

HOW MINING WORKS



BY W. SCOTT DUNBAR

PUBLISHED BY THE
SOCIETY FOR MINING, METALLURGY & EXPLORATION

Society for Mining, Metallurgy & Exploration (SME)

12999 E. Adam Aircraft Circle
Englewood, Colorado, USA 80112
(303) 948-4200 / (800) 763-3132
www.smenet.org

SME advances the worldwide mining and minerals community through information exchange and professional development. SME is the world's largest association of mining and minerals professionals.

Copyright © 2016 Society for Mining, Metallurgy & Exploration Inc.
Electronic edition published 2106.

All Rights Reserved. Printed in the United States of America.

Information contained in this work has been obtained by SME from sources believed to be reliable. However, neither SME nor its authors and editors guarantee the accuracy or completeness of any information published herein, and neither SME nor its authors and editors shall be responsible for any errors, omissions, or damages arising out of use of this information. This work is published with the understanding that SME and its authors and editors are supplying information but are not attempting to render engineering or other professional services. Any statement or views presented herein are those of individual authors and editors and are not necessarily those of SME. The mention of trade names for commercial products does not imply the approval or endorsement of SME.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of the publisher.

ISBN 978-0-87335-399-1
Ebook 978-0-87335-411-0

Library of Congress Cataloging-in-Publication Data

Dunbar, W. Scott, 1949- author.

How mining works / by W. Scott Dunbar.

pages cm

Includes bibliographical references and index.

ISBN 978-0-87335-399-1 (print) -- ISBN 978-0-87335-411-0 (ebook)

1. Mines and mineral resources--Popular works. 2. Mining engineering--Popular works.
3. Mineral industries--Popular works. I. Society for Mining, Metallurgy, and Exploration (U.S.) II. Title.

TN147.D86 2015

622--dc23

2015025722

Contents

Preface	v
1 The Where, What, and How	1
The Structure of Planet Earth	1
Earth History	2
Definitions	3
Concentrations of Metals	13
Ore-Forming Processes	15
Mine Exploration	26
2 Mining Methods	37
Surface Mining	37
Underground Mining	43
Mining Operations and Equipment	53
3 Mineral Processing and Metal Refining	67
Comminution	67
Flotation	77
Smelting and Refining	84
Hydrometallurgy	89
Biohydrometallurgy	103
Physical Separation Methods	106
4 Nonmetallic Minerals	113
Coal	113
Diamonds	119
Aggregates	124
5 Mine Waste Management	129
Mine Waste Streams and Disposal	130
Mine Waste Treatment Methods	144

6 Mining, People, and the Environment	151
Human Resources	151
Safety	152
Health	156
Mining and Communities	158
Sustainable Mining?	160
7 Mining and Money	165
Mineral Products	166
Metal Prices	171
Resources and Reserves	175
8 A Future of Mining	185
Drivers of Innovation in Mining	185
Paths for Innovation	188
Biotechnology to the Rescue?	191
Can the Industry “Grow Its Own”?	195
In Extremis	198
Appendix A: All the Chemistry You Need to Know	201
Atoms and Ions	201
Oxidation and Reduction	203
The Main Message	204
Kitchen Chemistry	205
Acid and Alkali Solutions	206
Index	207

Preface

Mining is interesting. It is a collection of processes that increase the very low concentrations of minerals and metals in the earth to levels that can be used in everyday life. In most cases, the increase in concentration is several orders of magnitude. The fact that it is physically, chemically, and economically feasible to do this is quite amazing. For some metals, the concentration process is like combing through a field of haystacks to find one needle every day for 10 years or more.

What is also interesting about mining is the different kinds of professionals required to make it happen: geologists, almost every kind of engineer or scientist, investment bankers, accountants, economists, health and safety specialists, community relations experts, and others. Furthermore, mining has economic effects at both global and local scales.

The intent of this book is to provide an understanding of the collection of processes, but to do so in a manner that makes the reader want to know more. The only requirement is an interest in science and technology. Very large and very small numbers are used to describe concepts. Some high school chemistry is used to describe processes, but it is not essential for understanding. Appendix A describes all the chemical concepts used.

The book consists of eight chapters. Chapter 1 provides an explanation of how mineral deposits are formed and how they are found. Chapter 2 describes mining methods, the systems and machines used to extract rock containing minerals of interest (called ore) from the earth. Chapter 3 describes a few of the methods used to process the ore and produce metals. Much of mining refers to the production of metals, but nonmetallic minerals are a huge part of the industry. Chapter 4 discusses the particular examples of coal, diamonds, and gravel (aggregates). In addition to minerals and metals, mining and processing ore produce large amounts of waste products that must be managed, often for an indefinite period. The science and technologies applied to this important part of mining are the topics of Chapter 5. Mining also involves people, the communities in which they live, and the government of the country in which the mine is located. As described in Chapter 6, the related issues are important, interesting, and sometimes challenging.

Chapter 7 describes the mechanisms for establishing prices of metals and minerals and discusses the legal definition of *ore*. Finally, Chapter 8 presents some ideas about mining in the future.

The majority of the images in the book were generously provided by many companies and individuals. Pictures in a book like this are worth far more than a thousand words, and the attributions under the figures do not begin to express my gratitude and appreciation. Many thanks are extended to those who helped illustrate the many topics. My colleagues Jocelyn Fraser, Mike Hitch, Bern Klein, Rick Lawrence, Allan Moss, and Dirk van Zyl helped with advice and ideas on content, but, of course, any errors are solely my responsibility.

I was encouraged to write this book by Jane Olivier, the books manager at SME, and I am so glad she asked. Diane Serafin edited the manuscript and kept me organized and her head cool despite delays and some software glitches.

The origins of this book lie with Steve Ralbovsky, a former partner at PricewaterhouseCoopers in Phoenix, Arizona, who in 1999 asked me to develop presentations that would explain mining to non-miners attending the PWC Annual School of Mines. For several years Steve twisted the dials and knobs to set the tone and level of the content. The presentations were mostly pictures, but over time I inserted many hidden slides with notes and explanations of the pictures. This was the starting point for this book. Thank you, Steve; it was fun.

In 2007, Simon Houlding of Edumine in Vancouver asked me to make a webcast from the slides, forcing me to learn to speak into a microphone and look into a camera at the same time, pretending that an audience was there. Simon then asked for an online course and quizzes. The information on the hidden slides helped, but good questions that don't frighten the learner are hard to compose. The staff at Edumine also encouraged me to keep the material up to date and to do a Spanish version of the webcast (No puedo. Si, se puede.) Challenges are good. Thank you Simon, Jennifer, Mariana, and Sandra.

Finally, thanks go to my wife Petra, who provided honest feedback, and to my sons and daughters for their comments, ideas, and inspiration.

The Where, What, and How

Have you ever wondered why mines are located where they are?

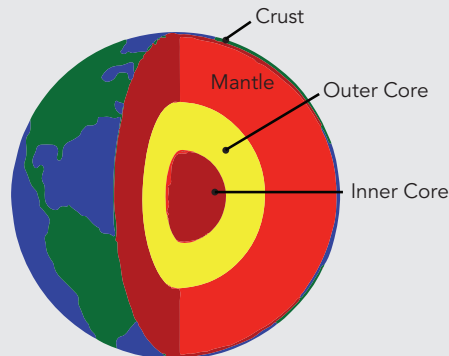
The ore deposits where mines are situated were formed millions of years ago in particular places by a number of different processes. Most of these processes continue to occur in the earth, but it can take millions of years for an ore deposit to form.

The material in this chapter will enable you to understand where and how ore deposits form and how geologists go about finding them. It will also define some common terms and concepts used in geology, mining, and mineral processing.

Let's start with what planet Earth looks like. It is the source of all the things we mine.

THE STRUCTURE OF PLANET EARTH

The earth is composed of three concentric shells (Figure 1.1). The *crust* is the outer shell, 30–50 km thick under the continents and 5–10 km under the oceans. It is underlain by the *mantle* that extends from the crust to the interface between the mantle and the earth's core at a depth of 2,900 km. The earth's core, which has a radius of about 3,400 km, consists of an outer liquid core and an inner solid core. The radius of the earth is about 6,371 km.



Courtesy of William Vann, EduPic.net.

FIGURE 1.1

Structure of the earth

The most interesting aspect of the geological processes involved in forming ore deposits is their scale, both in space and time. The formation of an ore deposit is essentially a concentration process that occurs within the crust and, in some cases, the upper mantle. However, these processes are fueled by heat generated deep within the earth's core and, in this sense, they are planetary in scale. The result is higher than average concentrations of minerals and metals at depths that are relatively shallow. The earth is a big planet. We have mined only as deep as 3–4 km, barely a pinprick.

EARTH HISTORY

The earth is very old—about 4.6 billion years old. Table 1.1 shows Earth's history from the time it formed until the present. There are names for particular eons, eras, and periods of Earth's history. The origins of these names is often interesting. For example, the Ordovician period was named after a Celtic tribe called the Ordovices in order to resolve a dispute between geologists who were assigning ages to rock formations in northern Wales as either Cambrian, an earlier period, or Silurian, a later period.

The nickel deposits near Sudbury, Ontario, are believed to have been formed about 2 billion years ago or 2,000 MYBP (million years before present). Oil deposits in western North America formed between 360 and 400 MYBP, coal deposits formed

TABLE 1.1

Earth's history

Eon	Era	Period	MYBP*	Major Events
Phanerozoic	Cenozoic	Quaternary	0–1.6	Mastodons and humanoids
		Tertiary	1.6–66	Dinosaur extinction 66 MYBP
	Mesozoic	Cretaceous	66–144	Ore deposits in western North America and South America
		Jurassic	144–208	Coal deposits in British Columbia and western United States
		Triassic	208–245	Dinosaurs appeared 230 MYBP
	Paleozoic	Permian	245–286	
		Pennsylvanian	286–320	Coal deposits in eastern United States
		Mississippian	320–360	
		Devonian	360–408	Oil deposits form in western North America
		Silurian	408–438	
Proterozoic	Ordovician	438–505	Trilobites appeared 500 MYBP	
	Cambrian	505–543		
Archean			543–2,500	Sudbury (Ontario) nickel deposits
			2,500–4,600	

*MYBP = million years before present.

between 150 and 200 MYBP, and several metallic ore deposits in North and South America were formed between 60 and 150 MYBP. Dinosaurs appeared about 230 MYBP and their extinction occurred about 66 MYBP, possibly due to the effects of a large meteor striking the earth. The evolution of humans is believed to have begun about 1.6 MYBP.

From Table 1.1 it is evident that geological processes are slow and span hundreds of millions of years. The processes of metal concentration are equally slow and might occur over a few hundred thousand to million years. An equally important concept is that the geological processes that occurred millions of years ago can also occur in the present. Hence the expression:

The present is the key to the past.

What this means is that the geological processes seen today likely occurred in the past. The climate might have been different, but the earth continued to do what it has always done. Consistency of geological processes over time is a useful concept in mine exploration.

DEFINITIONS

Keep thinking about big spatial scale and very long times as you read through these definitions of terms that will be used often in this book.

Chemical Elements

Chemical elements are a pure substance consisting of one type of atom. They are the building blocks of matter. Some examples are given here:

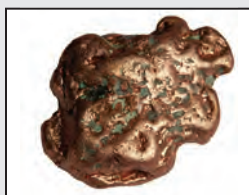
Al – aluminum	Mo – molybdenum
Ag – silver	O – oxygen
Au – gold	Pb – lead
Cu – copper	S – sulfur
Fe – iron	Si – silicon
H – hydrogen	Zn – zinc

Some of the symbols are simply the first letter of the name of the element. Others are derived from the Latin word for the element: **Argentum**, **Aurum**, **Cuprum**, **Ferrum**, **Plumbum**.

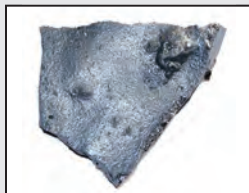
Figure 1.2 shows samples of particular elements. Native elements are those found in nature, but these are relatively rare and they are not pure. Elements of economic interest are often combined with other elements.

FIGURE 1.2

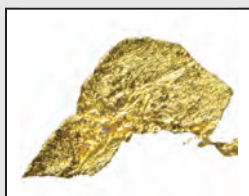
Samples of copper, silicon, and gold



Native copper nugget about 2.5 × 3.5 cm in size. Copper was the first element used by humans. It is combined with tin to form bronze and with zinc to form brass. Copper is the second best conductor of electricity, but it does corrode if exposed to moisture. (The best conductor is silver.)



Pure silicon. Silicon is one of the most abundant elements in the earth. It combines with oxygen to form quartz, a component of sand that is used to make glass. Since the mid-20th century silicon has been used in electronic devices.



Pure gold leaf about 1 cm long. Gold is very rare, which makes it valuable. It is also inert and malleable, which makes it useful for jewelry. Gold is the third best conductor of electricity behind silver and copper, but its inertness makes it useful in applications where corrosion would cause a problem.

Photos courtesy of Images-of-Elements.com 2014, CC BY 3.0.

Compounds

Elements combine to form *compounds*. A compound contains at least two *different* elements. Some examples are given in Table 1.2. The numerical subscripts in the chemical formulas denote the number of atoms in the compound. If there is no subscript, then only one atom is present.

TABLE 1.2

Examples of compounds

Compound	Chemical Formula
Salt: sodium (Na) and chlorine (Cl)	NaCl
Silver chloride: silver and chlorine	AgCl ₂
Vinegar (acetic acid): a bitter combination of carbon (C), oxygen, and hydrogen	CH ₃ CO ₂ H
Sulfuric acid: 2 hydrogen, 1 sulfur, and 4 oxygen atoms	H ₂ SO ₄
Copper sulfate: 1 copper, 1 sulfur, and 4 oxygen atoms	CuSO ₄

Minerals

The definition of a *mineral* is

A solid, naturally occurring, inorganic compound having a definite chemical composition (of elements) that may vary within limits.

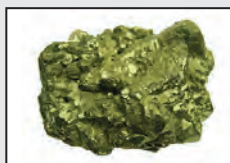
ARE YOU A BIT CONFUSED? WHAT IS A MOLECULE?

A molecule is formed when two or more atoms join together chemically. Compounds form when two or more *different* atoms join together. All compounds are molecules, but not all molecules are compounds. Molecular hydrogen (H_2), molecular oxygen (O_2), and molecular nitrogen (N_2) are not compounds because each is composed of a single element. Water (H_2O), carbon dioxide (CO_2), and methane (CH_4) are compounds because each is made from more than one element.

Some examples of minerals are shown in Figure 1.3.



Rose quartz, SiO_2 . The color, which may vary from pale pink to rose red, is due to trace amounts of metals such as iron, titanium, or aluminum. The color may be changed by irradiating the crystal with ionizing radiation. (Photo courtesy of Wikimedia Commons.)



Pyrite, FeS_2 , is an iron sulfide sometimes known as “fool’s gold” because it develops a sheen on its surface that looks like gold. The giveaway is the cubic crystals. Pyrite is the most common sulfide mineral. (Photo courtesy of Jonathan Zander 2007, CC BY-SA 3.0.)



Chalcopyrite, $CuFeS_2$. Except for the beak and eyes, this carving of an owl is made of chalcopyrite, a common copper sulfide found in most copper mines. The owl is about 6 cm high and is standing on quartz crystals. (Photo courtesy of Adrian Pingstone 2004, CC BY-SA 3.0.)

FIGURE 1.3

Hand-size samples of minerals

The following list describes other minerals of interest:

- Hematite (Fe_2O_3), an iron oxide, is the main source of iron. Hematite usually precipitates from standing water collecting in layers. It is typically dark colored, but weathering processes can cause it to become hydrated to form an iron hydroxide, essentially rust, that is responsible for the red color of many soils.
- Sphalerite (ZnS), which is zinc sulfide, and galena (PbS), which is lead sulfide, usually occur together in lead-zinc or lead-zinc-silver deposits.
- Pyrrhotite ($Fe_{1-x}S$, where $0 \leq x \leq 0.2$) is a magnetic iron sulfide with a strange chemical formula that seems to suggest partial atoms. However, this is merely

a convenient way to show a variable amount of iron. The end member of the series troilite FeS ($x = 0$) is nonmagnetic.

- The feldspar minerals— KAlSi_3O_8 , $\text{NaAlSi}_3\text{O}_8$, $\text{CaAl}_2\text{Si}_2\text{O}_8$ —are silicates that comprise 60% of the earth's crust, a feature that distinguishes the crust from the mantle, which has fewer silicate minerals.

MORE ABOUT MINERALS

The definition of *minerals* earlier in this chapter excludes substances formed by biogeochemical processes. However, there is a close link between the metabolic activities of microorganisms and mineral formation. In fact, microorganisms are capable of forming minerals and particular crystal structures that cannot be formed inorganically. Based on this, Skinner (2005) made the following expanded definition of a mineral:

An element or compound, amorphous or crystalline, formed through biogeochemical processes

where the prefix *bio* reflects the role of living systems in mineral formation. Skinner views all solids as potential minerals.

Minerals have been traditionally classified according to their chemical and crystal structure. For example, there are the silicates and the sulfides, the cubic and tetragonal crystal shapes, and so forth. This is a static classification system. Robert Hazen and John Ferry (2010) have shown that minerals evolved in a series of three eras beginning with an initial era of planetary accretion more than 4,550 MYBP when there were only about 60 minerals; through a second era of crust and mantle reworking to 2,500 MYBP, after which there were 1,500 minerals; and then into the current era in which living systems catalyze many mineral-forming reactions, resulting in the almost 4,400 mineral species known today. It is a very dynamic system that is ongoing.

Rock

A *rock* is a solid assemblage of minerals. A soil is also an assemblage of minerals but it is not solid. Soils are produced by weathering of rock, a part of the rock cycle that will be discussed later. There are many types of rocks, which will also be discussed later in context.

Ore Deposit

An *ore deposit* is a solid, naturally occurring mineral concentration useable as mined or from which one or more valuable constituents may be economically recovered.

The implications are that *current technology* and *economic conditions* make economic recovery possible. However, time is an important consideration. Technology can

turn an uneconomic deposit into an economic one. However, it can take some time for technology to develop into a practical form. Also, it is long-term economic conditions that govern whether a mine goes into operation and stays in operation. Short-term economic disruptions, such as the crisis in 2008, do not have much effect on mining operations.

This is not a legal definition of *ore*. The legal definition involves the issue of having the technical and legal ability to extract something of value from it. That aspect, and particularly the issue of how an ore deposit is reported to shareholders of a publicly traded mining company, are discussed in Chapter 7.

Base Metal and Precious Metal

A *base metal* is a metal basic to industry and society such as iron, copper, lead, zinc, and aluminum. A *precious metal* is a rare, naturally occurring metallic element of high economic value such as gold and silver and the platinum group metals: palladium, rhodium, iridium, osmium, and ruthenium.

What Is Ore Grade?

Ore grade is the concentration of economic mineral or metal in an ore deposit. A fundamental unit used in defining grade is tonnage. The definition of *one ton* has changed over the years but can be summarized as follows:

- One US ton (1 ton) is 2,000 lb; also called a short ton.
- One UK or Imperial ton is 2,240 lb; also called a long ton—obsolete since about 1965 when the United Kingdom adopted the metric system.
- One metric ton (1 t) is 1,000 kg. The term *tonne* is still used in many countries.

Given that 1 kg is about 2.2 lb, 1,000 kg or 1 t is about 2,200 lb, or about 1.1 times the mass of 1 US ton. (It is close to the mass of the Imperial ton, but there's no need to be confused with an obsolete unit.)

The grade of a base metal deposit is expressed as a mass percentage. For example, a fairly rich copper deposit might have a grade of 0.4%. This means there are $0.004 \times 1,000 \text{ kg} = 4 \text{ kg}$ of copper in each metric ton of ore. Alternatively there are $0.004 \times 2,000 = 8 \text{ lb}$ of copper in each US ton of ore. This all works out as shown in the following equation—watch the units (remembering that “t” is the metric ton and “ton” refers to the US ton):

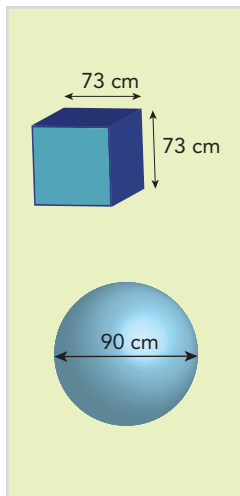
$$4\text{kg/t} = \frac{4 \text{ kg} \times 2.2 \text{ lb/kg}}{\text{t}} = \frac{8.8 \text{ lb}}{1 \text{ t} \times 1.1 \text{ ton/t}} = 8 \text{ lb/ton}$$

TROY OUNCES

The origin of the word *troy* comes from the city of Troyes in France, an important trading city in the Middle Ages. A troy ounce is about 10% larger than the avoirdupois ounce used to measure the weight of things like the weight of the human body or food items. However, if you consider your body precious, start measuring its weight in troy ounces, convert those troy ounces to troy pounds, where 12 troy ounces equals one troy pound, and you can fool yourself into thinking that dieting is unnecessary.

The grade of a precious metal deposit is expressed in grams per metric ton or troy ounces per ton, where the common abbreviations are g/t and oz/ton, respectively. The ounces are troy ounces where 1 oz = 1.097 ounces avoirdupois = 31.1 g. For example, the gold grade at the Eskay Creek mine in British Columbia was about 0.96 oz/ton or 29.856 g/t, which is a very rich ore. A more typical gold grade is 1–4 g/t for open pit mines, 4–6 g/t for marginal underground mines, and 8–10 g/t for high-quality underground mines.

Because there are 1,000 kg in a metric ton and 1,000 g in a kilogram, there are 1 million grams in a metric ton. Thus, if gold grade is given in grams per metric ton, then it is in parts per million (e.g., 6 g/t is 6 ppm).



HOW BIG IS 1 METRIC TON OF ROCK?

One cubic meter (m^3) of solid rock weighs between 2.5 and 3 t. This is the density of rock. Assume the density is 2.6 metric tons per cubic meter or 2.6 t/m^3 . Invert this to get $1/2.6 = 0.385 \text{ m}^3/\text{t}$. This means that 1 t of rock occupies a volume of 0.385 m^3 . This volume could be any shape. If it's a cube, then one side of the cube is $0.385^{1/3} = 0.73 \text{ m}$ or 73 cm. Such a cube is shown to the left.

If the volume is a sphere, then because the volume of a sphere of radius r is given by $4\pi r^3/3$, the radius of the sphere can be computed as $(3 \times 0.385/4\pi)^{1/3} = 0.45 \text{ m}$ or 45 cm. Its diameter is 90 cm. Such a sphere is shown to the left.

You can extend a measuring tape to these dimensions to get an idea of how big these volumes are.

To convert a weight percentage to parts per million, multiply the percentage by 10,000, that is, $10,000 \text{ ppm} = 1\%$. Thus 0.4% is $0.4 \times 10,000 = 4,000 \text{ ppm}$. Conversion of base metal grades to parts per million is not commonly done, but it serves to show the large difference—three orders of magnitude—between typical gold grades and typical base metal grades.

Diamond mine grades are measured in carats per metric ton (carat/t). Since 1 carat = 0.2 g, a diamond grade of 4 carats/t = $4 \times 0.2 = 0.8$ g/t or 0.8 ppm.

Rocks and the Rock Cycle

There are many physical and chemical cycles that occur in the earth (e.g., hydro-logic cycle, carbon cycle). A rock cycle is illustrated in Figure 1.4.

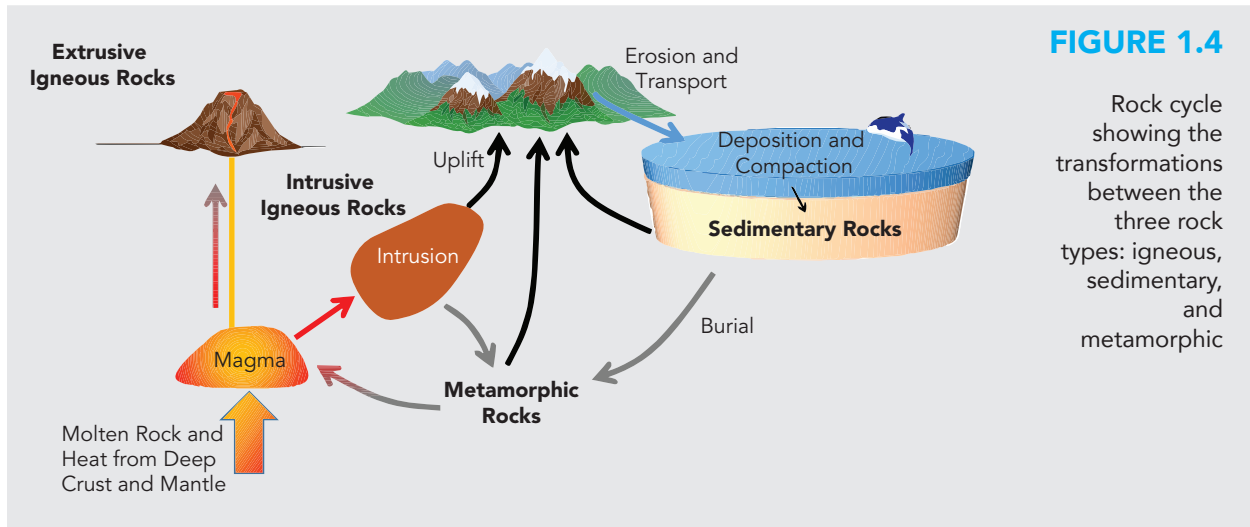


FIGURE 1.4

Rock cycle showing the transformations between the three rock types: igneous, sedimentary, and metamorphic

Three types of rock are shown in the rock cycle: igneous, sedimentary, and metamorphic. *Igneous rocks* are formed when rock melts at temperatures between 600 and 1,200°C. The melt is called *magma* if it stays within the earth; if it exits the earth, as in a volcano eruption, it is called *lava*. Melted rock is light and will flow toward the surface where, if it solidifies within the earth, it is called an *intrusive igneous rock* (or simply an *intrusion*). If it exits the earth, it solidifies very quickly and is called an *extrusive igneous rock*.

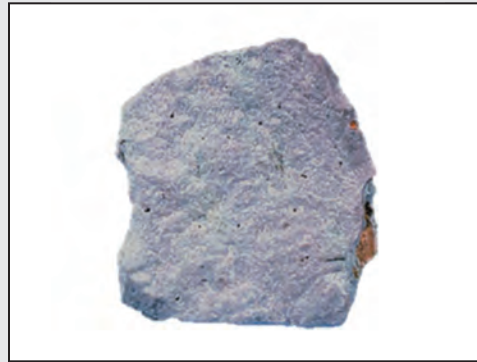
Figure 1.5 shows some examples of igneous rocks. The magma that formed the granite cooled slowly, allowing the large crystals to form. Figure 1.5 also shows rhyolite, which formed by fast cooling of lava from a volcano, resulting in small crystals. Both rocks have about the same chemical composition. Figure 1.5 includes a sample of basalt, a volcanic rock that contains less than 50% silica and a lot of heavy dark minerals that contain iron and magnesium. While granite is the most common rock in the continental crust, basalt is the most common rock in the oceanic crust. Figure 1.5 also shows basaltic lava that, because of its low silica content, flows very easily. The Columbia plateau in southern Washington state and adjacent Oregon and Idaho is a large (163,000 km²) “flood basalt” formed during volcanic

FIGURE 1.5

Examples of igneous rocks



Granite

Rhyolite (likely hand-size specimen)
(Courtesy of US Geological Survey.)

Basalt (Courtesy of US Geological Survey.)



Basaltic lava (Courtesy of US Geological Survey.)

activity 15 to 17 million years ago. Hawaii was formed and continues to be formed by basalt flows.

Sedimentary rocks consist of particles formed by weathering of rock transported by flowing water and deposited either on the earth's surface or at the bottom of a body of water. Unless disrupted by some other process, the deposition results in layers of sediments called *strata*. As more sediments are deposited, the layers become compacted and hard. An example of a sedimentary rock formation is shown in Figure 1.6. The sediments forming these rocks were deposited over several million years during the Triassic period, about 200–245 MYBP.

The appearance of the sediments reveals a lot about the environment in which the sediments were deposited. The lower red-colored rocks in Figure 1.6 are composed of silt (siltstones) and were deposited in a shallow, calm marine environment. The red color is due to iron minerals (hematite) formed by exposure to the atmosphere, essentially a rusting process. The upper gray-colored rocks are limestone composed



Courtesy of Mark A. Wilson via Wikipedia.

FIGURE 1.6

Part of the Virgin Formation, a sequence of sedimentary rocks in southwestern Utah formed during the Triassic period, about 200–245 MYBP

of the skeletal remains of marine organisms. These sediments were deposited in deeper water where the iron present was not exposed to the atmosphere.

Over time, igneous and sedimentary rocks may become buried and subjected to high pressures and temperatures, which cause physical and chemical transformations but do not melt the rock. The result is a *metamorphic rock*. The variety of sources combined with the large possible range of temperatures and pressures gives rise to a wide variety of chemical and crystal textures of metamorphic rocks. Two examples are shown in Figure 1.7.



Quartzite—originally sandstone (Photo courtesy of Siim Sepp 2005, CC BY-SA 3.0.)



Gneiss—originally igneous or sedimentary. The bands are caused by high shear forces that cause the rock to behave like plastic. (Photo courtesy of Siim Sepp 2005, CC BY-SA 3.0.)

FIGURE 1.7

Two examples of metamorphic rocks

Metamorphic rocks comprise about 85% of the earth's crust, and it is estimated that about 10% of the earth's crust is composed of sedimentary rocks. These sedimentary rocks must exist at or near the surface of the earth because at depth they would be exposed to high pressure and temperatures and become metamorphosed or melt to become igneous rocks.

As may be seen in Figure 1.4, the rock cycle actually consists of a number of sub-cycles. Rocks are continually transforming from one type to another over millions of years. Although the source of heat is deep within the earth (due to heat generated by radioactive decay), most of the processes shown in the rock cycle occur at depths less than 20 km.

Faults, Fractures, and Folds

The earth's crust is subjected to very large forces that lead to ruptures called *faults* and numerous *fractures*. There are several well-known faults, such as the San Andreas fault in California where two large plates of the earth's crust slide past one another and cause earthquakes. The Rocky Mountains in Canada were formed by thrusting of sedimentary rocks from the west to the east. Mount Rundle, one mountain in the Canadian Rockies, is shown in Figure 1.8. The uplifted layers can be seen on the left, the east side. The layers have been thrust from west to east along a subhorizontal fault over existing rocks, a process that has resulted in older sedimentary rocks being placed on top of younger ones, the reverse of what happens when sedimentary rocks are formed.

FIGURE 1.8

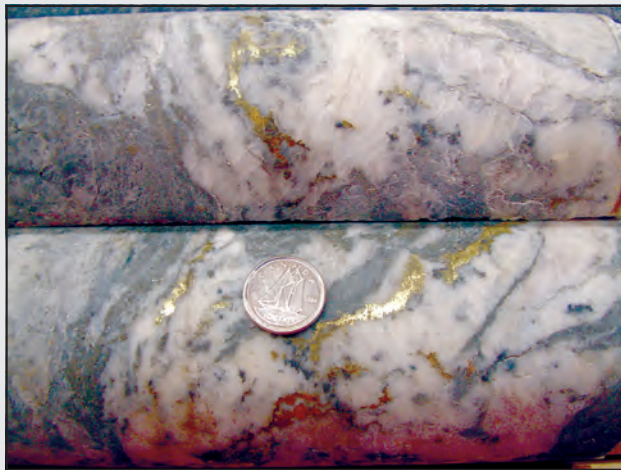
View looking south of Mount Rundle (Banff, Alberta), formed by a series of thrust faults



Adapted from Antony Stanley 2006, CC BY-SA 2.0.

Fractures (“mini-faults”) also result from the large forces imposed on rocks. Fluids with mineral solutions percolate through these fractures and deposit minerals or metals in the fractures, forming veins. An example of small veins containing visible gold is shown in Figure 1.9. (Visible gold is actually a rare occurrence.)

Stresses combined with temperatures and pore water pressure can soften rocks so that they bend easily or actually flow. Layers of sedimentary rocks that were originally horizontal can become *folded*, as shown in Figure 1.10. Folds are easily seen



Courtesy of Pretium Resources.

FIGURE 1.9

Gold veins at Brucejack property, northwestern British Columbia



Courtesy of Alberta Geological Survey.

FIGURE 1.10

Folded sedimentary rocks at Mount Head in the Canadian Rockies

in sedimentary rocks, but they also occur in metamorphic rocks and also form in igneous rocks subjected to stresses in the later stages of magma cooling.

CONCENTRATIONS OF METALS

Geochemical models can be used to estimate the average concentrations of metals in the crust of the earth. The details of these models are complex. However, the main observation is that the typical grade of an ore deposit is larger, sometimes much larger, than the average concentration of the metal in the earth's crust.

For example,

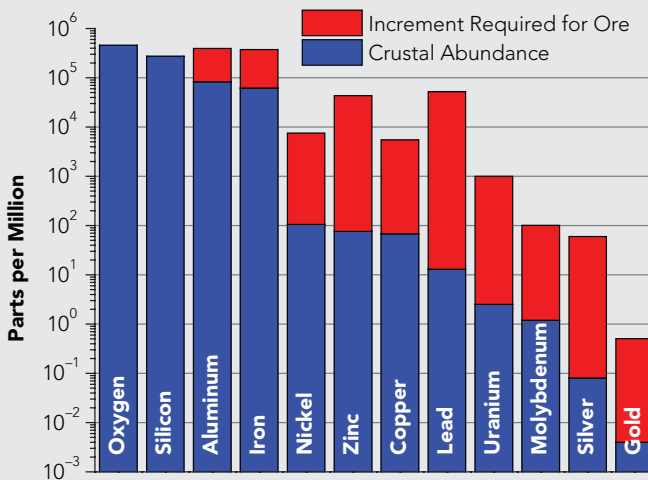
The grade of a typical gold deposit is of the order of thousands of times greater than the average concentration of gold in the earth's crust.

In contrast, the grade of an iron deposit is only 10 times greater than the average concentration of iron in the earth's crust.

These relationships are illustrated for different elements in Figure 1.11. Note the logarithmic scale where one major division denotes an order-of-magnitude difference (e.g., from $10^1 = 10$ to $10^2 = 100$). This scale is used because of the large range of concentrations.

FIGURE 1.11

Comparison of average metal grade (abundance) in the crust with average ore grade



The abundances of oxygen and silicon are shown for comparison:

Silicon ~300,000 ppm, Oxygen ~500,000 ppm

These two elements occur as components of minerals; that is, they are bound chemically to other elements.

The concentrations of metals in ore deposits depend on the current price of the metal because ore is what can be mined under current economic conditions. Thus, as the price goes up, the concentration of metal required to make rock an ore deposit goes down. However, relative to the concentrations in the earth's crust, the changes are not significant.

Index

Note: *f.* indicates figure; *t.* indicates table

A

acid, in rivers, 142
acid rock drainage (ARD), 141–143, 143*f.*
acid solutions, 206
acquisition, of mining companies, 26
activated carbon, 98–102
aerobic processes, of waste treatment, 149
aggregates
 business of, 125–126
 origin and occurrence, 124
 processing, 125, 125*f.*
 uses for, 124, 124*t.*
alkali solutions, 206
anaerobic processes, of waste treatment, 149
anomalies, 29, 30*f.*
aquifers, 62
ash, 114
asthenosphere, 18
at-mine return (AMR), 168
atomic weight, 81
atoms, 201–203, 201*f.*
aurocyanide
 and carbon adsorption, 98–102
 as by-product of gold ore processing,
 96–98
Australian Academy of Science, 187
automation, of the mining cycle, 189, 190*f.*

B

bacteria
 Delfia acidovorans, 193
 methanogens, 194
 oxidation by, 103–106
 Ralstonia metallidurans, 192, 192*f.*, 193*f.*

 sulfate-reducing bacteria (SRB), 147–148,
 147*f.*, 193
basalt, 9, 10*f.*
basaltic lava, 9–10, 10*f.*
base metals
 defined, 7
 separation of from precious metals, 83
benches, pit slope, 39, 39*f.*, 40*f.*
biohydrometallurgy, 103–106
biomining, 105, 106*f.*
“bio-ore,” 194
biotechnology, 191–196, 197*f.*
black smokers, 21
blasting, 55–56, 55*f.*, 56*f.*, 65*f.*
blister copper, 85
block caving, 50–52, 51*f.*, 52*t.*
block models, 34–35, 35*f.*, 180*f.*
Blusson, Stewart, on finding diamonds in the
 Canadian Arctic, 121
British Columbia, Canada, copper-gold
 occurrences and mines map, 27*f.*
by-products, 169–170

C

Canadian Securities Administrators, 181
capital productivity, 188–190
carbon adsorption
 vs. absorption, 100
 carbon in pulp (CIP) process, 99,
 100–101, 101*f.*
 carbon-in-column method, 99–100
 carbon-in-leach (CIL) process, 99, 100
 processes, 98–99, 99*f.*
cave front, 51

- centrifugal concentrators, 108, 108*f*.
 chalcopyrite, 5*f*.
 chemical elements
 defined, 2
 examples of, 4*f*.
 Chicago Mercantile Exchange (CME) Group, 174–175
 classification (separation process), 74
 clays, 113
 cleaner cells, 79
 coal
 formation of, 113–115, 114*f*.
 industry characteristics, 115
 processing, 115–119, 116*f*.
 rank, 113, 115*f*.
 as rock vs. mineral, 116
 run-of-mine (ROM), 116–117
 washing, 116
Code for Reporting of Mineral Resources and Ore Reserves (JORC), 183
 collectors (flotation chemical), 77, 78, 79
 comminution
 crushing, 69–71, 122–123
 cyclones (hydrocyclones), 74–75, 75*f*.
 defined, 67
 grinding, 71–74
 grinding circuits, 75–76, 76*f*.
 physics of, 72
 commodities, 165, 165*f*.
 commodity exchanges, 171, 174–175
 communities
 health in, 156–158
 and mining, 158–160
 compounds
 defined, 4
 examples of, 4*t*.
 concentrates, 78, 78*f*.
 See also copper concentrates; sulfide concentrates
 concentration
 calculating concentration factor (CF), 80–81, 80*f*.
 relationship to ore grade, 13–15, 14*f*.
 concentrators, 68*f*., 108–109, 108*f*., 109*f*.
 contact metamorphism, 24
 continental boundaries, 22, 22*f*.
 Cooney, James, on social license to operate (SLO), 158
 copper
 example of, 4*f*.
 plating experiments, 205–206, 205*f*.
 prices, 175, 175*f*.
 copper concentrates
 bio-heap leaching, 106
 refining, 86–88, 88*f*.
 smelting, 85–86, 86*f*.
 solvent extraction and electrowinning (SX/EW), 91–94, 92*f*., 93*f*., 95*f*.
 co-products, 169–170
 core, earth, 1
 corporate social responsibility (CSR), 156, 159
 costs, reduction of, 189
 cratons, 119
 crosscuts, 50
 crushers
 cone, 70–71, 70*f*.
 gyratory, 69–70, 69*f*.
 high-pressure grinding rolls (HPGR), 122–123, 122*f*.
 jaw, 70, 70*f*.
 crust, earth, 1, 18–22
 cut-and-fill mining, 46, 47*f*.
 cutoff grade, 179–180, 180*f*.
 cyclones (hydrocyclones), 74–75, 75*f*.
- D**
- dams, tailings
 centerline construction, 134–135, 134*f*.
 downstream construction, 134, 134*f*.
 history of, 136
 upstream construction, 133–134, 133*f*.
Delftia acidovorans, 193
 delivery contracts, 167
 dense media separation (DMS), 118, 118*f*.
 developing countries, and mining, 157–160
 dewatering, 61–62, 63*f*.

- diamonds
 age-dating, 120
 Canadian Arctic deposits, 120–121
 formation of, 119–120, 120*f.*
 processing, 122–124
- dilution, 62, 64, 64*f.*, 65*f.*
- dirigibles, 65, 66*f.*
- disclosure, 181–183
- disseminated deposits, 17
- Dobbs, Richard, on resource curse, 160
- dose, defined, 157
- drilling
 cost considerations, 33–34
 diamond core, 31, 32*f.*, 33
 equipment, 32*f.*, 54–55, 54*f.*, 55*f.*
 goal of, 34
 reverse circulation, 33, 33*f.*
- dry stack, tailings, 137, 138*f.*
- Dupont equation, 188
- E**
- earth
 history of, 2–3, 2*t.*
 plate tectonics, 18–22
 structure of, 1–2, 1*f.*
- economic analysis, 182–183, 182*f.*
- economic conditions, effect of on mining
 operations, 6–7
- electrolysis, 204
- electrons, 201–203, 201*f.*, 202*f.*
- electrorefining, as different from electrowinning, 92–93
- electrowinning, 89, 94, 101–102, 101*f.*, 166–167
 See also solvent extraction and electrowinning (SX/EW)
- elements, 2, 4*f.*
- Elsner reaction, 90
- emergence, 196
- employees
 health of, 156
 and safety behavior, 154–155
- engineering, and pit slope stability, 39–40
- engineers, 152
- environmental engineers, 129
- epithermal deposits, 17
- Equator Principles, 158
- equipment
 autonomous haul trucks, 189, 190*f.*
 centrifugal concentrators, 108, 108*f.*
 concentrators, 68*f.*
 crushers, 69–71, 69*f.*, 70*f.*
 cyclones (hydrocyclones), 74–75, 75*f.*
 dense media separation (DMS) machines, 118, 118*f.*
 drills, 32*f.*, 54–55, 54*f.*, 55*f.*
 filter press, 137, 138*f.*
 high-pressure grinding rolls (HPGR), 122–123, 122*f.*
 high-tensile steel mesh, 60, 60*f.*
 load-haul-dump (LHD) machines, 47, 58–59, 58*f.*, 59*f.*, 60, 65–66
 magnetic separators, 109–110, 110*f.*
 oxygen flash furnace, 85*f.*
 rock bolts, 61, 61*f.*
 rotary breakers, 117, 117*f.*
 screens, 117, 118*f.*
 shaking tables, 106–107, 107*f.*
 shearers, 50, 50*f.*
 sluice boxes, 107, 107*f.*
 spiral concentrators, 108–109, 109*f.*
 X-ray separators, 123–124, 123*f.*
- evaporite deposits, 24
- experiments, copper plating, 205–206, 205*f.*
- exploration
 drilling, 31, 32*f.*, 33–35, 33*f.*, 34*f.*
 expenditures vs. discoveries, 186–187, 186*f.*
 geochemical surveys, 31, 31*f.*
 geological mapping, 28–29
 geophysical surveys, 29–30, 29*f.*, 30*f.*
 and reserve ratios, 179
 role of in mining, 26–28
 satellite imaging, 28, 28*f.*
 See also reserves; resources
- external dilution, 64, 64*f.*
- extrusive igneous rocks, 9

F

faults, 12, 12*f.*
 feasibility studies, 181–182
 feldspars, 6, 17, 113
 Ferry, John, and mineral classification, 6
 filter cakes, tailings, 137
 filters, tailings, 131–132
 Fipke, Charles, on finding diamonds in the Canadian Arctic, 121
Fire into Ice: Charles Fipke and the Great Diamond Hunt (Frolick), 121
 flocculants, 110
 flotation
 cells, 79, 80*f.*
 circuits, 78–81, 79*f.*
 of coal, 118–119
 and grade recovery, 84
 mineral separation in, 81–83
 process, 77–78, 77*f.*
 folds, 12–13, 13*f.*
 fractures, 12
 freeboard, 132*f.*, 133
 Frolick, Vernon (*Fire into Ice*), 121
 froth flotation. *See* flotation
 frother, 77

G

gangue, 67, 69*f.*
 geochemical surveys, 30, 31*f.*
 geological mapping, 28–29
 geological processes, slowness of, 2
 geophysical surveys, 29–30, 29*f.*, 30*f.*
 geotechnical engineers, 129
 glacial till, 121, 121*f.*
 gneiss, 11*f.*
 gold
 alternatives to cyanide leaching, 102–103
 aurocyanide and carbon adsorption, 98–102
 and bacterial growth, 192
 biooxidation, 105
 carbon stripping and electrowinning, 101–102, 101*f.*, 102*f.*
 cyanide leaching, 96–97
 example of, 4*f.*

Merrill-Crowe process, 97–98, 97*f.*
 prices, 173–174, 173*f.*
 smelting, 102, 103*f.*
 and termite mounds, 193

gossan deposit, 26
 Gowan, Mike, on co-disposal, 146
 grade. *See* ore grade
 granite, 9, 10*f.*
 gravel pits, 126
 greenhouse gas (GHG) emissions, 161, 161*f.*
 grinding
 autogenous (AG), 71–73
 ball mill, 73–74, 74*f.*
 circuits, 75–76, 76*f.*
 semiautogenous (SAG), 71–73, 73*f.*

H

hazard, defined, 153
 Hazen, Robert, and mineral classification, 6
 health
 community, 156–158
 occupational, 156
 personal, 156
 See also safety
 Horn, Robert, on exploration challenges, 35
 human resources, 151–152
 hydraulic fill, 46
 hydrometallurgy
 defined, 89–90
 leaching, 90–91
 hydrothermal metamorphism, 24
 hydrothermal systems, 17
 hydrothermal vents, 20*f.*, 21
 hyperaccumulators, 194–195

I

igneous rocks
 defined, 9–10
 examples of, 10*f.*
 igneous-hydrothermal ore deposits, 16–17, 16*f.*
 indicator minerals, 121
 industrial minerals, 113
Industry Guide 7 (U.S. Securities & Exchange Commission), 183

inertinite, 115
 insect swarms, as model for biotechnology, 196
 intergenerational equity, 161
 internal dilution, 64, 64*f.*
 internal erosion, 132
 intrusive igneous rocks, 9
 ions, 201–203, 202*f.*, 203*f.*
 “iron hat” deposits, 26
 island arcs, 18*f.*, 19, 22, 22*f.*

J

Joint Ore Reserves Committee of the Australasian Institute of Mining and Metallurgy (JORC), 176, 183
 joint products, 169–170
 JORC diagram, 176

K

Kessler, Stephen, on deposit discovery rates, 187
 “Kilobots,” 196, 197*f.*
 kimberlite pipes, 119–120
 See also diamonds

L

laterites, 26
 lava, 9
 leachate, 91
 leaching
 alternatives to cyanide, 102–103
 bio-heap, 106
 biohydrometallurgy, 103–106
 carbon adsorption processes, 98–102
 cyanide, 96–103
 Merrill-Crowe process, 97–98, 97*f.*
 in pads, 90–91, 91*f.*
 pressure, 94–96
 reactions, 90
 in-situ, 90–91
 solvent extraction and electrowinning (SX/EW), 91–94
 lifts, 90
 liptinite, 115
 lithosphere, 18

lixiviant, 91
 London Bullion Market Association (LBMA), 172–173
 London Metal Exchange (LME), 174–175
 London Platinum and Palladium Market (LPPM), 172–173
 longhole stoping, 48
 longwall mining, 49–50, 50*f.*

M

macerals, 114
 magma
 defined, 9
 and ore deposit formation, 16–17, 16*f.*
 magnetic separators, 109–110, 110*f.*
 management, 152
 mantle, earth, 1, 119
 massive sulfide deposits
 formation of, 17
 volcanic (VMS), 21, 21*t.*
 matte, 85
 metal equivalents, 170–171
 metal streaming, 183
 metals
 calculating deposit grade, 7–9
 concentration of, 13–15
 defined, 7
 and microorganisms, 191–194
 noble, 204
 and plants, 194–195, 195*f.*
 prices, 171–175
 refining, 86–89
 separation of, 83
 solubility of, 204
 metamorphic rocks
 defined, 11
 examples of, 11*f.*
 metamorphic deposits, 24, 25*f.*
 methanogens, 194
 microorganisms, 191–194
 mid-ocean ridges, 18*f.*, 19–21, 20*f.*
 mine planning, use of block models in, 34–35, 35*f.*, 180*f.*
 mine waste
 acid rock drainage (ARD), 141–143
 calculating how many tons, 141

- co-disposal, 146–147, 146*f*.
- health effects of, 157
- management of, 129
- passive treatment systems, 148–149
- pit disposal, 145
- reclamation, 144–145
- sequestration, 145–146
- streams of, 130
- tailings, 130–139
- treatment methods, 144–149
- waste rock, 139–141
- wastewater, 141, 147–149
- mineral products
 - by-products, 169–170
 - co-products, 169–170
 - examples of, 165*f*.
 - and metal equivalents, 170–171
 - product streams, 166–167
 - and refinery contracts, 167–168, 168*f*.
 - and smelter contracts, 166, 167–168, 167*f*.
 - supply system, 166*f*.
- minerals
 - calculating deposit grade, 7–9
 - classification of, 6
 - defined, 4
 - deposit discovery rates, 186–187
 - descriptions of, 5–6
 - examples of, 5*f*.
 - indicator, 121
 - industrial, 113
 - separation of by flotation, 81–83
 - separation of by physical methods, 106–111
 - Skinner’s expanded definition, 6, 116
 - See also* mineral products
- mining cycle
 - blasting, 55–56
 - drilling, 54–55
 - load-haul-dump (LHD), 58–59, 65–66
 - stages of, 53–54, 53*f*.
 - support installation, 59–61
 - ventilation and refrigeration, 56–57
- mining industry
 - asset reduction in, 190
 - and biotechnology, 191–196
 - cost reduction in, 189
 - deposit discovery rates, 186–187
 - future of, 197*f*., 198
 - innovation in, 185
 - paths for innovation in, 188–190
 - and sustainability, 160–161, 186
 - Minto Deposit, resource classification
 - example, 177, 178*f*.
 - “modifying factors,” 176, 176*f*.
 - molecules, defined, 5
 - molybdenite, 82
 - muck, 48
- N**
 - National Instrument 43-101 (NI 43-101), 181, 183
 - native elements, 2
 - net smelter return (NSR), 168
 - noble metals, 204
 - nonmetallic minerals, 113
 - North America, subduction zones in, 23*f*.
- O**
 - occupational health, 156
 - open pit mining
 - pit slopes, 38–40, 38*f*., 39*f*., 40*f*., 41
 - pushbacks, 40–41, 40*f*., 42*f*.
 - strip ratios, 42–43, 42*t*.
 - typical configuration, 37–38, 37*f*., 38*f*.
 - operating productivity, 188–190
 - operations
 - blasting, 55–56
 - dewatering, 61–62
 - drilling, 54–55
 - grade control, 62, 64
 - load-haul-dump (LHD), 58–59, 65–66
 - support installation, 59–61, 63
 - ventilation and refrigeration, 56–57
 - ore, legal definition, 7, 175
 - ore deposits
 - correlation with volcanic activity, 15, 15*f*., 16*f*.
 - defined, 6–7
 - formation of, 2, 15, 19
 - igneous-hydrothermal, 16–17, 16*f*.
 - massive sulfide, 17

- metamorphic, 24, 25*f*.
 - oxide, 25–26, 25*f*.
 - sedimentary, 23–24
 - See also* concentration; ore grade
 - ore grade
 - calculating, 7–9
 - control, 62, 64
 - cutoff grade, 179–180, 180*f*.
 - defined, 7
 - flotation recovery and, 84
 - relationship to concentration, 13–15, 14*f*.
 - ore-body models, 34–35, 34*f*.
 - overflow, 75
 - oxidation, 25–26, 25*f*, 203–204, 203*t*.
 - by bacteria, 103–106
 - oxygen flash furnace, 85*f*.
- P**
- panel caving, 52
 - panels, 49, 52
 - paradox of plenty, 159–160
 - partial melt, 17
 - paste, tailings, 137, 137*f*.
 - paste backfill, 46
 - percentage paid, 168
 - pH scale, 206, 206*t*.
 - phytomining, 194–195, 195*f*.
 - phytoremediation, 194–195, 195*f*.
 - pillars, 48, 49, 49*f*.
 - pit slopes, 38–40, 38*f*, 39*f*, 40*f*, 41
 - placer deposits, 23, 24*f*.
 - plants, metals in, 194–195
 - plate tectonics, 19
 - plates
 - boundary types, 18*f*, 19–22
 - movement of, 18–19
 - precious metals
 - defined, 7
 - separation of from base metals, 83
 - preconcentration, 189–190
 - prefeasibility studies, 181
 - pregnant leach solution, 91
 - prices/pricing
 - commodity exchange, 171, 174–175
 - copper, 175, 175*f*.
 - gold, 173–174, 173*f*.
 - independent, 171, 172–174
 - negotiated, 171
 - producer, 171
 - processing
 - aggregates, 125
 - coal, 115–119
 - comminution, 67–76
 - diamond ore, 122–124
 - flotation, 77–84
 - gold ore, 96–103
 - guiding principle, 76, 79, 102
 - production level, 50
 - pushbacks, 40–41, 42*f*.
 - pyrite, 5*f*, 82, 83*f*.
- Q**
- qualified person (QP), 181
 - quarries, 126
 - quartz, rose, 5*f*.
 - quartzite, 11*f*.
- R**
- Ralstonia metallidurans*, 192, 192*f*, 193*f*.
 - reclamation, 144–145, 144*f*.
 - reduction, 203
 - refinery contracts, 167, 168–169, 168*f*
 - refining
 - of copper concentrates, 86–88, 88*f*.
 - by electrolysis, 204
 - of lead concentrates, 88
 - of lead-zinc concentrates, 89
 - of nickel sulfide concentrates, 89
 - of zinc concentrates, 88–89
 - refrigeration, 57
 - reporting standards, 181–183
 - reserve ratios, 178–179, 179*t*.
 - reserves
 - classification of, 176–177
 - defined, 175–176
 - reporting standards, 181–183
 - See also* exploration
 - residence time, 76, 80
 - resource curse, 159–160

- resources
 classification of, 176–177
 defined, 175
 in difficult places, 188, 188*f.*
 Minto Deposit classification example, 177, 178*f.*
 reporting standards, 181–183
See also exploration
- rhyolite, 9, 10*f.*
- Richards, J. P., on deposit discovery rates, 187
- rift zones, 18*f.*, 19
- risk, 153
- risk management, 153–154, 153*f.*
- rock bolts, 61, 61*f.*
- rock cycle, 9–12, 9*f.*
- rock(s), defined, 6
- room-and-pillar mining, 49, 49*f.*
- rose quartz, 5*f.*
- rougher cells, 79
- S**
- safety, 152–155
See also health
- safety culture, 154–155
- SAMREC Code, 183
- sand and gravel. *See* aggregates
- satellite imaging, 28, 28*f.*
- scavenger cells, 79
- sedimentary rocks
 defined, 10–11
 examples of, 11*f.*
 sedimentary ore deposits, 23–24
- sequestration, of acid-generating waste, 145–146, 146*f.*
- shaking tables, 106–107, 107*f.*
- shared value opportunities (SVO), 159
- shields, 49
- shotcrete, 61, 62*f.*
- shrinkage stoping, 48
- silicon, 4*f.*
- Skinner, H.C.W., expanded definition of minerals by, 6, 116
- slag, 85, 86
- sluice boxes, 107, 107*f.*
- smelter contracts, 166, 167–168, 167*f.*
- smelting
 chemical reactions in copper smelting, 87
 of copper concentrates, 85–86, 86*f.*
 gold, 102, 103*f.*
 of lead concentrates, 88
 of lead-zinc concentrates, 89
 of nickel sulfide concentrates, 89
 of zinc concentrates, 88–89
- soap, 79
- social license to operate (SLO), 158–159
- soil(s), defined, 6
- solvent extraction and electrowinning (SX/EW), 91–94, 92*f.*, 93*f.*, 95*f.*
- spalling, 60
- spiral concentrators, 108–109, 109*f.*
- split-off point, 169
- stockpiles, 71, 71*f.*
- stoping, 48, 48*f.*
- strata, 10
- Stratum International, mining professional survey, 152
- strip ratios, 42–43, 42*t.*
- subduction zones, 18*f.*, 22, 22*f.*, 23*f.*
- sulfate-reducing bacteria (SRB), 147–148, 147*f.*, 193
- sulfide concentrates
 biohydrometallurgy, 103–106, 105*f.*
 mineral recovery from slurry, 84, 84*f.*
 pressure leaching, 94–96, 95*f.*
 smelting, 84–86
 use of flotation to separate, 77–78
- sulfuric acid, 85–86
- surface mining. *See* open pit mining
- sustainable development, 160–161
- sustainable mining, 160–161, 186
- SX/EW. *See* solvent extraction and electrowinning (SX/EW)
- T**
- tailings
 dams, 131, 133–135, 133*f.*, 134*f.*, 136
 defined, 38, 129, 130
 example of, 129*f.*
 forms of, 131, 131*t.*
 impoundment, 131, 132*f.*

impoundment water balance, 135, 135*f.*
pit disposal, 145, 145*f.*
pond, 133
thickened, paste, and filtered disposal,
135, 137, 137*f.*, 138*f.*, 139
wet disposal, 131–133, 132*f.*
technical reports, 181–183
termites, and gold, 193
thickeners and clarifiers, 110–111, 110*f.*,
111*f.*
timber supports, 63
ton/tonne
defined, 7
size of one metric ton, 8
toxicity, 157
treatment and refining charges (TC/RC), 168
troy ounces, 8

U

undercut, 50
underflow, 75
underground mining
block caving, 50–52, 51*f.*, 52*t.*
comparison of methods, 52–53, 53*t.*
cut-and-fill, 46, 47*f.*
and exploration, 44–45
longwall, 49–50, 50*f.*
narrow vein mining, 47, 47*f.*
resources, 52
room-and-pillar, 49, 49*f.*
shaft construction, 45–46, 46*f.*
stopping, 48, 48*f.*

support installation, 59–61, 63
terminology, 44*t.*, 45*f.*
typical configuration, 43–44, 43*f.*

V

VALMIN Code, 183
valuation, of by-products and co-products,
169–170, 170*f.*
veins, 13*f.*
ventilation, 56–57, 57*f.*
vertical crater retreat (VCR), 48
vitrinite, 114–115, 115*f.*
volcanic massive sulfide (VMS) deposits, 21,
21*t.*
volcanos
map of active, 15*f.*
and ore deposit formation, 15–17, 16*f.*

W

waste rock/waste dump, 37, 139,
140*f.*, 141
pit disposal, 145, 145*f.*
See also strip ratios
wastewater, 141, 147–149
wetlands, 148–149, 148*f.*
workforce, 151–152

X

X-ray fluorescence, 123–124, 123*f.*

Z

zinc, 98

