INTRODUCTION TO MINERALOGY

WILLIAM D. NESSE

THIRD EDITION

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For Carl and Erik

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PREFACE TO THE THIRD EDITION

This book has been written to provide a text for teaching mineralogy to undergraduate students in geology and related fields. It is based on my experience teaching mineralogy and draws from the thoughtful suggestions and comments of my students and of numerous instructors from around the world. The challenge has been to provide a comprehensive survey of mineralogy that can meet the needs of students in a wide variety of curricula in a concise, well-organized, and clear manner.

The objectives in preparing the Third Edition have been to bring the text and references up-to-date and to improve the clarity and ease of use. The organization used in the first two editions has been retained. The three main sections are Crystallography and Crystal Chemistry (Part One), Mineral Properties, Study, and Identification (Part Two), and Mineral Descriptions (Part Three). Placing crystallography and crystal chemistry first provides the foundation required to understand the physical and optical properties of minerals and the various techniques of chemical and X-ray analysis. The introduction to physical properties and mineral identification in Chapter 1 has been retained so that students can begin laboratory study of minerals early in their course of study.

In addition to numerous revisions to improve the clarity of the text and figures, significant revisions in the Third Edition have been made in the treatment of the following subjects.

- Chemical bonding
- Partings
- Causes of mineral color
- Electron microprobe analysis
- Scanning electron microscope
- Microcrystalline varieties of silica

In addition, new sections have been added on quasicrystals and carbonaceous material, and more emphasis has been placed on the use of a hand lens in mineral identification.

This revision has benefited greatly from the thoughtful review by Graham Baird at the University of Northern Colorado. Additional individuals who provided reviews include Tasha Dunn (Colby College), David Gonzales (Fort Lewis College), Willis Hames (Auburn University), Tina Hill (University of Wisconsin–Milwaukee), Jonathan Martin (University of Florida), Stephen Nelson (Tulane University), Jeanette Sablock (Salem State University), and Thomas Sharp (Arizona State University). Their thoughtful comments and suggestions are greatly appreciated.

Most importantly, I am indebted to my wife, Marianne Workman-Nesse, for her support and for her thorough critique and editing of the book. If, despite the efforts of these individuals, errors, omissions, and inconsistencies remain, they are solely my responsibility, and I request that they be brought to my attention.

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Crystallography and Crystal Chemistry

Introduction

Almost every human endeavor is influenced by minerals. Many natural resources used in the manufacture of goods on which civilization and our lives depend begin as minerals in the ground. The crops that we eat are grown in soil composed of minerals. The safety and stability of structures such as buildings, roads, and bridges depend on the mechanical properties of the minerals that make up the rocks and soil on which they are built. In addition, the chemical composition, structure, and texture of the minerals that compose the rocks beneath our feet provide myriad clues that guide geoscientists as they attempt to decipher the history of the earth.

MINERALS

The term **mineral** is used in a variety of ways. In the economic sense it often means any valuable material extracted from the earth, including coal, oil, natural gas, groundwater, iron ore, gold, dimension stone, sand, gravel, or anything else that is mined. Nutritionists use the term "mineral" to mean any of a variety of chemical compounds or elements that are important for health. In common usage, anything that is neither animal nor vegetable might be considered mineral. As used in the geosciences, however, a different and more restrictive definition is applied.

A mineral is a naturally occurring crystalline solid.

A material that is **naturally occurring** is formed without the benefit of human action or intervention. It must be possible to find samples of it formed in the natural environment. Many crystalline solids with the same chemical and physical properties as their natural mineral counterparts may be synthesized in the laboratory. These materials are **synthetic minerals**.

Minerals must be **crystalline solids**. The atoms and/or ions that form crystalline materials are arranged and chemically bonded with a regular and repeating long-range order. At the macroscopic scale, symmetrically arranged crystal faces (Chapter 2) and cleavages (Chapter 6) are clear evidence that a material is crystalline. At the microscopic scale and smaller, the ability to diffract X-rays (Chapter 8) documents that a material is crystalline. The chemical

bonds (Chapter 3) that hold the atoms and ions in a regular and repeating pattern require that crystalline materials are solid. However, crystalline solids may deform in a ductile manner under appropriate temperature-pressure conditions.

Not all solids are crystalline. Glass, for example, is a solid, but the atoms/ions lack long-range atomic order, so it is considered **amorphous** or **non-crystalline**. In most cases the distinction between crystalline and non-crystalline is relatively clear, but not always. With biomineralization (Chapter 5), for example, "nano particles" (~1 to 100 nm, 1nm $= 10^{-9}$ meters) having a limited degree of order may be the initial material to precipitate. In addition, **the regular and repeating order in crystalline materials is never flawless**—imperfections and disorder always are present in varying amounts. Some of these imperfections are discussed in Chapters 4 and 5. Unfortunately, we do not have a rigorous way of quantifying the abundance of imperfections and disorder so that we can objectively deal with the gray area between crystalline and non-crystalline. For a discussion of the problems associated with defining crystallinity, consult Caraballo and others (2015).

As a necessary consequence of being crystalline solids, minerals have a definite, but not necessarily fixed, chemical composition. A chemical formula may be written for any mineral. An example is the common mineral quartz (SiO_2), which is composed of silicon and oxygen in a ratio of 1:2. The composition of many mineral species may vary within certain limits. An example is the mineral olivine that may be iron rich (Fe_2SiO_4) or magnesium rich (Mg_2SiO_4) or may have an intermediate composition. However, the proportions always work out so that the ratio (Fe + Mg):Si:O remains 2:1:4. Hence, different samples of a mineral species may have different compositions, but the variability is limited. Because minerals are crystalline and have a definite chemical composition, they also have definite physical properties. These physical properties also may vary within limits because they are controlled by the variation in chemical properties.

Some definitions of what constitutes a mineral require that it be formed by inorganic processes. This historical encrustation, which probably has its roots in Aristotle's division of matter into animal, vegetable, and

mineral, should have been jettisoned long ago. Minerals constitute an integral part of biologic structures and processes. Obvious examples are the minerals calcite and aragonite (both $CaCO_3$ but with different structures), which are secreted to form the shells of many marine invertebrates and whose remains are a major component of limestone layers found in the stratigraphic record. The mineral apatite $[Ca_5(PO_4)_3(OH, F, Cl)]$ makes up a substantial portion of the teeth and bones of vertebrates. If desired, these biologically produced minerals may be called **biominerals**.

Bacteria are an integral part of many geochemical processes at or near the surface of the Earth and directly influence the growth of many minerals. For example, the pyrite (FeS_2) found in many shale and coal beds is produced by the action of sulfate-reducing bacteria. The interaction of microbes and geologic processes is the focus of the emerging and exciting field of study called **geomicrobiology**. Numerous different minerals and mineraloids are now recognized to be produced by biologically induced and controlled mineralization processes (Weiner and Dove, 2003). Many more will undoubtedly be recognized as our understanding of these processes improves. Further, biologic processes have profoundly affected the Earth's near-surface chemical environment and therefore also have affected the types and distribution of the minerals found there.

MINERALOIDS

Mineraloids are mineral-like materials that lack a long-range crystalline structure. They include amorphous solids and glasses.

Amorphous solids lack long-range atomic order but may possess short-range (~10–100 Å) order. Opal is probably the best-known example and consists of silica gel, often arranged in small spherical masses. The crystalline structure of U- and Th-bearing minerals, such as zircon, may be extensively disrupted by radioactive decay of these elements. The term **metamict** is used to describe these disrupted structures, and once a mineral's structure becomes metamict, it is properly considered a mineraloid.

Natural glasses also may be considered mineraloids. Volcanic glass is the most common example. Frictional melts called **pseudotachylite** may be produced in fault zones in response to intense shearing. Meteorite impacts may, if large enough, release enough energy to melt the rocks that they strike, producing an **impact melt**. Small masses of glass called **tektites** are usually interpreted to be samples of now-solidified impact melt ejected from an impact crater. A lightning strike may heat soil or rock sufficiently to melt some of it and produce a **fulgurite**. Burning coal beds may generate enough heat to fuse the surrounding rock, forming scoriaceous or slaglike glasses referred to as **ash glass** or **clinker**.

MINERALOGY

Mineralogy is the study of minerals. The beginning of this particular branch of science extends back to prehistoric times, for our ancestors surely knew about and used many minerals. Evidence of mining and smelting minerals to extract useful metals such as copper, lead, and zinc is found in many ancient civilizations.

The modern study of mineralogy can be traced back to Theophrastus (ca. 387–272 BC) who wrote the earliest-preserved book dealing with minerals and rocks, titled *On Stones*. Some 400 years later, Pliny the Elder, who met his death at Pompeii, provided us with an encyclopedic review of mineralogy as it applied to the metallic ores, gemstones, and pigments in use in the Roman Empire circa AD 77. Some 1500 years later (1556). German physician and mining engineer Georg Bauer, known to us by his Latinized name Georgius Agricola, provided detailed mineral descriptions, and defined physical properties, such as hardness and cleavage, that continue to provide the basis for hand-sample identification of minerals.

Through the seventeenth, eighteenth, and nineteenth centuries a number of notable scholars provided significant advances to the science:

Niels Stensen (Nicholas Steno), Denmark. Demonstrated the law of constancy of interfacial angles (1669).

A. G. Werner, 1750–1817, Germany. Standardized nomenclature for mineral descriptions.

René-Juste Haüy, 1743–1822, France. "Father of mathematical crystallography." Showed that crystals were constructed by stacking together identical building blocks, which we now call unit cells, and developed the idea that crystal faces have rational orientations relative to these building blocks.

J. J. Berzelius 1779–1848, Sweden. Recognized that minerals are chemical compounds and provided the foundation for the chemical classification of minerals.

William Nicol, 1768–1851. Invented the Nicol prism (1828), which allowed the anisotropic behavior of light passing through minerals to be studied and provided the foundation for optical mineralogy.

James D. Dana, 1813–1895, Yale University. Published the first edition of *A System of Mineralogy* in 1837. The fourth edition (1854) introduced the chemical classification of minerals that is still in use.

Henry Clifton Sorby, 1826–1908. Developed the use (along with Cloizeaux in France) of the petrographic microscope for studying rocks and minerals.

Perhaps the most dramatic progress in understanding minerals came with the discovery of X-rays. In 1912 Max von Laue (1879–1960) demonstrated that crystals would diffract X-rays, thus proving that minerals possess

a regular and repeating internal arrangement of atoms. By 1914, W. H. Bragg (1862–1942) and his son W. L. Bragg (1890–1971) in Cambridge, England, had used X-rays to determine the crystal structure of minerals.

During the twentieth century a wide variety of instrumentation was developed that improved our ability to determine the chemical composition of minerals and refined our understanding of their crystal structures. In addition, petrologists and chemists immensely expanded our knowledge of the chemical and petrologic behavior of minerals in a wide range of geologic environments.

MINERAL NOMENCLATURE

A **mineral species** is distinguished from other minerals by a unique combination of composition (Chapter 3) and crystal structure (Chapter 4). Over 4900 mineral species have been identified, described, and named, although less than a hundred mineral species are at all common. The **Commission on New Minerals, Nomenclature and Classification** of the **International Mineralogical Association** provides criteria by which new minerals are recognized. A list of approved mineral names is available as a free Internet download from the International Mineralogical Association. New minerals are regularly discovered and a summary of new minerals is included in each issue of the *American Mineralogist*, published by the Mineralogical Society of America.

The criteria to be satisfied before a new mineral species is approved include the following.

- It must be a mineral as defined above.
- It must not previously have been described and named.
- The crystallography (Chapter 2), composition (Chapter 3), and crystal structure (Chapter 4) must be determined.
- Physical (Chapter 6) and optical (Chapter 7) properties must be described.
- The geologic and geographic setting in which the mineral was found must be described.
- A **type sample** of the mineral must be preserved in an appropriate repository, such as a museum or the collection of a research institute.

A mineral may be named after an individual, a place where it is found, or in reference to its chemical composition or a significant physical property. Some minerals have names whose origins are lost in the mists of antiquity. A detailed listing of the sources of mineral names can be found in Mitchell (1979). Gains and others (1997) also describe the origin of mineral names. A glossary of mineral synonyms (~35,000 of them) has been prepared by de Fourestier (1999) and a compilation of obsolete mineral names has been published by Bayliss (2000).

A mineral species may have more than one **mineral variety**. Different varieties of a mineral are distinguished by differences in color, habit (shape), or other properties. For example, the mineral corundum (Al_2O_3, Chapter 18) is typically gray and fairly mundane looking. However, ruby and sapphire are varieties that form beautiful gems. Ruby is red because it contains small amounts of Cr, and sapphire is blue because it contains small amounts of Ti + Fe. The terminology for mineral varieties is fairly haphazard; mostly it follows historical and colloquial practice.

A **mineral series** is two or more minerals among which there is a range of chemical compositions. An example is in the common plagioclase mineral series (Chapter 12). The two end members of the plagioclase series are the minerals albite ($NaAlSi_3O_8$) and anorthite ($CaAl_2Si_2O_8$). Natural plagioclase typically has a composition intermediate between albite and anorthite.

A **mineral group** is a set of minerals with the same basic structure but different compositions. The group is generally named for one of the constituent minerals. An example is the calcite group (Chapter 17) whose general chemical formula is XCO_3, where X is a metal cation (Chapter 3).

Calcite	$CaCO_3$
Magnesite	$MgCO_3$
Rhodochrosite	$MnCO_3$
Siderite	$FeCO_3$
Smithsonite	$ZnCO_3$

Members of a mineral group also may form a mineral series. For example, magnesite and siderite form a mineral series because intermediate compositions are common.

The term **crystal** has been used in two ways in mineralogy. In a restricted sense, a crystal is a piece of a mineral bounded, at least in part, by regular, smooth crystal faces produced during growth. The presence of crystal faces is a direct consequence of the fact that the atoms are arranged in a regular and repeating manner in minerals. In a broader sense, however, mineralogists often use the term *crystal* for any piece of a mineral, regardless of whether it displays crystal faces. Bounding surfaces may be crystal faces, fractures, cleavages, or contacts with adjacent mineral grains. It might be better to use the term *crystal* only when crystal faces are present, and use the term **mineral grain** when the nature of the bounding surfaces is not specified. In any event, the reader should be aware of the different ways that *crystal* is used in the literature. In this book, the term *crystal* is used in the restricted sense.

GENERAL REFERENCES ON MINERALOGY

This book is intended as an introduction to the study of minerals and, of necessity, cannot include the depth of coverage provided in more specialized resources. References will be provided in each chapter to sources for additional

information. However, all readers should be aware of a number of additional important sources.

Among the most important is the series of volumes by Deer and others titled *Rock-Forming Minerals*, which provides extensive information on the structure, chemistry, properties, and occurrence of common minerals. The same authors also have compiled a one-volume summary (Deer and others, 2013) that is highly recommended.

The seventh edition of *Dana's Manual of Mineralogy*, in three volumes (1942–1962), provides coverage of the physical and related properties of nonsilicate minerals, and quartz and its polymorphs. Unfortunately, much of the chemical and crystal-structure information is now out-of-date and volumes dealing with the silicates are not published. The eighth edition (Gains and others, 1997) provides an exhaustive compilation of minerals in one volume.

The *Handbook of Mineralogy*, in five volumes, by Anthony and others (1990–2003), provides another exhaustive compilation of mineralogical data. Separate files for each of the 3734 minerals included in the handbook may be downloaded from the Mineralogical Society of America. Struntz and Nickel (2001) provide additional data. Mineral data are widely available on the Internet. **Mindat.org** has one of the most comprehensive compilations, and other sources can be readily found with normal search tools.

The Mineralogical Society of America publishes the *Reviews in Mineralogy & Geochemistry* series, which now totals over 80 volumes. New volumes are published every year, often based on a short course offered at the Society's annual meeting. Each volume typically deals in depth with a specific group of minerals or some mineral-related topic. They are highly recommended. The Mineralogical Society of America and a host of other scientific societies also publish *Elements* quarterly. Each issue presents a group of articles addressing a topical issue related to mineralogy and geochemistry.

The literature of mineralogy is published in many journals in a variety of languages. The most widely circulated English-language journals are *American Mineralogist*, published by the Mineralogical Society of America; *Canadian Mineralogist*, published by the Mineralogical Society of Canada; *Mineralogical Magazine*, published by the Mineralogical Society of Great Britain and Ireland, and *European Journal of Mineralogy*, published by Schweizerbart Science Publishers.

MINERALS AND SOCIETY

Natural Resources

Civilization depends very directly on the materials obtained from minerals. A few metals, and the minerals from which they are extracted, are listed in Table 1.1. Because the distribution of economic mineral deposits—geologic concentrations of minerals that can be economically extracted—is uneven, it is essential for nations to establish a global trade

Table 1.1 Selected Metals and Some Minerals from Which They Are Extracted

Metal	Mineral	Chemical Formula	Major World Sources
Iron	Magnetite Hematite	Fe_2O_3 Fe_3O_4	Australia, Brazil, China
Copper	Chalcopyrite	Cu_5FeS_4	Chile, Peru, United States
Molybdenum	Molybdenite	MoS_2	Chile, United States, China
Lead	Galena	PbS	China, Australia, United States
Tungsten	Scheelite Wolframite	$CaWO_4$ $(Fe,Mn)WO_4$	China, Russia, Canada
Nickel	Pentlandite	$(Fe,Ni)_9S_8$	Russia, Canada, Indonesia
Aluminum	Bauxite	Mixed oxides of Al	Australia, China, Brazil
Titanium	Rutile Ilmenite	TiO_2 $FeTiO_3$	Australia, Norway, China
Zinc	Sphalerite	ZnS	China, Peru, Australia

Source: U.S. Geological Survey Minerals Yearbook 2007, 2008.

in these resources. The United States, for example, has large economic resources of molybdenum and gold but little nickel and tungsten, and for many other resources, production is insufficient to meet domestic requirements. American manufacturers must, therefore, purchase raw materials from worldwide sources. The same applies to manufacturers in England, China, Germany, Japan, and all the other countries in the world. This international trade allows the generation of wealth that supports our society.

Because minerals are valuable, it is not surprising that wars are fought over access to mineral resources. Further, trade in minerals also can support brutal and repressive regimes. A good example is provided by the conflicts in Angola, Democratic Republic of the Congo, Liberia, Côte d'Ivoire, and adjacent areas in Africa that have ties to the global trade in diamonds. Most conflicts in human history have involved competition for natural resources, either directly or as a strategic consideration.

World War II is instructive. Iron is absolutely essential to support modern industry and to support a strong military. At the beginning of the war Germany had only modest iron ore production, whereas France, Sweden, the

Table 1.2 Iron Ore Production in 1937 from
Selected Countries

Country	Amount (million metric tons)
Luxembourg	8
Germany	10
United Kingdom	14
Sweden	15
Soviet Union	26
France	38
United States	73

Source: U.S. Geologic Survey Minerals Yearbook 1939.

Soviet Union, and the United Kingdom each had significantly more production (Table 1.2). Even tiny Luxembourg had nearly as much iron ore production as Germany. If Germany was to succeed with its military ambitions, it was essential to acquire at least some of the iron ore production from other sources in Europe. The German invasion of France and Luxembourg served to lock up the supplies of iron from those countries. Also of great importance was the Swedish supply of iron ore in Kiruna, which was all transshipped through Narvik, on the west coast of Norway. The German invasion of Norway, and particularly Narvik, in 1940, had as one strategic goal the acquisition of those supplies from neutral Sweden. Fortunately for Great Britain and the other allies, the United States had abundant supplies of iron ore that were available for the war effort both before and after the United States entered the conflict on December 8, 1941.

Minerals and Health

Over 2000 years ago the Greek physician Hippocrates established a correlation between disease and location, demonstrating that geological environment influences the incidence of disease. We now recognize that some of these spatial variations in disease are tied to the mineralogical composition of the soils and rocks on which we live. Selenium provides a good example because it is an essential nutrient and is taken up by plants from the soil. Thus humans and animals eating plants grown in soil that is deficient in selenium may develop health problems from a selenium deficiency. Too much selenium, however, may also lead to significant health problems. Many other metals ultimately derived from minerals in the soil and bedrock are essential nutrients in small amounts but toxic in large amounts; examples include arsenic, chromium, cobalt, copper, iron, manganese, molybdenum, nickel, tin, tungsten, vanadium, and zinc.

Other chemical elements, such as hexavalent chromium, lead, and mercury, do not have known nutritional benefits and can be quite toxic. While poisoning from natural sources of these elements has occurred, most cases of toxicity come from anthropogenic sources. The metals

are mined and used in products or industrial processes that make them available to people. Lead in paint, gasoline, and solder is a good example.

Our bodies are generally well equipped to deal with the routine and unavoidable inhalation of environmental mineral dust. However, chronic inhalation of significant quantities of any mineral dust can be hazardous to one's health. Several minerals appear to pose particular problems.

One of the most widely recognized problems is with the group of minerals referred to as asbestos, which form thin flexible fibers that are useful for a number of products and industrial processes. The commonly used asbestos minerals are chrysotile (Chapter 13) and amphibole (Chapter 14). While many uses of asbestos have now been banned, in the past asbestos minerals were used in insulation, flooring, automotive brakes, and many other products. Inhalation of the fibrous mineral particles has been documented to cause cancer and a variety of other lung-related pathologies. In response to the real and imagined threat posed by asbestos, this material has been removed at considerable expense from homes, schools, and other buildings.

Quartz (Chapter 12) dust also has been documented to cause silicosis, a pathology most commonly found in miners and mill workers exposed to high levels of dust in the work environment. The accumulation of high levels of quartz particles in the lungs leads to scarring and decreased lung function. Other pulmonary diseases, including cancer, also have been linked to silicosis. However, it seems unlikely that routine casual environmental exposure presents significant health risks because life has evolved for billions of years in close contact with quartz.

Chronic inhalation of other mineral dusts (e.g., kaolinite, pyrophyllite, montmorillonite, zircon) also has been documented to cause medical problems. Chronic inhalation of almost any particulate material, mineral or otherwise, should be avoided because of the potential to cause problems.

Medical Uses of Minerals

Minerals have probably been used for medical purposes from before the start of recorded history. Before the development of modern pharmaceuticals, physicians and healers had to rely on a relatively limited collection of natural materials. This included minerals in addition to materials from plants and animals. Pliny, who died at Pompeii in AD 79, mentions the medical uses of minerals (Bostock and Riley, 1857), and the earliest textbook on mineralogy (Agricola, 1546) includes a section in which the medical uses of minerals are described. Limpitlaw (2006) has documented that about 100 different minerals have been used for medicinal purposes and that some continue to be an integral part of the modern pharmacy.

Many minerals are used in folk remedies, and in homeopathic and other preparations for which scientific documentation of their efficacy is notably lacking. In many cases,

these uses probably do no harm and are only successful to the degree that they trigger the placebo effect. The placebo effect is based on the observation in medical trials that placebos (pills/preparations with no active ingredient) can produce benefits to patients simply because the patient believes that they will. This example of the nearly infinite human capacity for self-delusion probably helps explain the common historical use of gemstones, beautiful crystals, and other precious or rare minerals for medical purposes. These uses still flourish, as an Internet search will readily confirm.

The most common means of application include ingestion of powders, preparing a "tea" or extract by soaking the mineral in water, beer, wine, or other liquid, and then drinking the liquid, preparing a poultice of the powdered mineral, and carrying the mineral in an amulet. Homeopathic preparations are commony diluted to the point that only traces (or none) of the original material are present. The modern practice of wearing gemstones derives, in part, from ancient beliefs that the gems provided protection from, or a cure for, various ailments.

Some of the historical medical uses of minerals were definitely hazardous to the patient's health. Among the minerals that did considerable harm was calomel, a mercury chloride (Hg_2Cl_2), used to treat gastrointestinal problems, infections, and other maladies from at least 1500 up to the 1860s. It also produced mercury poisoning. Preparations made with gold were claimed to energize and assure longevity. Diane de Poitiers, mistress to King Henry II of France in the sixteenth century, routinely drank an elixir made from gold and probably died from gold poisoning (Charlier and others, 2009). Lead oxides such as minium (Pb_3O_4) continue to be used as a folk remedy to treat diarrhea in certain Central American societies and can lead to serious lead poisoning.

The reader should not infer that all medical uses of minerals are bunk. A significant number of minerals are routinely and productively used for modern medical purposes. These include the clay minerals (Chapter 13), zeolites (Chapter 12), and calcite (Chapter 17).

Medical uses of some minerals are mentioned as part of the descriptions in Chapters 12 through 20. The reader is cautioned that the author does not endorse any of these uses, and that qualified physicians and pharmacists should be consulted about the appropriate treatment for any medical condition. The reader also is cautioned that mineral uses that now seem improbable may yet prove to be beneficial.

GETTING STARTED

Students are understandably eager to get their hands on minerals in the lab as they start a mineralogy course. However, the detailed discussion of the physical properties that provides the basis for identification of unknown samples is not presented until Chapter 6. The reason for this organization is that an understanding of mineral physical properties (habit, color, luster, streak, hardness, specific gravity, cleavage, fracture, etc.) requires an understanding of crystallography and crystal chemistry, the topics of Chapters 2 through 5. The objective of studying minerals is not simply to collect, identify, and catalog them. Much of the Earth's geologic history is recorded in the compositions, textures, associations, and spatial and temporal distributions of the minerals that compose the rocks, sediments, and soils that make up the solid Earth. Without a working knowledge of crystallography and crystal chemistry, it is not possible to accurately document and interpret the information that minerals have to provide.

It is assumed here that students using this text will have completed at least one course in introductory geology, to provide them with basic information about minerals, rocks, and geologic processes and environments. A review of the relevant chapters in any introductory geology textbook is strongly recommended for all readers and will make the study of the following chapters easier and more informative. A brief review of the physical properties that are routinely used to identify hand samples of minerals is provided in Box 1.1.

Box 1.1 Getting Started: Mineral Physical Properties

The properties used to identify minerals can be grouped into those that involve shape, mass (density and specific gravity), mechanical properties (hardness, cleavage, fracture), interaction with light (luster, color, streak), and other properties (magnetism, taste, smell, reaction with acid).

Mineral Shape

Minerals commonly form beautiful crystals; each mineral forms crystals with a specific set of shapes and crystal faces. For example, quartz crystals form prisms with six sides, and pyrite commonly forms cubes with striated faces. These shapes can be described with common terminology—elongate, stubby, fibrous, cubic, prismatic, and so forth. However, the detailed study of crystals has revealed symmetrical relationships among crystal faces and has developed into the subject of crystallography. Chapter 2, on crystallography, explores symmetry in minerals, and establishes a coordinate system of crystal axes and an extensive nomenclature for crystals. This background allows us to systematically describe and discuss the properties of minerals.

Continued

Box 1.1 *Continued*

Mass-Related Properties

The mass-related properties of **density** and **specific gravity** are closely related. Density (ρ) is defined as mass (m) per volume (v):

$$\rho = m/v$$

The usual units are grams per cubic centimeter (g/cm^3). Specific gravity (G) is the ratio of the density of a material (ρ) divided by the density of water at 4°C (ρ_{H_2O}).

$$G = \frac{\rho}{\rho_{H_2O}}$$

G is unitless because it is a ratio of densities. Because the density of water at 4°C is essentially 1 g/cm^3, the numerical value for specific gravity is the same as the specific gravity expressed in terms of grams per cubic centimeter. Details of how specific gravity is measured are provided in Chapter 6, but a rough estimate can be made by simply hefting a sample of a mineral in one's hand and comparing it to a sample whose specific gravity is known, such as quartz ($G = 2.65$). The controls of density are chemical composition (Chapter 3) and the manner in which the atoms that compose the mineral are packed and chemically bonded together (Chapter 4).

Mechanical Properties

Hardness (H) is a measure of the resistance of a mineral to being scratched. The Mohs scale of hardness ranks minerals from 1 for very soft, easily scratched minerals, to 10 for the hardest mineral, diamond (Table 1.3). To provide a standard of comparison, specific minerals are assigned to each hardness number. A mineral with hardness 5 will scratch a mineral with hardness 4 and be scratched by a mineral with hardness 6, for example. To make comparisons in the lab and field easier, mineral hardness is routinely tested with common materials of known hardness—a fingernail (2+), a steel nail or knife blade (~5), window glass (~6), and a piece of quartz (7). The identification tables at the end of this book (Appendix B) use groupings based on these values.

Hardness is fundamentally controlled by the nature of the chemical bonds among the atoms that compose a mineral. The detailed discussion of hardness in Chapter 6 depends on an understanding of chemical

Table 1.3 Mohs Scale of Hardness

1	Talc
2	Gypsum
3	Calcite
4	Fluorite
5	Apatite
6	Orthoclase
7	Quartz
8	Topaz
9	Corundum
10	Diamond

bonding (Chapter 3) and crystal structure (Chapter 4). Both of these are intimately related to a mineral's symmetry (Chapter 2).

Cleavage and **fracture** both refer to the manner in which a mineral breaks. All minerals fracture when hit with a hammer or otherwise are forced to break. When a mineral fractures, it breaks on an irregular surface. If the surface is a smooth curved surface, like broken glass, the fracture is **conchoidal**. **Irregular**, **hackly**, and **splintery** fracture are terms that indicate increasing degree of relief ("pointyness") on the fracture surface. Only some minerals display cleavage, where the breaks are on smooth planar surfaces that are planes of weakness in a mineral. The cleavage may be described as perfect, good, fair, or poor, depending on the ease with which the cleavage can be produced, as well as how smooth and continuous the surfaces are. Minerals with cleavage may have one, two, three, or more different directions along which they break. Table B.1 in Appendix B groups minerals based on the number of cleavages. Because cleavages are planes of weakness in a mineral's structure (Chapter 4), they have crystallographic control and are identified with the nomenclature of crystallography (Chapter 2). A detailed discussion is provided in Chapter 5.

Color Properties

A mineral's **luster** and **color** are perhaps the first things that an observer notices. Luster is generally categorized as **metallic** or **nonmetallic**. Whether we perceive a mineral to be metallic or nonmetallic is not a function of color—rather, it is a function of how much of the incident light is reflected, which is discussed in Chapters 6 and 7. Separate identification tables are provided in Appendix B for metallic and nonmetallic minerals. Color for minerals with a metallic luster is generally quite consistent for different samples of the mineral and is therefore a useful diagnostic property. For nonmetallic minerals, however, color can be quite variable. Quartz, for example, can be almost any color, and K-feldspar, another very common mineral, can be pink, white, gray, green, or blue. An understanding of the controls of a mineral's color requires knowledge of chemical bonding and the interaction of light with matter. These topics are covered in Chapters 3, 6, and 7. Fluorescence and related properties are covered in Chapter 6.

For most minerals, it turns out that the **streak** is quite consistent. Streak color is the color of the powdered mineral. In most mineral laboratories, the streak color is obtained by rubbing a mineral sample on an unglazed white porcelain tile, called a streak plate.

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