Risk, and substitutability, importance of applications and other factors for Impact of Supply Restriction. The committee did not select specific components nor delineate the methodology in detail, but did make rough criticality approximations for 11 metals and groups of metals. Those showed the most critical to be rhodium, the least copper, and the others at various locations in between. The committee emphasised that the evaluations were largely to demonstrate the concept, not in any way to be definitive.

A second important evaluation was initiated by the European Commission (EC) in 2009, with a report published in the following year (European Commission, 2010). The EC working group retained the two-axis concept, with supply risk being one of the parameters, but defined the second axis on the basis of the potential economic impact of supply disruption on European industry. Supply risk was further defined as an aggregate of three parameters: the political stability of the producing countries, the potential to substitute the metal being evaluated, and the extent to which the metals are recycled. The evaluation also included environmental risks as a separate concern, and the classification 'critical' was assigned to a raw material if a certain threshold for both economic importance and at least one of the complementary metrics was exceeded. In practice, the metals ranked of most environmental concern were already designated as critical based on other factors.

The EC working group evaluated forty one metals and minerals. The result is shown in Figure 1.7. Arbitrarily drawing lines of




Ag, silver; Al, aluminium; Be, beryllium; Bt, barytes; Bx, bauxite; Bn, bentonite; Bo, borate; Co, cobalt; Cr, chromium; Cu, copper; Cy, clays; Dt, diatomite; Fe, iron; Fp, feldspar; Fl, fluorspar; Ga, gallium; Ge, Germanium; Gr, graphite; Gy, gypsum; In, indium; Li, lithium; Ls, limestone; Mg, magnesium; Mn, manganese; Mo, molybdenum; Mt, magnesite; Nb, niobium; Ni, nickel; Pe, perlite; PGM, platinum-group metals; Re, rhenium; REE, rare earth elements; Sb, antimony; Sl, silica; Ta, tantalum; Tc, talc; Te, tellurium; Ti, titanium; V, vanadium; W, tungsten; Zn, zinc.

Figure 1.7 The criticality matrix of the European Commission (2010). The horizontal axis reflects the economic impact of supply restriction on a broad group of European industries; supply risk constitutes the vertical axis. The 14 raw materials falling within the top-right cluster are regarded as critical to the European Union. (Modified from European Commission, 2010.)

demarcation, the working group designated ten metals as critical: antimony, beryllium, cobalt, gallium, germanium, indium, magnesium, niobium, tantalum and tungsten, as well as two groups of metals, the rare earth elements and the platinum-group metals.

There have been other efforts to designate metals as critical, including those of Morley and Etherley (2008), the U.S. Department of Energy (2010 and 2011) and the Joint Research Council of the EC (JRC, 2011). These, together with the National Research Council and European Commission studies and others, have been reviewed by Erdmann and Graedel (2011) and Buijs and Sievers (2012). They found that the great differences in methodology, the sets of metals reviewed, and selection criteria render it less than convincing at present to single out some metals for special attention while neglecting others, as distinctions between critical and non-critical metals are too complex to be easily resolved. It is clear that, although this topic is generating a high level of interest from governments and corporations throughout the world, the methodology is immature and the results are not necessarily helpful to all parties whose ultimate aim is to secure future supplies of minerals (Buijs et al., 2012).

The availability of suitable high-quality data is a serious issue that can impact on the results of the criticality assessment. For example, in the EU study (EC, 2010) the diagram (Figure 1.7) suggested that the highest level of concern should be for the rare earth and platinum-group elements. These groupings turn out not to be particularly helpful so far as criticality is concerned, in view of the fact that some elements in each group (e.g. platinum, neodymium) are widely used and have a possible claim to criticality, while others in each group (e.g. osmium, holmium) are rarely employed and clearly not critical. This situation arose because some data used in the analysis was available only for the element groups and not for individual PGM and REE. Similarly, for some minor metals trade data is not available in sufficient detail to allow accurate definition of global import and export patterns.

Given the inherent complexities and the data shortcomings it is inevitable that such criticality assessments will not deliver results of universal application, and also that they may fail to identify potential problems. They may suggest that certain materials are at risk when, in fact, market forces may be able to solve the problems in the short or medium term. They may also produce false negatives whereby supplies of some materials are incorrectly identified as secure. However, as these limitations have come to be appreciated and while interest in criticality remains at a high level, so there have been continual refinements of the methodology, adapting it for particular purposes, different organisational levels (corporate, national and global), and over different timescales.

More recently, Graedel and co-workers at Yale University have proposed a comprehensive and flexible methodology for the determination of metal criticality by enhancing the US National Research Council approach (Graedel et al., 2012; NRC, 2008). This method involves three dimensions: Supply Risk, Environmental Implications and Vulnerability to Supply Restriction. It uses a combination of data and expert judgement, the latter especially important for speciality metals used in high-tech application for which little data are available. Supply risk is estimated for both the medium term (5–10 years, with corporations and governments in mind) and for the longer term (a few decades, of interest to planners and the academic community concerned with sustainable resource management). Environmental Implications address both issues of toxicity and of energy use (and thus climate impact), and is of particular interest to designers, governments and non-government agencies. Vulnerability to Supply Restriction (VSR) varies according to organisational level: a particular metal may be crucial to the products or operations of one company but of little or no importance to another. An example of the results of this approach is shown in Figure 1.8.

### *Improving criticality assessment*

While it is clear that no single criticality assessment is universally applicable, shortlists of critical raw materials have an important role to play in warning decision makers in government and industry about current issues of concern and possible impacts on security of supply in the short term. Development of a longer-term capacity to explore potential supply issues is the ultimate goal of such assessments, but there are many intricacies to address before this can be achieved. Key requirements include the necessity to analyse individual metals and underlying issues in more detail, to acquire better data, and to analyse trends and patterns of future demand.

One of the challenges of providing perspective on the long-term supply and demand of metals is that their uses evolve in ways not always predictable. Nonetheless, various studies have attempted to consider technology scenarios considering how wind power, photovoltaic solar power, automotive fuel cells, and other technologies could develop in the next few decades (e.g. European Commission, 2003; IEA, 2008; Shell, 2008). In a typical study, Kleijn and van der Voet (2010) evaluated the resource requirements needed to meet several technology

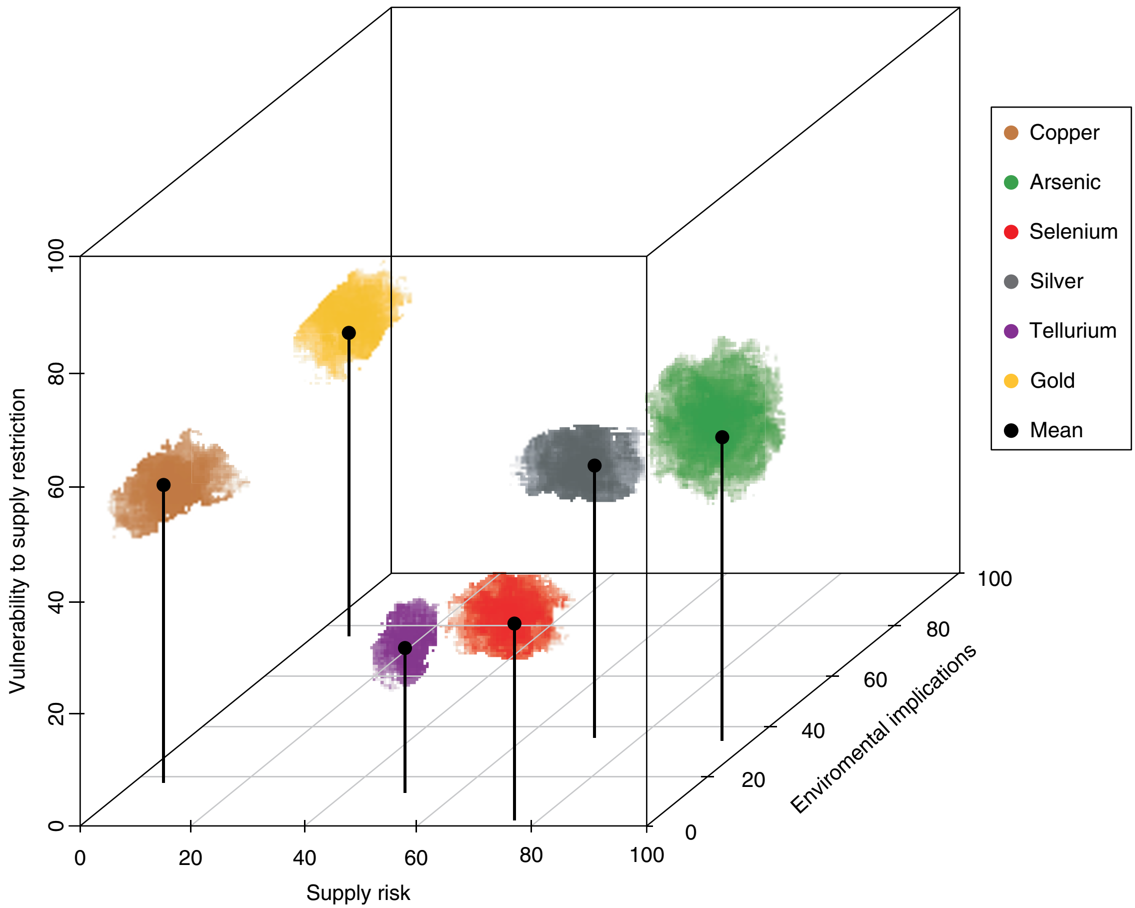



Figure 1.8 The criticality of the geological copper group of metals as determined by the Yale University methodology. (After Nassar et al., 2012.)

projections. They found that substantial deployment of wind turbines, photovoltaic solar cells, hybrid vehicles, enhanced transmission grids, among others, have a strong potential to be restricted because of the large quantities of metal that would be required. Their study indicates that future technology planning will need to have at its centre an assessment of the impacts on metal demand, especially for the scarce metals that are acquired as by-products.

Very few studies have attempted to predict demand for a broad spectrum of technologies (e.g. Angerer et al., 2009) and most have focused on material requirements for the clean energy sector (e.g. U.S. Department of Energy, 2010 and 2011; JRC, 2011). In general, the inclusion of projections in criticality assessment will be a step forward because it will reduce reliance on the future validity of indicators compiled from historic and current data. However, projections inevitably represent a present view of future market states and, though useful for orientation, cannot be relied upon to provide accurate assessments of future demand.

## *Implications of criticality for corporate and governmental policy*

Modern technology makes extensive use of the metals designated as critical by the various assessments discussed above. In virtually all cases, these uses result in improved product performance: faster computers, sharper images on the display screen, wider ranges of operating temperatures, etc. Sometimes no suitable substitute for a critical metal in a particular use is known, as with rhodium (employed in automobile catalytic converters to oxidise harmful nitrogen oxide gases, $NO_x$), or neodymium (a component of high-strength magnets used in hybrid vehicles to facilitate electric motor performance). In other circumstances a substitute might be available, but its use would downgrade a product's utility, as would be the case for hafnium in computer chips or samarium in missiles. Thus, the potential or actual scarcity of one of these materials has dramatic implications for the industrial using sectors, or for countries or regions containing those sectors.

There exist a number of possible responses to the realisation that a particular material is or may be critical. For corporations (e.g. Duclos et al., 2010):

- vigorously investigate possible substitute materials;
- improve material utilisation in manufacturing;
- redesign products to eliminate or reduce critical material use;
- investigate the potential for recycled materials to replace or supplement virgin material supplies;
- consider entering into long-term contracts or creating stockpiles to ensure supplies for future manufacturing activities.

For governments:

- support geological research to locate new mineral deposits and to better evaluate known deposits;
- support research into improved technologies for recycling;
- consider voluntary programmes or legislation to improve rates of collection and appropriate processing of discarded products containing recyclable materials.

Ensuring supplies of critical materials to corporations, countries or regions inevitably involves international trade, because no country or region possesses the full palette of materials – one area may have good platinum-group metal deposits but few or no rare earth deposits, while another may be rich in copper deposits but lacking those of nickel. Because metal use is diverse, the world's countries and continents are linked by their mutual need for the full spectrum of materials, and this situation requires continued international collaboration.

Recycling efficiency remains a major challenge for most metals. In principle, metals are endlessly reusable. In practice, they are typically reused only once or twice (Eckelman et al., 2011). Social commitment and policy initiatives can play major roles in improving this picture.

Thus, designation of metals or metal groups as critical carries with it policy implications for corporations and governments. The responses need to be focused, forward-looking and pursued with dedication if the consequences of critical metal supply constraints are to be minimised or avoided.

## Outlining this book

It is not possible in a single book to cover the entire range of potentially critical metals, nor to unambiguously select those that might be of most concern. As a practical and reasonable choice, however, we address those deemed critical by the European Union working group (2010): antimony, beryllium, cobalt, gallium, germanium, indium, magnesium, niobium, the platinum-group metals, the rare earth elements, tantalum and tungsten. Lithium is included as well, on account of its increasing importance in battery technology and current concerns over its long-term availability. A chapter on rhenium has also been added.

Following this first chapter, two chapters address topics generic to all the metals. The first treats the mining industry, explaining its nature and how it responds to changing demand. The second is on

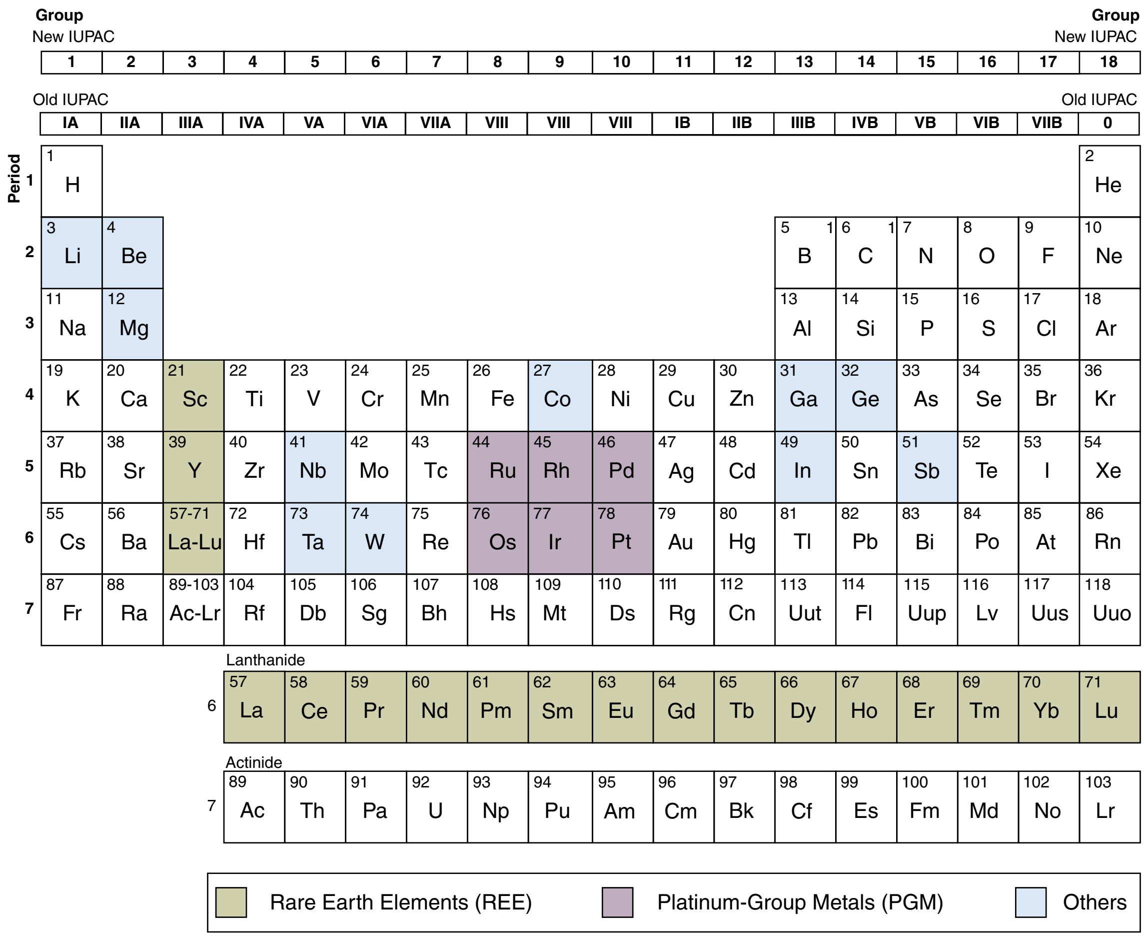



Figure 1.9 The Periodic Table of the chemical elements highlighting the metals described in this book. The new IUPAC (International Union of Pure and Applied Chemistry) naming system for the groups is used in this book. The old IUPAC system is shown for comparison.

recycling, and provides the basis for an understanding of recycling prospects and limitations.

Each of the individual metals or metal groups listed above is then given its own chapter, which provides a summary of appropriate information, including physical and chemical properties, geology, production, trade, recycling and future outlook. While not exhaustive, this information constitutes a basic understanding of the element or element group's criticality aspects and challenges, as well as a perspective on its supply, demand and prospects. These metals and the metal groups covered are shown in the Periodic Table (Figure 1.9).

## Acknowledgements

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## Note

1. In mineralogy and petrology a different definition is used and a mineral is defined as an inorganic substance with a definite chemical composition and a characteristic crystal structure.

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# 2. The mining industry and the supply of critical minerals

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Mineral products are bought for their utility, this utility being reflected in the price which consumers are prepared to pay for them. Properly functioning markets should ensure that an appropriate supply of such products is available to meet consumer demand. A shortage of the sought-after mineral serves to push prices up and stimulate companies to invest in new production capacity. A surfeit of supply leads to a fall in price and a curtailment of output.

The issue of a mineral's 'criticality' enters into the equation because the global economy is composed not just of companies and consumers but also of nations, and nations have strategic interests. Within the broader, strategic, context, mineral products are viewed not only as having utility to consumers but also in terms of the contribution they make to national projects, such as raising the living standards of the nation's citizens, maintaining a capability to produce certain important industrial goods, or ensuring that the nation has the ability to defend itself militarily. In making the transition from being simply 'useful' to being 'critical', minerals and their supply become not just matters for the market but also matters of national security. The process of transition is thus often referred to as 'securitisation'.

The role played by the mining industry in meeting the demand for minerals is subject to a similar duality. The economic function of mining companies is to respond to the requirements of the market, as expressed through mineral prices. For the most part, the industry does this quite effectively. The industry has always had a strong enterprise culture and rising mineral prices can usually be relied upon to prompt mining and exploration companies to develop mines and search for new mineral deposits.

As with mineral consumers, producers operate in a national setting. National authorities are responsible for establishing the legal, fiscal and environmental parameters within which mining companies work. However, like consuming nations, producing nations have strategic objectives. In this context, mining may be perceived as a vehicle for the promotion of broader objectives such as economic development, the reduction of poverty or the assertion of national self-determination. In a direct parallel with the process of securitisation in consuming countries, the assertion of these strategic priorities results in the politicisation of the mineral products and conditions the ability of the mining industry to respond to market signals and thus to supply the minerals that consumers require.

This chapter is divided into five sections. The first looks at the mining industry and its major corporate components, the miners and explorers. The second discusses how the mining industry

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Table 2.1 World's largest mining companies by market capitalisation, mid-March 2013. (Data from author's estimates based on web sources.)

| Rank | Company | Country | Market Cap $bn |
|---|---|---|---|
| 1 | BHP Billiton | Australia | 190 |
| 2 | Rio Tinto | UK | 92 |
| 3 | Vale | Brazil | 90 |
| 4 | Xstrata | Switzerland | 51 |
| 5 | Anglo American | UK | 39 |
| 6 | Freeport McMoRan | USA | 34 |
| 7 | Grupo Mexico | Mexico | 32 |
| 8 | Norilsk Nickel | Russia | 32 |
| 9 | Barrick Gold | Canada | 29 |
| 10 | Goldcorp | Canada | 26 |
| 11 | Newmont Mining | USA | 20 |
| 12 | Newcrest Mining | Australia | 18 |
| 13 | Teck Resources | Canada | 17 |
| 14 | Antofagasta | UK | 16 |
| 15 | Fresnillo | UK | 16 |
| 16 | AngloGold Ashanti | South Africa | 13 |
| 17 | Fortescue Metals Group | Australia | 13 |
| 18 | Yamana Gold | Canada | 11 |
| 19 | Impala Platinum | South Africa | 9 |
| 20 | Kinross Gold | Canada | 9 |

responds to the demand for minerals and to changes in the level of demand. The third examines the factors which inhibit the mining industry's responses to changes in demand. The fourth looks at some of the specific issues posed for miners by the minerals currently deemed 'critical' and at the role of China in mineral markets. The fifth considers some of the things that governments of consuming countries can do to promote the supply responsiveness of the mining industry.

## Suppliers of minerals – miners and explorers

The mining industry exists to meet the mineral requirements of consumers and, in so doing, make profits for shareholders. Although not on the scale of the oil and gas industries, the mining industry is, nevertheless, a very large industry. The enterprise value[1] of the global mining industry in 2010 is estimated to have been around US$2100 billion (Citi, 2011a). London lies right at the heart of this industry, and is host to the headquarters of several of the world's largest mining companies. As of March 2013, there were thirteen mining and metals companies in the FTSE 100 having a combined market capitalisation of US$340 billion, 12.7 per cent of the total value of the FTSE100 (FTSE, 2013). Seven years earlier, the share was six per cent.

The structure of the global mining industry today is the product of a long and complex history. The largest and most publicly visible companies are the so-called 'global diversified miners', or mining 'majors'. These are, by any standards, large companies, operating across many geographies and minerals. Following a period of consolidation during the first decade of the century, this group currently comprises BHP Billiton, Vale, Rio Tinto, Anglo American and Xstrata.[2] The market capitalisation of the world's largest mining companies is shown in Table 2.1. The country indicated is the country of the company's primary stock market listing. The table, it should be noted, excludes aluminium companies, this because most of the value of aluminium, like steel, is created through metallurgical processing rather than through mining.

At the next level down in terms of scale, companies tend to be more focused with respect to either commodity or country. Freeport McMoRan, Grupo Mexico and Antofagasta, for example, are focused on copper, while Barrick Gold, Goldcorp and AngloGold Ashanti are, as their names suggest, focused on the production of gold. Companies which produce a variety of products, but which operate predominantly in one country, include several from the former Soviet Bloc, most notably Norilsk Nickel, but also Kazakhmys and ENRC (Eurasian Natural Resources Corp.) which fall just outside the top twenty companies listed.

Most of the world's largest miners, and all of those in Table 2.1, are public companies, quoted on stock markets (from which their market capitalisations are derived). There are, in addition, a few mining companies comparable in the scale of their mineral output to those listed in the table which are either wholly or predominantly owned by the state. These include the world's largest copper producer, Codelco, which is owned by the state of Chile, and a handful of Chinese companies such as China Shenhua, Yanzhou Coal, China Minmetals Corporation (Minmetals), Chinalco, Metallurgical Corporation of China, (MCC) China Nonferrous Metal Mining Corp. (CNMC) and the Jinchuan Group. Although production from state-owned enterprises is significant and growing, the extent of state ownership in mining is still very much less than is the case with oil and gas.

Beyond the larger and mid-sized mining companies, there are huge numbers of smaller miners, ranging from quoted companies with two or three mines to small family enterprises. Some produce for international markets and some just for local markets. The nature of the mineral product and the form of its occurrence play an important part in determining what products such producers focus on. Small miners do not generally try to compete in mineral markets where producers need scale economies and correspondingly large capital outlays, like iron ore. They can, however, operate in markets where demand is small or where ore deposits can be worked on a relatively small scale, like precious metals or semi-precious stones. At the extreme end of this part of the industry are the artisanal miners. These are very small, maybe even part-time, operators, recovering minerals that can be easily mined near surface (such as alluvial gold, tin, tantalum and diamonds) using very little capital. Such production activity is commonly lightly regulated or indeed wholly unregulated, with miners operating under very basic, and often unsafe and environmentally unsound, conditions. Artisanal mines do, nonetheless make a significant, if not always terribly reliable, contribution to the supply of several critical minerals.

The other key players in the mineral supply equation are exploration companies. This is the entrepreneurial end of the business – the equivalent of technology start-ups – the end where small companies go out to find mineral deposits in the hope either of being able to mine them themselves or else (and more often) sell them on at a good profit to a larger company for development. Since exploration can create enormous value for shareholders, turning what might otherwise be a fairly worthless piece of land into a profitable business opportunity, exploration companies have a strong pioneering quality. The highest rewards typically go to those with innovative ideas about ore genesis (an example might be those which uncovered significant diamond resources in Canada) or which are prepared to go looking in remote and difficult places. By the same token, exploration is also an extremely high-risk activity, and much exploration ends in failure and in investors losing their money.

Accordingly, exploration companies have their own particular economics and their own specialist investors. Banks, which might well be interested in helping a mining company with proven mineral reserves to finance the construction of a mine, are not generally interested in financing exploration. Exploration companies therefore tend to have to rely on equity (i.e. stock market) financing for their activities or on the support of large private

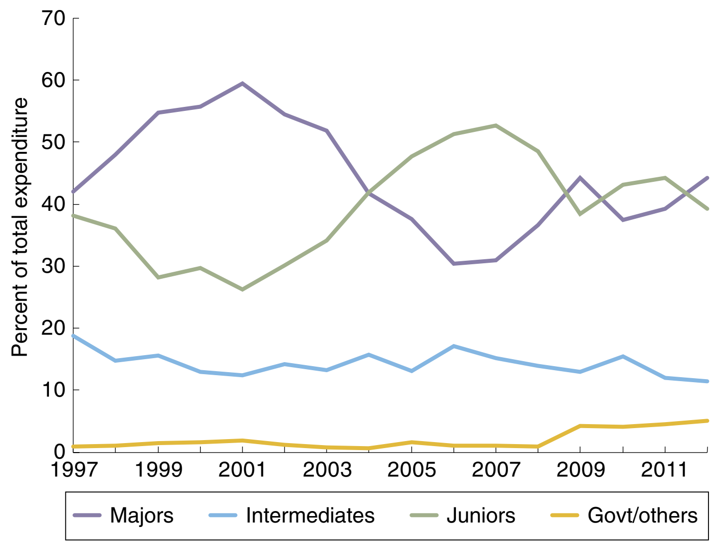


Figure 2.1 Worldwide exploration by company type: per cent shares, 1997–2012. (Data from MEG, 2012.)

investors. Some stock markets specialise in the provision of this sort of financing, notably the Toronto stock exchange (TSX) the Australian stock exchange (ASX) and the alternative investment market (AIM) of the London stock exchange (LSE). Because of the nature of its activities and of its financing, this is much the most responsive part of the mining industry and the part that is quickest to adjust to changes in market perceptions.

Metals Economics Group (MEG) has, for many years, compiled data on global exploration spending. For 2012, it estimated that expenditure was at a record level of US$21.5 billion (MEG 2012). Figure 2.1 shows the distribution of exploration expenditure in recent years split between that undertaken by mining majors, by intermediates, by juniors and by government or other organisations. Two points are apparent from this figure. First, spending by the juniors was much more responsive to rising prices during the course of the metal price boom in 2004–2007 and more responsive also to the falling off of prices in 2008–2009. Secondly, despite the small size of the companies in this sector, the juniors collectively account for a very large proportion of total exploration, this share rising to over 50 per cent of total spend in 2006 and 2007. A high proportion of exploration spending by juniors is accounted for by gold, the small scale of many gold deposits combined with the easy saleability of the product making this metal the target of choice for many juniors. A final point to note is that MEG data is focused on private-sector exploration and accordingly does not take full account of exploration by state companies and other state organisations. In light of the fast growth of state-funded exploration in countries such as Russia, India and, above all, China, in recent years, Raw Materials Group of Sweden considers that MEG's data understate the total exploration spend (Ericsson, 2011a).

## Industry dynamics

The larger mining companies do not generally give much thought to a mineral's perceived criticality when evaluating an investment. Their role is to produce minerals for which there is a proven market and to make a profit by so doing.

It is certainly the case that part of the assessment of whether something can be mined profitably resides in a miner's judgement about the strength of demand for the mineral in question and the price that consumers will be prepared to pay for it. However, for the most part these cannot be very accurately determined. Mineral demand and mineral prices are functions of the economic cycle, the forecasting of which is a very inexact science. Moreover, proving up resources and bringing them into production is a process that can take several years and a lot can change in the condition of markets during that time. Thus, while a miner must have some general level of confidence that a market will exist for the product to be produced and that prices will be sufficient to generate a positive return on capital, detailed projections of demand growth are not normally the primary factor behind a decision to invest. Mining companies cannot realistically lay claim to any particular comparative advantage in the art of economic forecasting and will generally, and rightly, be sceptical about the claims which appear in the popular press from time to time about the glittering prospects of this or that exotic-sounding mineral.

The situation with junior miners and exploration companies is a little different. As already noted, these companies are generally dependent on equity markets for their financing. Their survival thus depends on their ability to spark and to sustain interest amongst investors. Accordingly, they tend to be rather more sensitive to market perceptions about the desirability of different minerals than are large mining companies and will often creatively talk up the prospects for the products which they are hoping to find and to mine.

This being the case, exploration companies and junior miners are that much more likely than larger, well-established, mining companies to be responsive to the notion of a mineral's criticality. A project becomes easier to promote if the product it is expected to recover is viewed as having an exciting growth prospect, or is used in new and exotic applications; especially when this is reflected in strongly rising prices. It may not be that the mineral in question is suffering from insufficient investment, or even that there is a realistic prospect of getting a mine into operation in time to relieve any shortage, it is simply that funding is more readily available at such times. The identification of rare earth elements and lithium as critical minerals in recent years has helped generate huge interest in exploration for these minerals. There are believed to be some three hundred rare earth deposits under evaluation (Chegwidden and Kingsnorth, 2011) and over one hundred lithium projects (Mining Journal, 2011). This gold rush mentality – wherein high levels of exploration feed expectations about the demand prospects for a mineral, and vice versa – is an age-old feature of the mining industry.

Only a very few of the many thousands of mineral prospects that are explored ever actually make it through to production. And when it comes to the determination of whether a mineral deposit is to be developed, then judgements about the outlook for demand may well take second place to judgements about the economics of production. After all, if too many companies are pursuing the same growth segment for a given mineral, then there is always the risk that the market will at some point tip over into serious oversupply, at which point the relative competitiveness of producers becomes rather important. Many large mining companies, it might be noted, talk about their strategic objective as being to secure and operate low-cost, long-life, mines without reference to any particular mineral or its demand outlook.

In order for a prospect to be developed, a mining company will generally want to be sure that the resource is of a scale, quality and consistency to support production long enough to permit the recovery of the initial capital investment. It will need to be sure that the conditions of the rock are such as to permit safe and efficient mining. It will need to be sure that power and water are available to the project and that transport exists to get the product to market. In essence, what this will all ultimately boil down to is that the company will want to be confident, or as confident as it is possible in business to be, that it will be able to produce at costs which will make it profitable over the long term. This will, of course, depend in part on its assessment of the long-run price of the