MINERAL RESOURCES, ECONOMICS AND THE ENVIRONMENT

STEPHEN E. KESLER and ADAM C. SIMON

SECOND EDITION

Mineral Resources, Economics and the Environment

Written for students and professionals, this revised textbook surveys the mineral industry from a geological, environmental, and economic perspective. Thoroughly updated, the text equips readers with the skills they need to contribute to the energy and mineral questions currently facing society, including issues regarding oil pipelines, nuclear power plants, water availability, resource tax policy, and new mining locations.

Key features

- A new chapter on metals used in the technology industry is included as well as separate chapters on mineral economics and environmental geochemistry.
- Topics of special interest are highlighted in boxes, technical terms are highlighted when first used, and references are included to allow students to delve more deeply into areas of interest.
- Carefully designed figures simplify difficult concepts and show the location of important deposits and trade patterns, emphasizing the true global nature of mineral resources.

Stephen E. Kesler is an Emeritus Professor in the Earth and Environmental Sciences department at the University of Michigan, and a leading expert in the field of mineral resources. He has taught economic geology for almost 50 years, and worked with numerous exploration, mining, and energy companies worldwide. His research interests include geology and geochemistry of ore deposits, and mineral exploration and economics.

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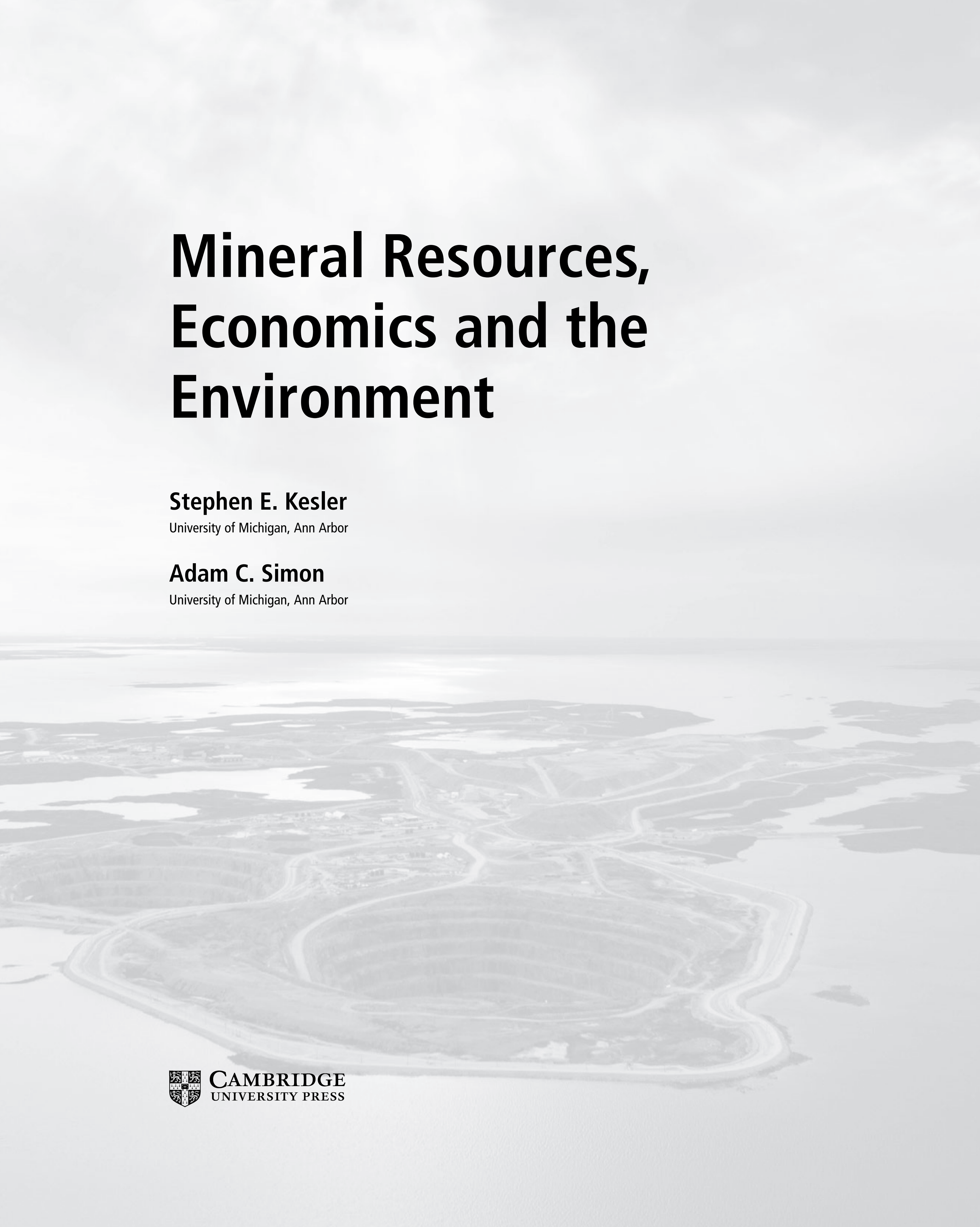
“Stephen Kesler and Adam Simon have done a remarkably good job at presenting a wealth of information about mineral resources along with a balanced view of their economic, environmental and political context that should be easy to understand by technical and non-technical readers alike. They have made particularly good use of text boxes to highlight relevant information and to draw attention to some rather provocative topics that deserve discussion and debate. I strongly recommend this book as a necessary reference to all who are serious about understanding the role of mineral resources in societies today.”
Dr. M. Stephen Enders, *Colorado School of Mines*

“I have been encouraging development of this revised edition for some time, as *Mineral Resources, Economics and the Environment* includes the ideal mix of topics for a course that I teach on global issues in Earth resources. In addition to the coverage of major energy, metallic, and industrial mineral commodities, the new chapter on technology elements is particularly timely. The new pedagogic insets are an excellent means to guide critical thinking on the complex interplay of societal mineral resources demand and its consequences. This revised edition should continue to be a leading textbook on Earth resources, as well as a useful reference for the non-specialist.”
Professor J. Richard Kyle, *University of Texas at Austin*

“This book will be an ideal text for senior undergraduates and postgraduate students. The information is up-to-date, informative and well-illustrated and will allow readers to make valued decisions on the relevance and importance of mineral resources and energy to our civilization. In addition, this book will be of great interest to the general public wanting to learn about mineral resources, economics and the environment.”
Professor Bruce Gemmell, *University of Tasmania*



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To Elias, Kai, and Torsten – the next generation of mineral consumers

Steve Kesler

To Alicia, Abigail, James, Laura, and Ethan – for everything

Adam Simon

CONTENTS

6

7

8

9

Light and base metals 206

10

Technology elements 234

11

Precious metals and gems 257

12

Agricultural and chemical minerals 288

13

Construction and industrial minerals 314

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Stephen E. Kesler and Adam C. Simon
Frontmatter
More information

The color plates appear between pages 212 and 213.

PREFACE

As we move into the twenty-first century, mineral supplies have become a truly global concern. For most of human history, developed countries have consumed far more than their per capita share of world mineral production. Everyone talked about the day when the rest of the world might want its share of the pie, but it was largely an abstract notion. Now, they are at the door. In fact, China has become the world's largest consumer of mineral resources, and India is not far behind. This momentous change poses two threats. First, there is the possibility that we will run out of the minerals even sooner than we thought. Second, there is the increased pollution caused by their extraction and consumption, which has already destroyed the environment in some areas.

These threats have generated a wide range of opinions about mineral resources and the environment. At one end of the spectrum are those who advocate a dramatic reduction in new mineral production with recycling and conservation providing for the future. At the other end are those who feel that vigorous exploration will always find new minerals and that they can be produced safely with minimal attention to the environment. Both camps are on perilous ground. Many mineral commodities, such as oil and fertilizers, cannot be recycled and the growing demand from developing countries will consume any minerals that are conserved by developed countries. To make matters worse, numerous studies have shown that Earth's storehouse of mineral deposits is indeed finite and that substitutes for important mineral commodities are scarce. Finally, we cannot ignore the environmental catastrophes that have been caused by past mineral production or the impending problems likely to be caused by increasing global mineral consumption.

Unless we are willing to make a dramatic reduction in our standard of living, however, we must find a way to produce and consume the enormous volumes of minerals that we need without significant degradation of the environment. In other words, we must find a middle ground in these arguments, and this means compromise. Unfortunately, compromise is impossible if the parties involved do not understand the problem. That is where this book comes in. It provides an introduction to the geologic, engineering, economic, and environmental factors that govern the production and consumption of mineral resources. This sort of comprehensive information is required if we are to understand all sides of an argument and, hopefully, find a solution.

The book is intended largely for use as a college text, although it can also be used as a primer for anyone with an interest in mineral resources. Mineral professionals who seek a broader view of their field will also find it useful. Because this audience has such a wide range of backgrounds, an effort has been made to make the book a self-contained document, in which all terms and concepts are explained. A basic high school education is all that is needed to read this book. Introductory material on geology, chemistry, engineering, economics, and accounting have been included, along with a glossary of terms, which appear in bold in the text on first mention. Appendices with information on elements, minerals, rocks, mineral commodities, units of weight and measure (including useful conversion factors), and mineral reserves and resources, have also been included, as have references to recent literature. In keeping with their wide use throughout the world, metric (SI) units are used as much as possible in this book, including the term tonne for metric ton, although the (US) short ton, or more simply ton, and (British) long ton are used in some cases where data were reported in these units. Other units, such as flasks and troy ounces, are also employed where dictated by convention.

This book deals with controversial subjects and we have expressed opinions about some of them. We have tried to do this on a case-by-case basis, without following any specific agenda or point of view. It is encouraging in that respect that the book has been cited as too "industry oriented" by some and too "environmentally oriented" by others. Hopefully, each camp will find much that is familiar and friendly, but also much that challenges assumptions and encourages factual debate intended to solve problems and produce a consensus. We will all find many areas in which more data are needed before final decisions can be reached.

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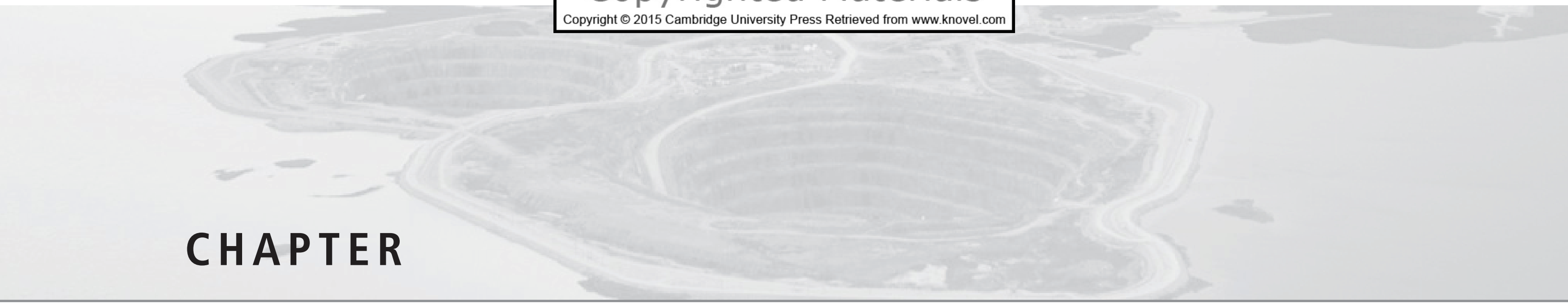
Frontmatter
More information

Although this book has two authors, it is the product of many minds. We are very grateful to the numerous geologists, mining and petroleum engineers, metallurgists, mineral economists, and other professionals who have allowed access to their projects or operations over the years, and to the many environmentalists who have discussed their research and concerns with us. We are equally grateful to the many students, particularly those in GS/ES380 at the University of Michigan, who have been a constant source of new information and challenging questions. We are grateful to Dale Austin and Marc Gellote for invaluable assistance with the figures, to Hannah Sherman for help with the references, and to Zoë Lewin for especially careful review of the entire manuscript.



CHAPTER

1

Introduction

1.1 Our mineral resource crisis

We are facing a global mineral resource crisis. In fact, we have two of them. First, Earth has a finite supply of minerals for a population that is growing faster than at any time in history (Figure 1.1). Second, mineral consumption is growing even faster than the population. Until recently, we were deeply concerned that most minerals were used in more developed countries (MDCs) with smaller consumption in less developed countries (LDCs) (Table 1.1). Although MDCs account for only 13% of world population, they consume 40% of world oil, 34% of world copper, 28% of world aluminum, 23% of world coal, and 21% of world steel, far more than their share. Now, the MDCs have been joined by China, which alone consumes 49% of world coal, 46% of world steel, 43% of world aluminum, 34% of world copper, and 11% of world oil, also far above its 20% share of world population. Demand is also increasing from India and other large LDCs as global affluence grows.

This creates a dilemma. Although we need more minerals to supply civilization, we are becoming increasingly aware that their production and use are polluting the planet. Effects that were once local in scale have become truly global, with mineral consumption implicated strongly in problems ranging from global warming and acid rain to destruction of the **ozone** layer and pollution of groundwater. Just when we need to expand mineral production, there is concern that Earth is reaching its limit of mineral-related pollution.

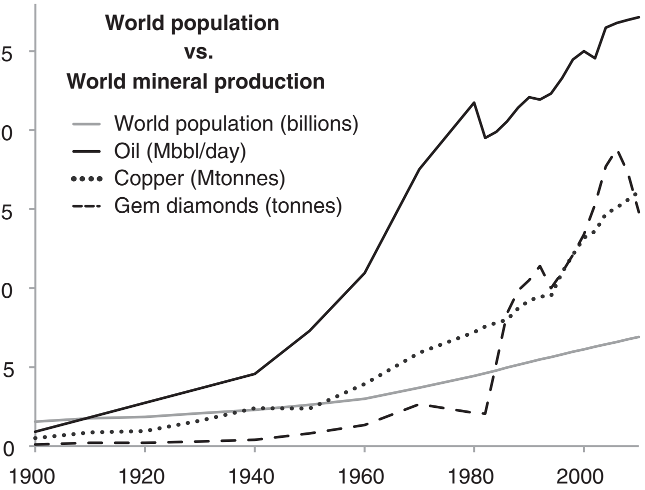


Figure 1.1 Change in world population since 1960 compared to the increased production of oil, copper, and gem diamonds (based on data of the US Geological Survey)

We cannot ignore this crisis. Our civilization is based on mineral resources. Most of the equipment that supports a modern life style is made of metals and powered by energy from fossil fuels. The machines that we have developed to transition us into a renewable energy future are also made entirely of mined materials. Our dependence on minerals pervades society and managing their flow is a major challenge to society (Figure 1.2). Large-scale production of food for growing populations depends on mineral fertilizers, the buildings in which we live and work are made almost entirely of mineral material, and even the gems and gold that we use for adornment and to support global trade come from minerals. Although some might seek a return to Walden Pond to free them from mineral dependency, most of Earth's 7 billion inhabitants are actively seeking the comforts that mineral consumption can provide. If global population and affluence continue to grow as rapidly as many estimates suggest, the pressure to find and produce minerals will be enormous.

Table 1.1 High-income countries, termed more developed countries (MDCs) in this book, listed in order of decreasing per capita gross national income (GNI) in US dollars. This list is based on data for 2012 from the World Bank and does not include data for the following countries that have been listed as high-income in previous years: Andorra, Bahrain, Bermuda, Israel, Kuwait, Liechtenstein, Libya, Macao, Monaco, New Zealand, Oman, Qatar, Saudi Arabia, and San Marino. All other countries are referred to in this book as less developed countries (LDCs).

Norway	98,860	Germany	44,010	Slovak Republic	17,180
Switzerland	82,730	France	41,750	Estonia	15,830
Luxembourg	76,960	Ireland	38,970	Barbados	15,080
Denmark	59,770	Iceland	38,710	Trinidad-Tobago	14,400
Australia	59,570	United Kingdom	38,250	Chile	14,280
Sweden	56,210	Italy	33840	Latvia	14,200
Canada	50,970	Spain	30,110	Lithuania	13,920
United States	50,120	Cyprus	26,000	Equatorial Guinea	13,560
Netherlands	48,250	Greece	23260	Uruguay	13,510
Austria	48,160	Slovenia	22,810	St. Kitts and Nevis	13,330
Japan	47,870	Korea, Rep.	22,670	Croatia	13,290
Singapore	47,210	Portugal	20,580	Russian Federation	12,700
Finland	46,940	Malta	19,760	Poland	12,660
Belgium	44,990	Czech Republic	18,130	Antigua-Barbuda	12,640

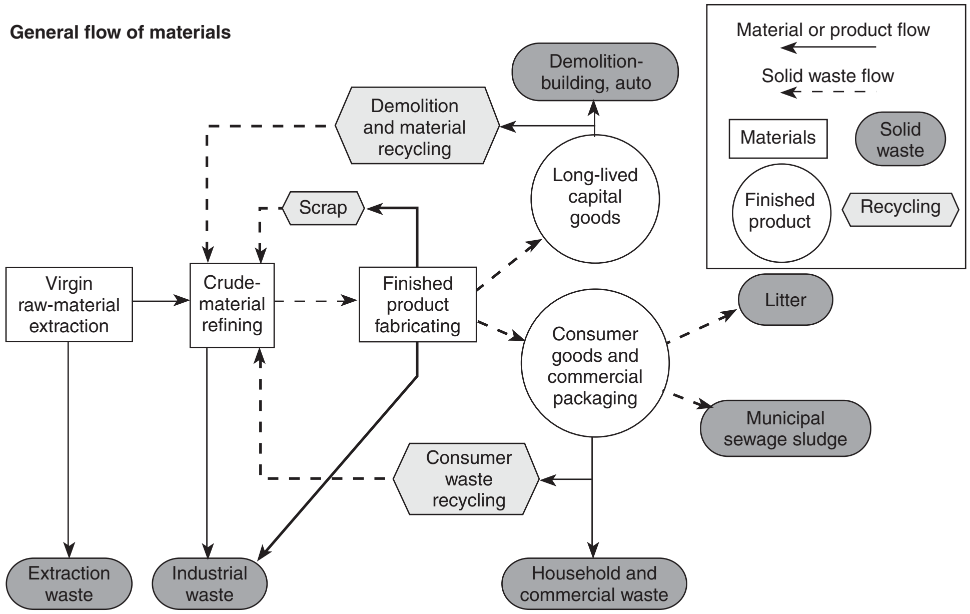


Figure 1.2 Flow of mineral materials through the US economy showing the role of both waste and recycling

Although the magnitude of our growing demand is easy to see, we have become dangerously complacent about it. This would have been unimaginable to the authors of *Limits to Growth* (Meadows *et al.*, 1972), who alerted the world in 1972 to its finite mineral supplies and soaring consumption. The collision between these forces had been developing for almost a century as world living standards improved. Between 1900 and 1973, world oil consumption grew by more than 7%

annually, with each succeeding decade using about as much oil as had been consumed throughout all previous history. World oil supplies were said to be on their way to exhaustion by the turn of the century (Bartlett, 1980a). With steel, aluminum, coal, and other commodities following similar trends, it appeared that we were about to witness the end of a brief mineral-using era in the history of civilization (Petersen and Maxwell, 1979).

However, this did not happen. In the mid 1970s, world mineral consumption slowed just as *Limits to Growth* was published. At the same time, exploration, stimulated by predicted mineral shortages, fanned out across the globe, dramatically increasing reserves for most mineral commodities. In fact, production increased so much that it created a glut of minerals on world markets. Thus, just when we were supposed to feel the cold breath of shortages and rising prices, the world saw an excess of mineral supplies and plummeting prices.

Unfortunately, the respite was brief. As can be seen in Figure 1.1, production curves resumed their climb by the early 1980s and since then production has continued to rise with short interruptions for economic downturns. Interestingly, the urgency expressed by *Limits to Growth* did not resurface as production began to rise again. Instead, it was replaced by a new concern about the environment.

Only a short time ago, our mineral supplies were determined largely by geologic, engineering, and economic factors. Their relation to Earth's mineral endowment was usually depicted as shown in Figure 1.3. Here it can be seen that the most important part of the mineral endowment consists of **reserves**, material that has been identified geologically and that can be extracted at a profit at the present time. **Resources** include reserves plus any undiscovered deposits, regardless of economic or engineering factors. But, addition of environmental factors to the vertical axis of this diagram has made the situation much more complex. Now, we must ask, not only whether the deposit can be extracted at a profit, but can we also do it in a way that does not compromise the quality of our planet. Environmental costs impact the economic axis of Figure 1.3, thereby controlling the overall profitability of extraction. Just as importantly, however, and more difficult to show in the diagram, are government regulations and public opinion. Today, extraction of mineral deposits in most MDCs and many LDCs must be approved by environmental regulators and accepted by the public, regardless of their economic and engineering merits. The social license to find and operate mineral deposits has become a major constraint on our ability to supply society with minerals (Thompson and Boutilier, 2011).

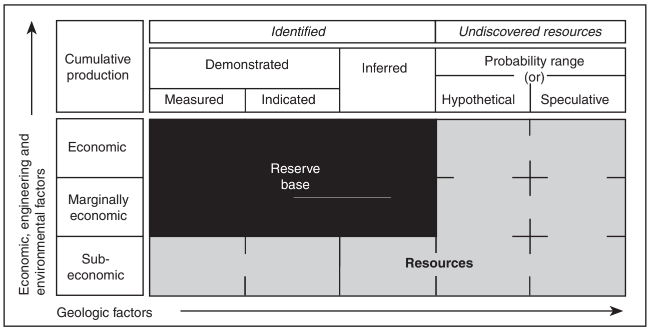


Figure 1.3 Mineral resource classification of the US Geological Survey. The horizontal axis of the diagram represents the level of geological knowledge about deposits, possible deposits, and even undiscovered deposits. The horizontal axis conflates all other information, which affects economic, engineering, and environmental factors that determine whether a deposit might be extracted economically.

Thus, the nature and extent of our global mineral endowment is no longer controlled strictly by market forces and administered by mineral professionals who make decisions on the basis of geologic, engineering, and economic factors. Instead, it is in the hands of a broader constituency with a more complex agenda focused largely on the environment, but with additional concerns about distribution of wealth. Addition of this new constituency threatens to push the challenge of supplying society with minerals into the realm of wicked problems, those in which there is a lack of certainty about how actions are related to outcomes and where there is much debate about the relative values of constraints (Metlay and Sarewitz, 2012; Freeman and Highsmith, 2014).

As more and more of us express opinions about mineral deposits, we incur an obligation to understand the factors that control their distribution, extraction, and use. That is what this book is about. We will start with a brief review of the four major factors that control mineral availability.

1.2 Factors controlling mineral availability

1.2.1 Geologic factors

Our mineral supplies come from **mineral deposits**, which are concentrations of elements or minerals that formed by geologic processes. Where something can be recovered at a profit from these concentrations, they are referred to as **ore deposits**. Mineral deposits can be divided into four main

BOX 1.1 NIMBY – THE "NOT-IN-MY-BACKYARD" SYNDROME

Many mineral deposits are in "inconvenient" places, including heavily settled regions, and production from them is often resisted by local residents. Other activities, such as half-way houses for persons released from prison to garbage dumps, are also resisted, and the practice has become known as the "not-in-my-backyard" (NIMBY) syndrome. However, if we need the minerals, they must be produced somewhere. This brings up the question of whether the NIMBY approach, whether by individuals and governments, is fair to others. Hydraulic fracturing (fracking) provides a good example of the problem. In 2014, the state of New York banned fracking, spurred in part by environmental problems at early gas production wells. Similar anti-fracking moves have been made by some towns in the United States and even by the French parliament. We will learn about fracking later in the book, but for the moment consider the ramifications of this decision. New York is a major consumer of natural gas, and a large proportion of its supply comes from adjacent states where fracking is applied. If fracking is too risky for residents of New York, why would they want to subject Pennsylvanians to that risk? A similar question might be asked of people who expect to use copper mined in other countries with lower levels of environmental regulation. Unless we find a way to get our minerals from an uninhabited asteroid or planet, we will ultimately have to face the moral dilemma posed by the NIMBY syndrome.

groups. The most basic group comprises soil and water, which lack the excitement of gold and oil, but have been essential to civilization from its beginning. **Energy resources** can be divided into the **fossil fuels**, including **crude oil**, **natural gas**, **coal**, **oil shale**, and **tar sand**; the nuclear fuels, including uranium and thorium; and geothermal power. As interesting as they are for the future, wind, tidal, and solar power are not derived from minerals and, along with hydroelectric power, have been omitted from this discussion in order that we can concentrate on minerals, as the title suggests. **Metal resources** range from structural metals such as iron, aluminum, and copper, to ornamental and economic metals such as gold and platinum, and the technological metals such as lithium and rare earths. **Industrial mineral resources**, the least widely known of the four groups, include more than 30 commodities such as salt, potash, and sand, which are critical to our modern agricultural, chemical, and construction industries.

The essential resources, soil and water, require special consideration in our discussion of mineral resources. Our interest in most of the other mineral resources discussed here deals with the balance between the benefits that we derive from them and the environmental damage that they cause. In contrast, soil and water have become the main dumping grounds for most of the wastes that are produced by modern society, including those related to mineral resources. Thus, the essential resources become the context in which we assess the environmental cost–benefit ratios of other mineral resources. Rather than being the focus of a single chapter, then, their role in world mineral extraction and use must be discussed throughout the text.

As we will see throughout this book, there is a close relation between the type of mineral resource found in an area and its geologic setting. Just as common sense tells us not to look for oil in the crater of a volcano, study of Earth has taught us to look for minerals in favorable geologic environments. As population pressures place more demand on land, geologic controls on the distribution of mineral deposits will become increasingly important in land-use decisions.

1.2.2 Engineering factors

Engineering factors affect mineral availability in two ways, technical and economic. Technical constraints are imposed when we simply cannot do something regardless of desire or funding. An example is extraction of iron from Earth's **core**, which is too deep and hot to be reached by any mining method. Economic factors constrain mineral availability only when we judge the cost of a project to be too great. We could build the necessary equipment to mine the Moon, for instance, but the cost of the equipment and the mining expedition would far exceed any benefit that the minerals might afford us.

Engineering considerations place important limits on our ability to extract minerals from Earth. Mining does not extend below about 2.3 km in most areas and the gold mines of South

BOX 1.2 ARE MINERAL RESOURCES SUSTAINABLE?

Mineral deposits have two geologic characteristics that make them a real challenge to modern civilization. First, almost all of them are **non-renewable resources**; they form by geologic processes that are much slower than the rate at which we exploit them. Whereas balanced harvesting of fishery and forest resources might allow them to last essentially forever, there is little likelihood that we will be able to grow mineral deposits at a rate equal to our consumption of them. Recent estimates suggest that we are consuming gold about 17,000 times faster than it is being concentrated in deposits (Kesler and Wilkinson, 2009). This means that the term sustainability cannot be applied in its strictest sense to mineral resources. Second, mineral deposits have a place value. We cannot decide where to extract them; Nature made that decision for us when the deposits were formed. The only decision that we can make is whether to extract the resource or leave it in the ground.

Africa, the deepest in the world, reach depths only to about 3.7 km. Wells extend to deeper levels; some oil and gas production comes from depths of about 8 km and experimental wells extend to 12 km (Figure 1.4a). However, there is little likelihood that significant production will come from these depths in the near future simply because few rocks at these levels have holes from which fluids can be pumped. Additional engineering constraints are imposed by the need to process most raw minerals to produce forms that can be used in industry and by the need to handle wastes efficiently and effectively.

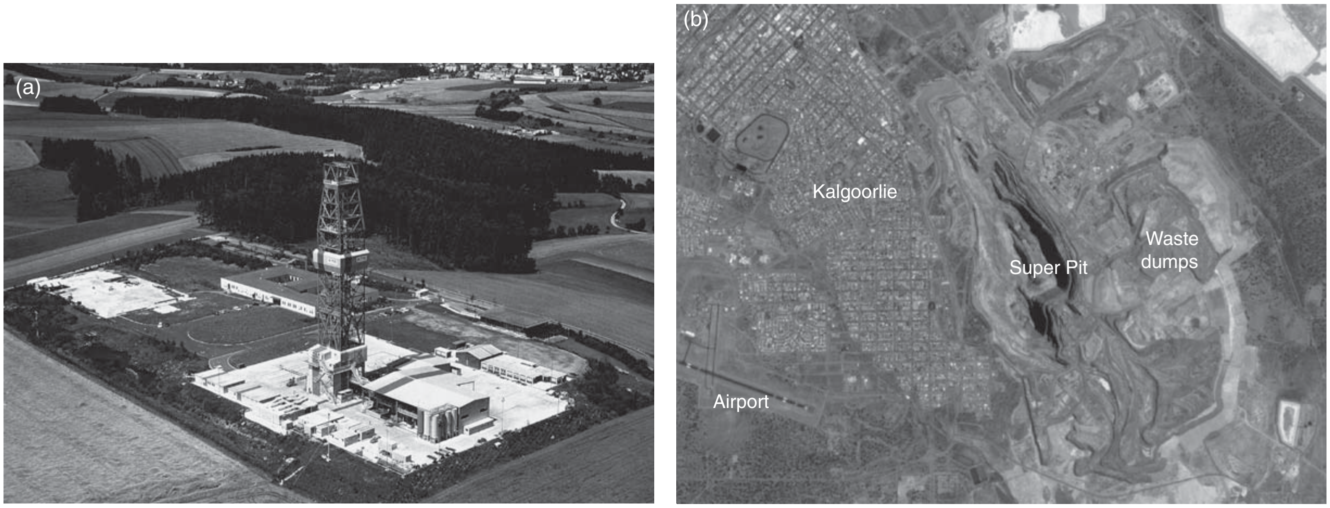


Figure 1.4 (a) The German ultra-deep borehole project was undertaken to provide information on geologic conditions at depth in Earth's crust. Two separate holes, which were drilled from the station shown here, reached a total depth of 4 km. Temperatures at the bottom of the holes were 120 °C and pressures were 40 megapascals, conditions that are extremely challenging for drilling equipment (photograph courtesy of KTB-Archive, GFZ Potsdam). (b) The Finiston Pit (also known as the Super Pit) at Kalgoorlie, Western Australia is one of the largest open pit mines in the world, measuring 3.5 km long, 1.5 km wide, and 0.6 km deep. The pit moves about 15 million tonnes of rock annually containing about 20,000 kg of gold. Waste rock removed to reach the gold ore is placed on the gray waste-rock dumps to the right of the mine and pulverized ore after processing to remove gold is placed in the white tailings ponds in the upper right. See color plate section.

1.2.3 Environmental factors

Environmental concerns about mineral resources focus on two main problems. The first to be recognized was pollution associated with mineral production (Figure 1.4b). Mining and mineral processing wastes are ten times greater by volume than municipal waste, and by far the largest amount of waste generated in the economic cycle (Hudson-Edwards *et al.*, 2011). The study of older mineral extraction sites has shown that elements and compounds were dispersed into the environment around them for distances of many kilometers. In an effort to prevent future calamities of this type, laws and regulations have been developed to control the generation and disposal of waste products from mineral exploration and production. The cost of compliance with these regulations has increased enormously and has become a growing factor in determining whether a mineral deposit can be extracted profitably. Only recently, have we begun to explore ways to reuse these wastes (Bian *et al.*, 2014).

We have been slower to recognize the importance of wastes associated with mineral consumption, but are making up for lost time. These wastes are more widely dispersed and it has required longer periods of observation and better analytical techniques to demonstrate that the soil, water, and air around us are changing in response to our activities (Figure 1.5). This recognition has produced legislation to remove lead from gasoline, to decrease the amount of SO_2 emitted from smelters, and to limit the release of salt and fertilizers from storage areas, important changes that improve environmental quality but add to the cost of using minerals.

1.2.4 Economic factors

Economic factors that control mineral production include those on the supply side, which are largely engineering and environmental costs related to extraction and processing, and those on the demand side, which include commodity prices, taxation, land tenure, and other legal policies of the host government. Although the balance among these forces can be considered from many political and economic perspectives, it is impossible to avoid the fact that the cost of producing a mineral must be borne by the deposit from which it comes or, in some special cases, by some other segment of the host economy.

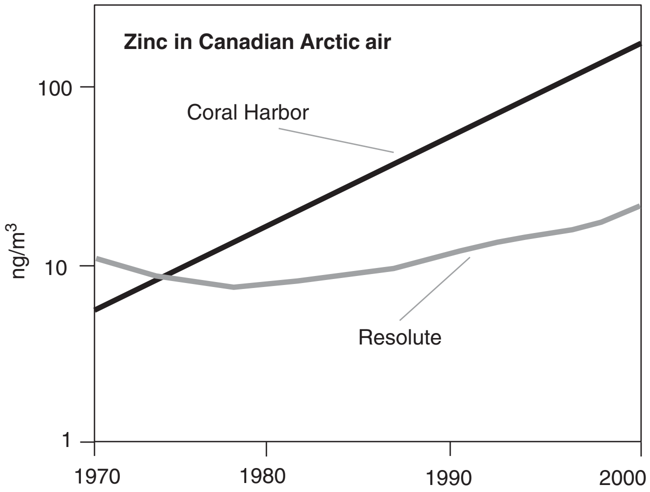


Figure 1.5 Although most airborne pollutants have decreased in concentration over the last few decades in response to environmental clean-up, some continue to increase. Shown here is the change in zinc content in air at Resolute and Coral Harbor in Arctic Canada, which has increased. Note that the scale for this diagram is logarithmic, indicating an enormous, and as yet poorly understood, increase in airborne zinc at these remote locations (based on data in Li and Cornett, 2011).

BOX 1.3 THE RIGHT TO MINERAL RESOURCES

The globalization of environmental concerns presents complex ethical problems that we have just begun to face. Just what right does any country have to pollute the atmosphere and ocean, when that pollution affects other countries? MDCs are at least trying to limit damaging emissions, but many LDCs continue to be major polluters. A related problem is the tendency of MDCs to "export" pollution by importing raw and sometimes even processed minerals from LDCs with fewer environmental regulations. In a world with finite resources and growing demand, the decision not to exploit one deposit requires that another be exploited to supply world demand. What might have happened, for instance, if Kuwait had responded to the environmental damage of Iraqi sabotage during the 1991 war by limiting oil production to just enough for its own energy needs? Would the MDCs have accepted that, and increased domestic exploration and production, or do they expect environmental sacrifices from supplier countries, which they are not willing to make themselves? Finally, what about states and nations whose increased environmental awareness leads them to forbid specific mineral production activities, such as has happened with the ban on fracking for oil and gas production in New York? Do these entities have a right to expect others to supply their mineral needs, or should they be excluded from commerce in that commodity? As demand increases these questions might well become more than tantalizing thought experiments.

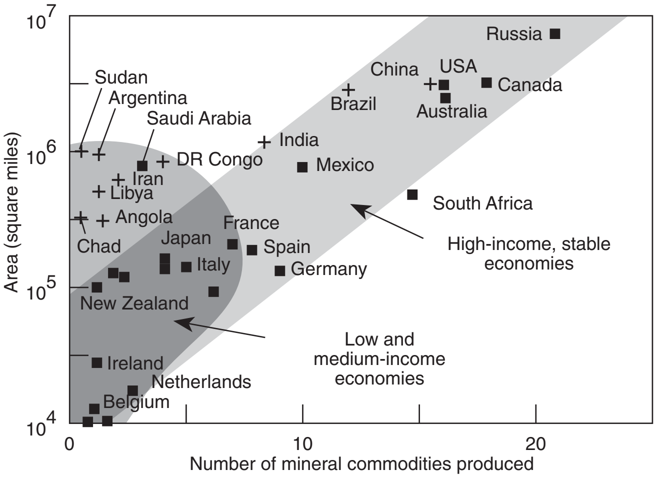


Figure 1.6 Relation between land area and number of minerals produced by various countries showing a good relation for high-income, stable economies and a poor relation for low and medium-income countries with less stable economies. This distinction between countries is similar to the LDC–MDC distinction used in this book and shows that countries with large land areas (and consequent variable geology) and stable fiscal and operational regulations are more likely to host operating mineral deposits.

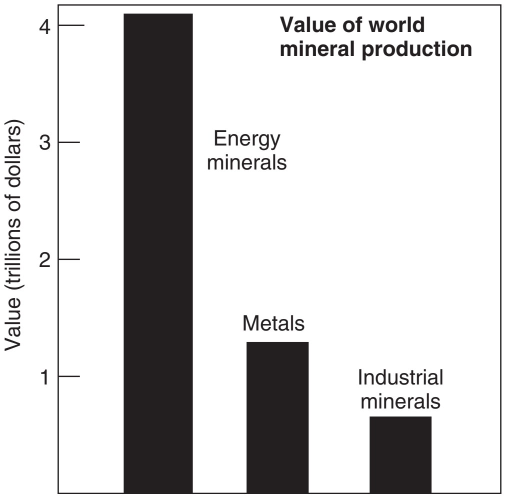


Figure 1.7 Value of world production for the three main classes of mineral products. Recycled material is not included. Steel and cement are the only processed mineral products included here and the exclusion of these would cause the metals and industrial minerals totals to drop to \$0.8 billion and \$0.4 billion, respectively (compiled from data of the US Geological Survey and International Energy Agency).

In a free market, costs and prices are usually part of a global system, which places similar constraints on all countries. However, legal, tax, and environmental regulations differ from country to country. The overall importance of these factors to mineral availability is shown by the positive correlation between the number of minerals produced and land area for countries with high-income, stable economies (Figure 1.6). This correlation supports the notion that large areas of Earth are more likely to have lots of important mineral resources than small areas. A similar correlation is not seen for low- and middle-income countries. In view of the relatively weak environmental regulations in most LDCs, the lack of a correlation in these countries probably reflects a more uncertain legal and tax framework, which discourages investment (Govett and Govett, 1977). For this reason, we have included chapters on land tenure and on mineral economics and taxation in the book.

1.3 Minerals and global economic patterns

The impact of minerals on the global economy is enormous. World fuel and metal production are worth about \$4.2 and \$1.3 trillion, respectively, and industrial mineral production is worth about \$550 billion (Figure 1.7). A good indication of the role of mineral production in economic activity in any country can be obtained by comparing the value of mineral production and gross domestic product (GDP). As can be seen in Table 1.2, raw mineral production makes up only a few percent of GDP in MDCs such as the United States, the Netherlands, and Sweden, but reaches 7 to 12% in others, including Australia and Canada. Norway holds the crown among MDCs with mineral production making up more than 35% of the GDP. Such unusually high percentages are more common in some LDCs including Papua New Guinea and Zambia, which are major copper producers, and the Persian Gulf countries that supply most of the world's oil. It is a mistake to conclude that countries are unimportant mineral producers just because raw mineral production makes up a small percentage of the GDP, however. The United States, for instance, is the leading world producer of many mineral commodities with a total value of more than \$520 billion and, according to the US Geological Survey, the value added to the US economy by major industries that consume these minerals is about \$2.44 trillion.

Classical theory holds that economic activity depends on domestic mineral resource availability (Hewett, 1929). According to this scheme raw-mineral exports occur early in a nation's development, as mineral deposits are discovered (Figure 1.8a). Profits from these exports are used to build an industrial infrastructure, which supports growing exports of

Table 1.2 Approximate value of energy and mining production in major producing countries (in billions of $US). Compiled from data of the World Bank, International Energy Agency, and International Council on Mining and Metals.

Energy production			Mined mineral production		
Country	*Value*	*% of GDP*	*Country*	*Value*	*% of GDP*
Russia	$534	20.85%	Australia	$72	7.80%
United States	$499	3.11%	China	$69	1.20%
China	$486	3.87%	Brazil	$47	2.30%
Saudi Arabia	$401	46.80%	Chile	$31	14.70%
Canada	$167	11.15%	Russia	$29	1.90%
Iran	$164	15.41%	South Africa	$27	7.50%
United Arab Emirates,	$125	46.04%	India	$26	1.50%
Venezuela	$114	28.93%	United States	$23	0.20%
Kuwait	$109	99.67%	Peru	$19	12.00%
Qatar	$107	50.37%	Canada	$14	0.90%
Iraq	$104	45.17%	Indonesia	$12	1.70%
Norway	$94	35.53%	Ukraine	$9.3	6.70%
Indonesia	$93	7.24%	Mexico	$8.4	0.80%
Australia	$68	7.07%	Kazakhstan	$7.3	4.90%
India	$54	1.12%	Iran	$4.4	1.30%
South Africa	$23	4.13%	Philippines	$4.2	2.10%
Netherlands	$19	2.57%	Sweden	$4.0	0.90%
Germany	$18	0.01%	Ghana	$3.9	12.70%
Poland	$13	0.01%	Zambia	$3.8	23.80%
Kazakhstan	$11	4.53%	Papua New Guinea	$3.2	33.40%

goods manufactured from domestic raw materials. As mineral reserves dwindle, imports rise to support continued manufacturing. Many LDCs, such as Zambia and the Democratic Republic of Congo, have been bogged down at the start of this evolution and their national budgets and overall welfare are highly dependent on raw-mineral prices. Because these prices vary unpredictably, these countries cannot control their revenues, a factor that limits stable development. This situation is a universal sore spot, with almost all countries wishing to sell more finished goods and less raw minerals. Even Canada, which occupies an enviable position in a global context, agonizes about its role as "hewer of wood and drawer of water" for the world.

It can therefore be seen that classical mineral economic theory predicts disaster for countries that lack raw minerals to support manufacturing and exports. But things have changed. Japan has a strong positive balance of trade in spite of an enormous annual deficit in mineral imports (Figure 1.8b). Lower wages and higher domestic productivity are commonly cited reasons for Japan's success. Just as important, and less widely recognized, have been the Japanese raw-material trade policies. During the last two decades Japan has invested in mineral extraction projects throughout the world. Most of these investments have involved agreements to buy some or all of the production, thus assuring an orderly supply of minerals.

A more modern view of global mineral trade is shown in Figure 1.9 using iron and steel as an example. Note that Japan and Korea, both major exporters of manufactured goods, are heavily dependent on imported raw material. The European

BOX 1.4 THE GLOBAL FOOTPRINT OF A SMARTPHONE

In 2015, 70% of the world's population, almost 5 billion people, owned a mobile phone, with nearly 2 billion of these being smartphones that function as handheld computers. This is a dramatic increase from none in 1990. The technology embedded in a smartphone exceeds that in the Apollo Guidance Computer used in 1969 to send humans to the Moon. That computer weighed 70 pounds, cost $150,000, and had a total storage capacity of 4 thousand bytes of information. Compare this to an Apple iPhone that weighs less than 4 ounces, costs only a few hundred dollars and comes standard with a storage capacity of 64 billion bytes of data. This remarkable technology comes with a huge natural-resource footprint. Among the more than 40 elements used are aluminum, potassium, and silicon for the ion-strengthened glass screen; carbon, cobalt, and lithium for the batteries; indium and tin to conduct electricity in the transparent touch screen; nickel for the microphone; lead and tin used as solder; antimony, arsenic, boron, phosphorus, and silicon in various semiconductors and chips; oil for the plastic housing; bromine in the plastic for fire retardation; copper, gold, and silver in the wiring; tantalum for the capacitors; the rare-earth elements gadolinium, neodymium, and praseodymium for the magnet, neodymium, dysprosium, and terbium to reduce vibration, and dysprosium, gadolinium, europium, lanthanum, terbium, praseodymium, and yttrium to produce colors. That is roughly one-half of all naturally occurring elements. Mining all of these resources consumes vast quantities of energy, as does shipping them and the finished products around the world. Almost 90% of the rare earths are mined in China, lithium is mined in Chile, cobalt in the Democratic Republic of Congo, aluminum in Australia, phosphorus in Morocco, nickel in Canada, and oil is extracted by using hydraulic fracturing to stimulate permeability in unconventional shale reservoirs. Smartphones truly have a global environmental footprint. And in the United States the average user buys a new phone every 2 years.

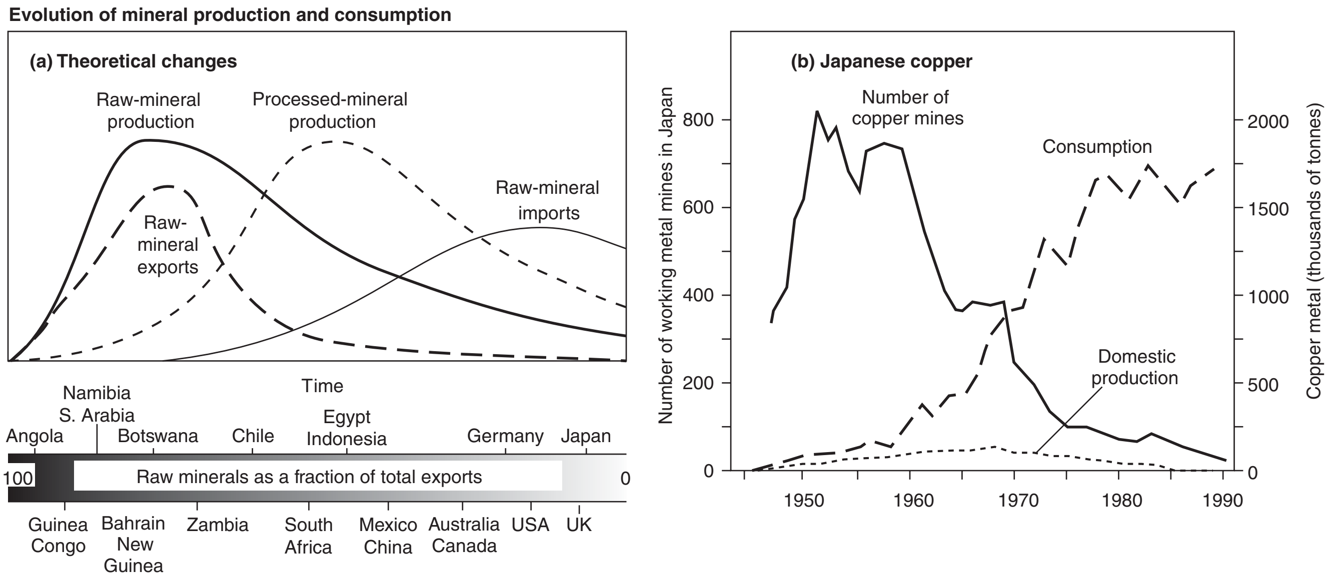


Figure 1.8 (a) Classical relation between economic development and mineral supplies showing the position of several mineral-producing countries as indicated by the proportion of minerals in their total exports. (b) Change in copper mining and production in Japan from 1940 to 1990 showing increased consumption despite decreased domestic production (based on Ishihara, 1992).

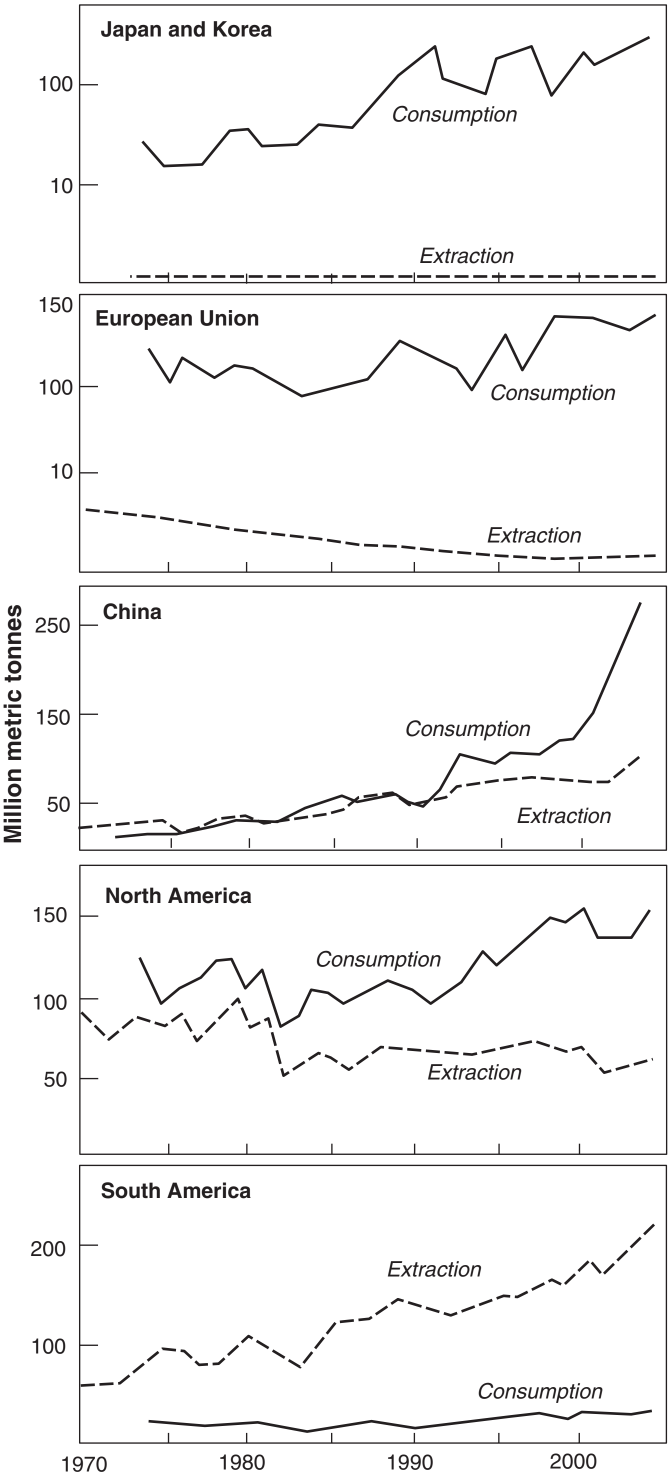


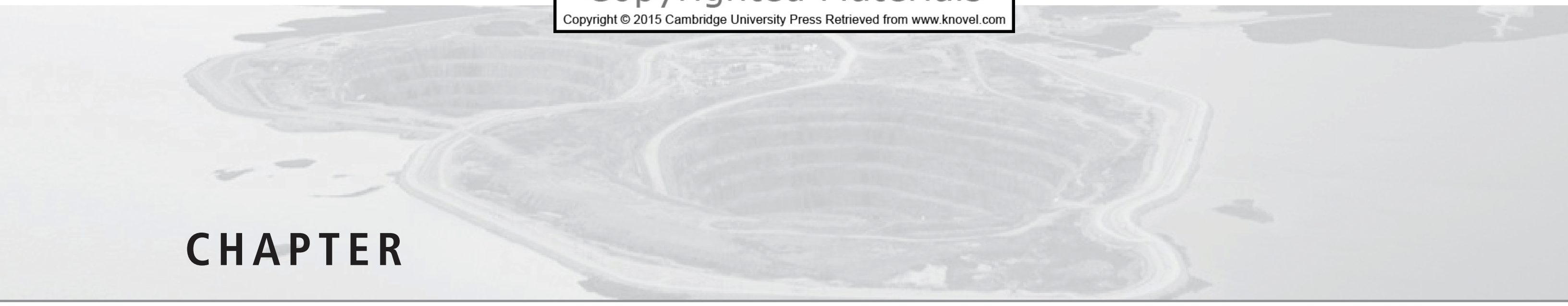
Figure 1.9 Relation between consumption and extraction for iron and steel in various parts of the world, showing the high dependency of the European Union and Japan–Korea on imports, with lesser dependence in China and North America and a large export market for South America (compiled from Rogich and Matos, 2008)

Union is in only slightly better shape. China, despite its major role as a raw-mineral importer, is able to supply a much larger proportion of its needs domestically, in part because of its larger size and greater geologic diversity. North America comes even closer to self-sufficiency, and South America is a major source of raw materials. Thus, the pattern of mineral use is global, with LDCs supplying mineral raw materials to MDCs that manufacture goods and export them (Graedel and Cao, 2010).

Some feel that the great increase in the global trade of minerals has weakened the concept of **strategic minerals**, which holds that the security of a country depends on its mineral supplies, particularly those that are necessary for defense needs. However, the 1991 Iraq war and its successors in the Middle East have shown just how hard MDCs will fight for access to mineral supplies, suggesting that the strategic minerals concept has not died away. Global mineral trade has, however, eroded the power of mineral cartels by promoting market transparency, in which production and consumption data are shared by producers throughout the world.

1.4 The new era of world minerals

Mineral resource availability is entering a new era, one in which traditional geologic, engineering, and economic constraints are joined and often trumped by environmental considerations. Dealing with these many factors and the uncertainties that they involve, while moving ahead to supply the next generation with minerals, will require compromises based on a full understanding of the issues. As a first step in this direction, this book explores the ramifications and interrelations of geologic, engineering, economic, and environmental constraints on global mineral resources. We hope it makes you a better decision maker as we approach these major problems.



CHAPTER

2

Origin of mineral deposits

A cubic kilometer of average rock contains millions of dollars worth of mineral commodities (Table 2.1). Although this might make you think that we could supply our mineral needs from average rock, this notion is dispelled by a look at the costs involved. A tonne of average rock contains only a few cents worth of gold versus the several dollars that you would have to spend to extract the gold. Unfortunately, you cannot get around this constraint by extracting other metals from the same tonne of average rock because most mineral commodities require different processes, each with its own high cost. To help keep things in perspective, remember that it takes several dollars just to buy a tonne of gravel, which takes essentially no processing. That is why we have to depend on **mineral deposits** for our needs. Mineral deposits are simply places where Earth has concentrated one or more mineral commodities. Where the degree of concentration is high enough for profitable extraction, we have an **ore deposit**.

Table 2.1 Value of selected mineral commodities in a cubic kilometer of average upper crustal rock and in 1 tonne of rock based on 2014 prices. The total value of just these commodities in a cubic kilometer of average rock is more than $200 billion!

Element	Value in 1 km^3 of crust ($million)	Value in 1 tonne of crust ($)	Average crustal abundance (ppm)
Aluminum	172,000	140.00	81,500
Iron	37,000	30.00	39,200
Manganese	2,100	1.70	774
Nickel	1,100	0.91	47
Copper	233	0.19	28
Zinc	170	0.14	67
Gold	83	0.068	0.0015
Tin	59	0.05	2.1
Lead	43	0.035	17
Molybdenum	42	0.034	1.1
Platinum	3.1	0.003	0.0005

With all of these factors to consider, you might lose sight of the fundamental fact that we can only produce minerals from mineral deposits. So, we begin with a review of the geologic setting and formation of mineral deposits.

2.1 Geologic framework of Earth and mineral deposits

Earth consists of four global-scale divisions: the **atmosphere**, **hydrosphere**, **biosphere**, and lithosphere (Figure 2.1). Mineral deposits are part of the **lithosphere**, which is made up largely of rocks and minerals. **Minerals**, which control the distribution of elements in Earth, are naturally occurring solids with a characteristic crystal structure and definite chemical composition. They are divided into groups on the basis of their chemical compositions (Appendix 2, Table A2.1). Although about 3,800 minerals are known, only about 30 minerals make up almost all common rocks, another 50 or so account for most metal ores, and about 100 comprise the industrial minerals (Appendix 2).

Rocks consist of grains of minerals that hold together well enough to be thrown across a room. They are divided into groups on the basis of their origin and composition

BOX 2.1 MINERAL DEPOSITS VS. ORE DEPOSITS

The distinction between ore deposits and mineral deposits is a dynamic function of economic, engineering, political, and environmental factors. For example, the need to use catalytic converters to clean automobile exhaust changed platinum-bearing mineral deposits around Rustenburg, South Africa, into profitable ore deposits. Similarly, increased oil prices in the 1970s provided the key to large-scale mining of the extensive tar sands of Alberta, and subsequent price increases in the 2000s transformed Canada into a major oil producer. On the other side of the coin, mining of lithium from the large **pegmatite** deposits at Kings Mountain, North Carolina, came to a halt when production began from the large brine deposits in the Atacama Desert of Chile, simply because it is much easier to get lithium from a liquid than from a mineral.

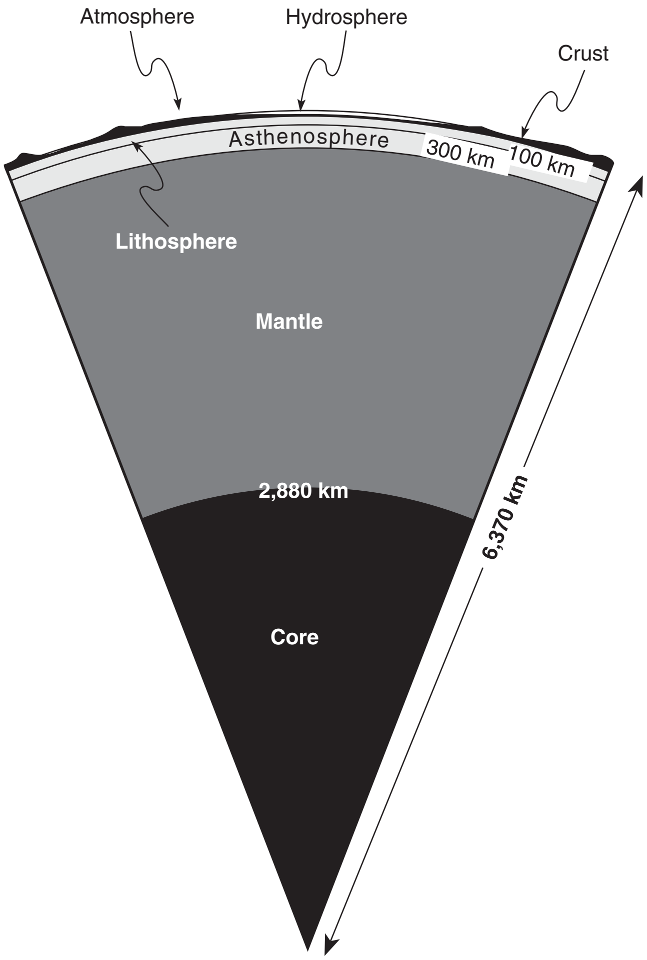


Figure 2.1 Distribution of the lithosphere, hydrosphere, and atmosphere (the biosphere is too small to be shown at this scale) and major divisions of the solid Earth (core, mantle, asthenosphere, and lithosphere). Note that the term lithosphere as used by environmental geochemists refers to the entire solid part of the planet rather than the outer 100-km-thick plate that geologists call the lithosphere.

(Appendix 1; Table A2.2). **Igneous rocks** form by crystallization or solidification of molten rock called **magma**, which is less dense than rock and will rise through the lithosphere. Where magma reaches the Earth's surface it is called **lava** and forms **extrusive rocks**, including volcanoes. Where magma solidifies below the surface, it forms **intrusive rocks**, including large bodies known as **stocks** and **batholiths** and tabular bodies known as **sills** and **dikes**. Most **igneous rocks** consist largely of silicon and aluminum, but they are divided into smaller groups on the basis of their mineral and chemical compositions, as discussed later. **Sedimentary rocks** consist of material that was deposited by water, wind, or ice. They can consist of clasts or fragments of pre-existing rocks, of minerals precipitated from water, or organic matter. **Metamorphic rocks** form when other rocks are buried in the crust where high heat and pressure recrystallize original minerals, forming new minerals and textures.

The solid Earth, or lithosphere, is divided into the core, mantle, and crust (Figure 2.1). The **core**, which consists largely of iron, is one big mineral deposit. Unfortunately, engineering constraints prevent us from extracting it, although cores of failed planets come to us in meteorites. The **mantle**, which forms a thick shell around the core, consists of **ultramafic** rocks that are strongly enriched in magnesium; they contain locally important concentrations of chromium, cobalt, and nickel. Even the mantle is too deep to be within reach of mining, although we do extract ore from it where mantle rocks have been moved to the surface by plate tectonics, as discussed later.

Most of our mineral deposits are in the **crust**, which covers the mantle and contains the greatest variety of Earth's rocks. It is divided into two parts: **ocean crust**, which is 5 to 10 km thick and consists of **mafic** igneous rocks, largely **basalt**, that is enriched in iron, calcium, and magnesium; and **continental**

crust, which is 20 to 70 km thick and consists of **felsic** igneous rocks that are enriched in sodium and potassium, metamorphic rocks, and a covering layer of sedimentary rocks. Even the ocean crust is difficult to reach from an engineering standpoint, and we extract mineral resources from it mostly where it has been moved onto the continents by faulting. It is the continental crust that hosts the vast majority of our mineral resources.

BOX 2.2 LOOK IT UP

Throughout the book, we have tried to explain most terms and concepts that might be new to you. If we have failed, have a look in the glossary. And, if you want to get a little more information on the composition and classification of common rocks and minerals, the main ore minerals for each element, or the most important weights and measures that we deal with in the book, you can look at the appendices. We make specific reference to the appendices in this chapter, but will not do so in the remaining chapters and will trust you to *look it up*.

BOX 2.3 PLATE TECTONICS

Earth's upper part is divided into large lithospheric plates (Figure Box 2.3.1) that move about by the process known as **plate tectonics**. The plates are about 100 km thick and consist of ocean and/or continental crust and some of the underlying mantle (Figure Box 2.3.2). They are underlain by plastic mantle known as **asthenosphere**. The plates meet in three types of **margins**. **Divergent margins** form where plates move apart, such as at **mid-ocean ridges** where rising mantle melts to produce mafic basalt magma that flows onto the ocean floor creating new ocean crust. Divergent margins beneath continental crust create **rifts** such as the Dead Sea, which enlarge to form new oceans such as the Red Sea. **Convergent margins** form where plates move together. Most convergent margins include **subduction zones**, where the ocean crust sinks back into the mantle causing the production of **intermediate** to felsic magmas that form stocks and batholiths in the crust and volcanoes at the surface. At some convergent margins, neither plate sinks and one rides onto the other along **obduction zones**. **Transform margins** form where two plates move horizontally past each other along features like the San Andreas fault in California.

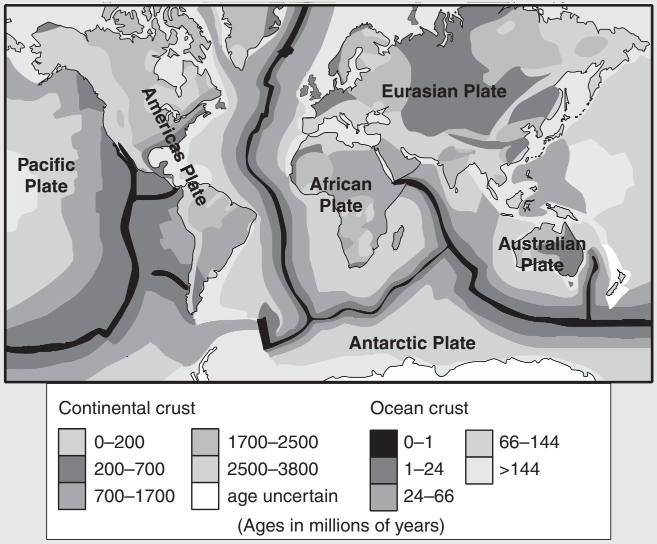


Figure Box 2.3.1 Distribution of lithospheric plates. Note that continental crust is much older than ocean crust and the ages of ocean crust increase away from spreading ridges.

BOX 2.3 (CONT.)

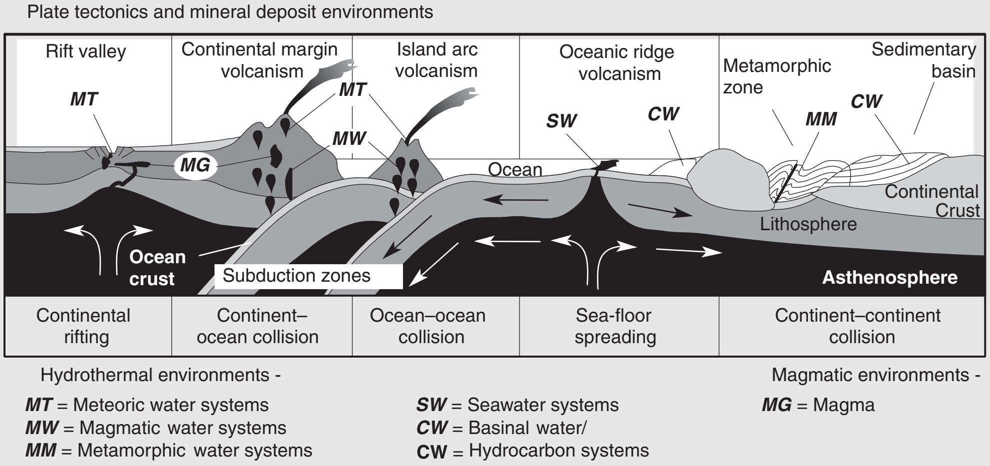


Figure Box 2.3.2 Plate-tectonic environments, showing their relation to ore-forming magmatic and hydrothermal processes discussed in this chapter and shown in Figure 2.12

The continents are buoyant features that float on the mantle, whereas denser ocean crust sinks into the mantle at subduction zones. In fact, the oldest known ocean crust is only about 200 million years (Ma) old, whereas the oldest rocks on the continents are about 4 billion years old (Figure 2.2). Even these old continental rocks are significantly younger than the 4.65 billion year (Ga) age of Earth because the oldest rocks have been destroyed by erosion or covered by younger ones. Thus, even on the continents, rocks of the four major divisions of Earth history, the **Hadean**, **Archean**, **Proterozoic**, and **Phanerozoic** eons (Appendix 1, Table A1.3), become progressively less abundant with increasing age. In most cases, rocks of Hadean and Archean age form stable cores for the continents, which are known as **cratons** or **shields**, and Proterozoic and Phanerozoic rocks are found largely in deformed belts surrounding them.

Plate tectonics moves the lithospheric plates at the agonizingly slow rate of a few centimeters per year. This rate, in turn, controls magma formation, erosion, and sedimentation, all of which form mineral deposits (Sawkins, 1990). The resulting rate at which individual mineral deposits form is much slower than the rate at which we extract them, which is why we refer to mineral deposits as **non-renewable resources**. This distinguishes them from **renewable resources** such as forests and fisheries. It also highlights the fact that, in the long run, mineral resources are not really sustainable, at least not in the sense that we can use them at a rate equal to the rate at which Earth forms them.

2.2 Geologic characteristics of mineral deposits

Ore deposits represent work that nature does for us. For instance, Earth's crust contains an average of about 55 ppm (parts per million) of copper, whereas copper ore deposits must contain about 5,000 ppm (0.5%) copper before we can mine them. Thus, geologic processes need to concentrate the average copper content of the crust by about 100 times to make a copper ore deposit that we can use (Table 2.1). We then use industrial processes to convert copper ore into pure copper metal, an increase of about 200 times. By a fortunate natural coincidence, elements and materials that we use in large amounts need less natural concentration than those that we use in small amounts. Thus, we are likely to have larger deposits of mineral commodities that we use in large amounts. As long as energy costs remain high, the relation between work that we can afford to do and work that we expect nature to do will control the lower limit of natural concentrations that we can exploit, and this puts very real limits on our global mineral resources.

Most ore deposits contain an **ore mineral** in which the element or substance of interest has been concentrated. For instance, the common zinc ore mineral, sphalerite (ZnS), contains about 64% (640,000 ppm) zinc. In rocks that contain sphalerite, the production of zinc is greatly simplified because grains of sphalerite (Figure 2.2a) can be separated from the ore to produce a smaller volume of material for further treatment to obtain zinc metal. Zinc does not form sphalerite everywhere, however. Most of the Earth's zinc **substitutes** at very low (ppm) concentrations for iron in silicate minerals that make up most of the crust. Ore deposits form only where geologic processes liberate this zinc and combine it with sulfur to form sphalerite. Formation of most mineral deposits requires this sort of concentration, first into an ore mineral and then into a large enough concentration of the ore mineral to be of economic interest. In some cases, the concentrated material is not actually a mineral. For instance, crude oil and natural gas deposits form when **organic material** dispersed through sedimentary rock accumulates in concentrations that we can exploit (Figure 2.2b) and groundwater accumulates in zones call aquifers.

Figure 2.2 (a) The dark crystals of galena grew on top of smaller crystals of white dolomite. Whereas the dolomite contains almost no zinc, sphalerite contains as much as 64% by weight and is our principal ore mineral for zinc. (b) The dark material is solidified crude oil known as **bitumen**, which is lining a cavity in the white limestone. See color plate section.

The importance of ore minerals or compounds is well illustrated by molybdenum and germanium, which have approximately the same average concentrations in the crust, about 1.5 ppm. In spite of this, the world molybdenum production of 270,000 tonnes is over 2,000 times greater than that for germanium. This difference reflects the fact that molybdenum forms the common ore mineral, molybdenite (MoS_2), whereas germanium forms no common minerals.

Ore minerals such as sphalerite and molybdenite are rarely found in massive clumps that can be extracted directly. Instead, they are found in mixtures with minerals that have no commercial value in that setting, known as **gangue minerals**. For instance, quartz (SiO_2) is a common gangue mineral in many metal deposits and is discarded as waste, although pure deposits of quartz are valuable for glass sand and other uses. The concentration of the element or compound of interest in an ore is referred to as the **grade** of a deposit, and the minimum concentration needed to extract the ore at a profit is known as the **cut-off grade**. Many zinc deposits have an average grade of about 5% zinc, almost all of which is in sphalerite. Grades for natural gas, crude oil, and other fluids are not usually quoted as percentages. Instead, they are given as the amount of fluid that can be recovered from a given volume of rock.

In addition to grade, a mineral deposit must attain a minimum size. No matter how high its grade, a deposit must contain enough ore to pay for the equipment, labor, and costs of extraction. The size of solid mineral deposits is almost always given as the mass of ore, which is specified in metric tons (tonnes) and the size of fluid deposits is given as the volume of fluid, with the understanding that it can be recovered from a given volume of rock.

Although we refer to processes that form mineral deposits as ore-forming processes, many deposits are not actually ores. In the following discussion, we divide ore-forming processes into those that take place at or near Earth's surface and those that take place at depth (Table 2.2).

2.3 Ore-forming processes

2.3.1 Surface and near-surface ore-forming processes

Weathering and soils

Weathering is the geologic term for the wide range of processes that take place in the **critical zone**, where rocks and minerals that formed at depth equilibrate with water, air, and plants near the Earth's surface (Lin, 2010). Weathering

Table 2.2 Geologic processes that form mineral deposits, with examples of deposits formed by each process and elements concentrated in them.

Type of process	Types of deposits formed and minerals concentrated surface processes
Surface processes	
Weathering	Laterite deposits – nickel, bauxite, gold, clay soil
Physical sedimentation	
Flowing water	Placer deposits – gold, platinum, diamond, ilmenite, rutile, zircon, sand, gravel
Wind	Dune deposits – sand
Chemical sedimentation	
Precipitation from or in water	Evaporite deposits – halite, sylvite, borax, trona Chemical deposits – iron, manganese
Organic sedimentation	
Organic activity or accumulation	Hydrocarbon deposits – oil, natural gas, coal Other deposits – sulfur, phosphate
Subsurface processes	
Involving water	Groundwater and related deposits – uranium, sulfur Basinal brines – Mississippi Valley-type (MVT), sedimentary exhalative (SEDEX) Seawater – volcanogenic massive sulfide, SEDEX Magmatic water – porphyry copper–molybdenum, skarn Metamorphic water – gold, copper
Involving magmas	Crystal segregation – chromium, vanadium Immiscible magma separation – nickel, copper, cobalt, platinum-group elements

produces the **regolith**, a layer of partly decomposed rock and soil that covers most of the land surface from depths of a few centimeters to several hundred meters. Some civil engineers refer to essentially all of the regolith as **soil**. Farmers refer to soil as the upper part of the regolith that will support marketable plant life. Most geologists and environmentalists extend this definition to take in the upper part of the regolith throughout the world, including materials somewhat deeper than the soil of agriculture. This layer contains most of the minerals that are produced by weathering and it bears the brunt of environmental pollution (Foth, 1984; Sparks, 2002; Hillel, 2007).

In warm, humid climates, soil forms largely by chemical and biological weathering involving the dissolution of common rock-forming minerals. Dissolved elements such as sodium, potassium, calcium, and magnesium are carried by streams to the ocean. Because most common rock-forming minerals are not very soluble, weathering depends heavily on acid water and on biological activity (Chorover *et al.*, 2007). Acid rain is generated by dissolution of atmospheric gases such as CO_2 and SO_2, as discussed in the next chapter, and acidity is increased in the soil by bacterial activity that boosts CO_2 concentrations to levels of several percent versus only 0.03% in the atmosphere; by decomposition of pyrite and other sulfide minerals to form sulfuric acid; and by acids formed during the decay of organic matter. Some rock-forming elements, such as iron and carbon, are oxidized during weathering, further contributing to the decomposition of minerals containing them, and plant roots create special chemical environments that enhance mineral dissolution.

Physical weathering involves processes that actually break the rock into pieces. Root growth has this effect, as does ice, which has a volume 9% greater than an equivalent amount of water. Growth of salt and calcite crystals when water evaporates from cracks can also fracture a rock. Diurnal (daily) and seasonal temperature changes cause expansion and contraction that gradually promote fracturing, as does the removal of overlying sediment by erosion. These effects dominate only in arid and Arctic environments, where chemical processes are limited by the absence of moisture or by low temperatures.

Weathering and soil formation actually form ore deposits of two main types. First, these processes can remove soluble constituents leaving behind relatively insoluble elements and minerals of value in residual deposits. The most obvious

BOX 2.4 CLASSIFICATION OF SOILS

Soils can be classified on the basis of their vertical zonation. In humid areas where population concentrations are greatest and environmental effects of greatest interest, the generalized soil profile shown in Figure Box 2.4.1 is a useful start. It consists of an upper O horizon rich in organic material from vegetation, which grades downward into an A horizon dominated by silicate and oxide minerals formed by weathering of the original rock. Acid water leaches material from the lower part of the A horizon, which is sometimes given the separate name E horizon. These dissolved constituents move downward and are deposited in the B horizon, which becomes enriched in soluble material. Underlying all of these is the C horizon, which consists of variably weathered bedrock. In many areas of deep weathering, the C horizon consists of intensely weathered material known as saprolite, which retains the original textures of the parent rock. In more arid regions and in areas of restricted drainage such as swamps this zonation is not as well developed.

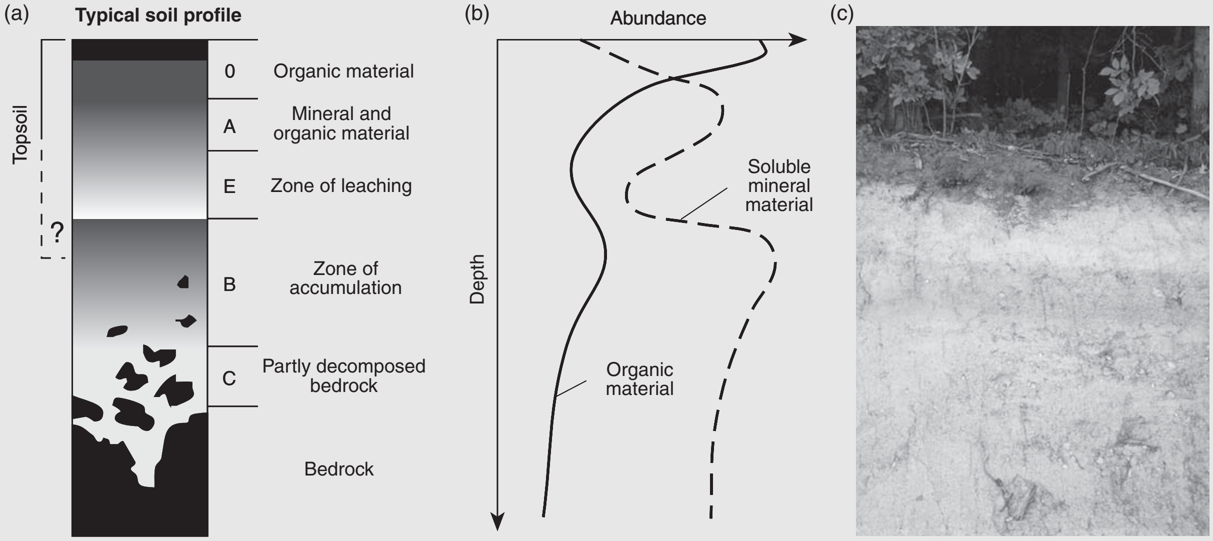


Figure Box 2.4.1 Typical soil profile (a) with the related abundances of soluble mineral and organic material (b) of a well-drained soil in a humid temperate region showing zones in which soluble mineral and organic matter are leached and accumulated. (c) Photo of soil profile showing organic matter at the top (gray), leached A zone (white) and zone of accumulation (reddish-brown). See color plate section.

example is grains of gold in rocks; the rocks decompose but the gold remains in the residuum. Similar processes form concentrations of barite, ilmenite, and other less-soluble minerals when their enclosing rocks dissolve and disintegrate. Redistribution of soluble constituents in the soil also creates mineral deposits such as **laterites** in which aluminum, iron, nickel, or other elements accumulate in the lower part of the B or the C horizons. Laterites often make up the upper part of saprolite zones, and represent the parts of the weathering zone where original rock textures have been totally destroyed.

Soil is actually our most important mineral resource. It is the basis for agriculture as well as the principal host of many microorganisms that carry out chemical reactions essential to life. It is also subject to many assaults, of which erosion is the most dangerous. By its very nature, soil is not coherent or lithified like rock, and this makes it easy to erode. Soil is held in place largely by plant roots and where they are removed, soil that has taken thousands of years to form can be removed in a few hours (Dotterweich, 2013). Humans are more important to global erosion and destruction of soils than natural processes. Human activity has lowered continental land surfaces by about 6 cm, an enormous amount in view of the short time that we have been on Earth (Wilkinson and McElroy, 2007). Soil is also subject to **desertification**, which occurs naturally on the margins of deserts, but is also caused by