

INTRODUCTION TO MINERALOGY

WILLIAM D. NESSE

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WILLIAM D. NESSE

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Preface

This book was written to provide a comprehensive text for teaching mineralogy to undergraduate students in the geosciences. Mineralogy is an essential because all geoscientists continually deal directly or indirectly with minerals in their professional work. The details of what specifically should be included in mineralogy courses are, however, subject to some debate and the point is often made that most students taking mineralogy courses are not going to be mineralogists. The challenge, therefore, is to present a survey of mineralogy that is sufficiently comprehensive to be useful in a wide range of mineralogy courses. The text must both provide specific knowledge about minerals needed by students for their future professional work and, perhaps more importantly, help students develop the intellectual tools and habits of mind that are essential parts of a scientific education. It is assumed that students using this book have the background normally acquired in a conventional introductory physical geology course and at least some exposure to college-level chemistry.

The organization of subjects allows the concepts of mineralogy to be logically developed within the framework that a textbook allows. An understanding of mineral hardness, for example, requires knowledge of chemical bonding and mineral structure, hence those subjects are presented first. Many instructors, to engage and maintain student interest, structure their courses in ways that do not follow the sequence of this text. Individual sections, therefore, have been written to be reasonably self-contained.

The concepts of symmetry, crystallography, crystal chemistry, and related subjects are presented in Part I (Crystallography and Crystal Chemistry). This section provides the foundation necessary to understand physical and optical properties, X-ray diffraction, chemical analysis and mineral

associations, and the nomenclature required to systematically describe minerals.

Part II (Mineral Properties, Study, and Identification) includes five chapters describing the routine techniques and procedures students will use in their study of minerals. The chapter on optical mineralogy is fairly comprehensive because many schools do not have the luxury of a separate optical mineralogy/crystallography course. An instructor may choose to include basic optical mineralogy as part of a one-semester mineralogy course, or use this chapter as part of a subsequent petrology/petrography course.

Part III (Mineral Descriptions) provides detailed descriptions of common minerals with additional less-common minerals listed in selected tables. Sections are provided to describe and explain mineral occurrences in common rocks and mineral deposits. Both physical and optical properties are included. Because minerals are absolutely essential to civilization, the uses of minerals are described in some detail.

Except as noted, all illustrations were prepared by the author. *Shape* and *Atoms*, two fine software programs from Eric Dowty, were used to prepare the crystal and mineral-structure drawings, respectively.

I gratefully acknowledge Micky Gunter for his thorough review of the entire manuscript and Paul Ribbe, who reviewed selected parts. Their suggestions and criticisms are very much appreciated. I am deeply indebted to my wife, Marianne Workman-Nesse, who edited and critiqued the entire manuscript, for her unflagging help and support. If, despite the guidance of these individuals, errors or inconsistencies persist, they are solely my responsibility and I would appreciate being informed of them.

Greeley, Colorado WDN

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PART I

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 comprise the rocks and soil on which they are built. In addition, the chemical composition, structure, and texture of the minerals that comprise the rocks beneath our feet provide a myriad of 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, sand and gravel, iron ore, or other mined commodity, even groundwater. Nutritionists use the term mineral to mean any of a variety of chemical compounds or elements that are important for nutrition. 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 with a definite, but not necessarily fixed, chemical composition.

A material that is **naturally occurring** is formed without the benefit of human action or intervention. It must be possible to find samples 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 comprise crystalline materials are arranged and chemically bonded in a regular and repeating long-range

pattern. The beautiful, symmetrically arranged crystal faces that adorn many mineral samples are a consequence of this internally ordered atomic structure. Solids such as glass lacking long-range atomic order are considered **amorphous**. They are not minerals. To be considered crystalline a material must be a solid, although crystalline materials may deform in a ductile manner under appropriate temperature—pressure conditions.

All 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, which 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 $(\text{Fe} + \text{Mg})\text{:Si:O}$ 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 may also vary within limits because they are controlled by the variation in chemical properties.

Some definitions of a mineral require them to be formed by inorganic processes. This historical encrustation should have been jettisoned long ago. It is widely recognized that minerals are produced by organic processes. The shells of many marine invertebrates are formed of the minerals calcite or aragonite (CaCO_3). These shells are a major component of many limestone layers. The mineral apatite [$\text{Ca}_5(\text{PO}_4)_3(\text{OH},\text{F},\text{CL})$] makes up a substantial portion of teeth and bones of vertebrates. Bacteria are an integral part of many geochemical processes at or near the surface of the earth and directly influence the growth of a number of minerals. For example, the pyrite (FeS_2) found in many shale and coal beds is produced by the action of sulfate-reducing bacteria.

♦ 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 ($\sim 10\text{--}100\text{ \AA}$) 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 bombardment. The term **metamict** is applied to these disrupted structures, and once a mineral's structure becomes metamict, it is properly considered a mineraloid.

Natural glasses may also be considered mineraloids. Volcanic glass is the most common example. Frictional melts may be produced in fault or mylonite zones in response to intense shearing. Meteorite impacts may, if large enough, release enough energy to melt the rocks that they strike. A lightning strike may heat soil or rock sufficiently to melt some of it and produce a **fulgarite**. Burning coal beds may generate enough heat to fuse the surrounding rock forming scoriaceous or slag-like glasses referred to as ash glass or **clinker**.

♦ Mineralogy

Mineralogy is the study of minerals. The beginning of this particular branch of science extends well 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 77 AD. Some 1500 years later (1556) German physician and mining engineer Georg Bauer, known to us by his Latinized name Georgius Agricola, provided detailed 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 that 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) that 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 has been developed to improve our ability to determine the chemical composition of minerals and refine our understanding of their crystal structures. In addition, petrologists and chemists have immensely expanded our knowledge of the chemical and petrologic behavior of minerals in a wide range of geologic environments.

♦ Mineral Names

About 3500 minerals have been identified, described, and named, although less than a hundred mineral species are at all common. Fleischer and Mandarino (1995) and Nickel and Nichols (1991) provide authoritative lists of mineral names approved by the **Commission on New Minerals and New Mineral Names** of 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.

A number of criteria must be satisfied before a new mineral name is approved. The candidate material must be a mineral as defined above and must not previously have been described and named. In addition, the crystal structure

and composition must be accurately determined, and a type sample must be preserved in an appropriate repository such as a museum or in the collection of a research institute.

A mineral may be named after an individual, a place where it is found, or in allusion to its chemical composition or a significant physical property. Some minerals have names whose origins are lost in mists of antiquity. A detailed listing of the sources of mineral names can be found in Mitchell (1979); Dana and others (1997) also describe the origin of mineral names.

◆ 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. Reference will be provided in each chapter to sources for additional information. However, there are a number of important sources with which all readers should be aware.

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, 1992) of *Rock Forming Minerals* that is highly recommended.

The seventh edition of *Dana's Manual of Mineralogy* is in three volumes (1942–1962) and 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 (Dana and others, 1997) provides an exhaustive compilation of all the extant minerals in one volume.

The *Handbook of Mineralogy* by Anthony and others (1990, 1995, 1997) provides another exhaustive compilation of mineralogical data. This compilation, unfortunately, also is not yet complete, and as this is written, only three of five planned volumes have been published. Strunz (1970) provides additional data. Mineral data also are available in electronic format for computer use.

The Mineralogical Society of America publishes the *Reviews in Mineralogy* series. A new volume is published about 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.

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

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CHAPTER 2

Crystallography

◆ Introduction

The descriptive nomenclature of crystallography has evolved over a period of several centuries to describe the shape, symmetry, and crystal structure of minerals. The discussion that follows contains only an introduction to crystallography and omits development of the theoretical and mathematical foundation on which the descriptive material depends. Interested readers are strongly encouraged to refer to Bloss (1971), Smith (1982), or O'Keeffe and Hyde (1996) for more extensive coverage of crystallography. The mathematical foundations of crystallography are described by Boisen and Gibbs (1985). The questions to be addressed in this chapter include the following:

What is the symmetry of crystals and crystal structures?
What is the descriptive nomenclature of crystals and crystallographic features?

Because minerals must have a regular and repeating structure, it follows that they must display symmetry, which in its various guises deals with repetition of objects or motifs. This symmetry is directly reflected in the symmetrical arrangements of crystal faces and of the internal structure of crystals that control cleavage or the diffraction of X-rays. It is not surprising, then, that the basic concepts of crystallography are all built on an understanding of symmetry.

Symmetry operations may be divided into two groups: those that involve translation or repetition of a motif through a volume and those that involve repetition of a motif around a point. Simple translational symmetry will be considered first because it leads directly to the concepts of the crystal lattice, unit cell, crystal axes, and crystal systems. This is followed by a discussion of point symmetry operations that lead to the development of the 32 crystal classes. Point and translation symmetry operations are combined to produce the 230 space groups. The nomenclature for describing crystal faces, crystallographic planes and directions, crystal forms, and related features follow from these concepts of symmetry.

◆ Translational Symmetry

Plane Lattices

Consider a spot, which could represent a collection of atoms (Figure 2.1a). That spot can be repeated by translating parallel to vector a toward the bottom of the page again and again. The result is a row of dots extending to infinity. The dots also can be repeated by translating parallel to vector b at angle γ from the a direction (Figure 2.1b). Repeated translations parallel to a and b produce a continuous repeating pattern of dots known as a **plane**

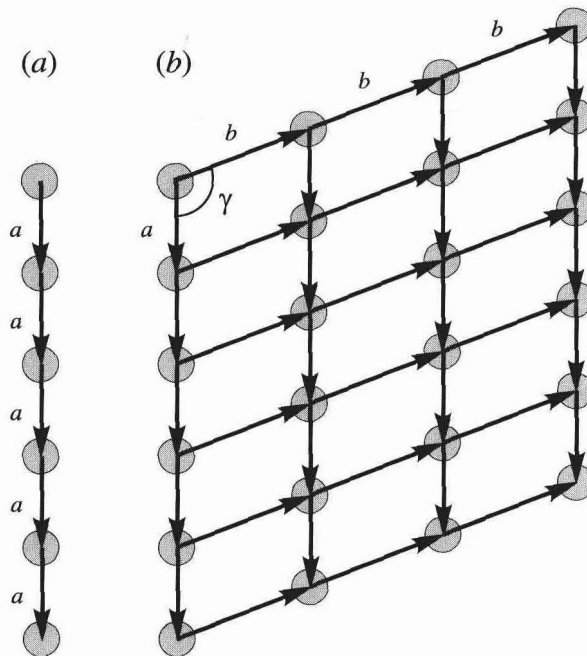


Figure 2.1 Simple translation to form a plane lattice. (a) A spot, representing a collection of atoms, is repeated by translation distance a toward the bottom of the page. (b) Repeated translation of these spots distance b at angle γ produces a two-dimensional plane lattice. The spots represent the lattice nodes.

lattice that extends to infinity in the ab plane. The center of each spot at the intersection of the lattice lines is called a **lattice node**.

The five different plane lattices that can be produced by simple translation in two dimensions (Figure 2.2a) are the square, rectangle, diamond or centered rectangle, hexagonal, and oblique plane lattices. The five plane lattices comprise only four fundamentally different shapes, called **unit**

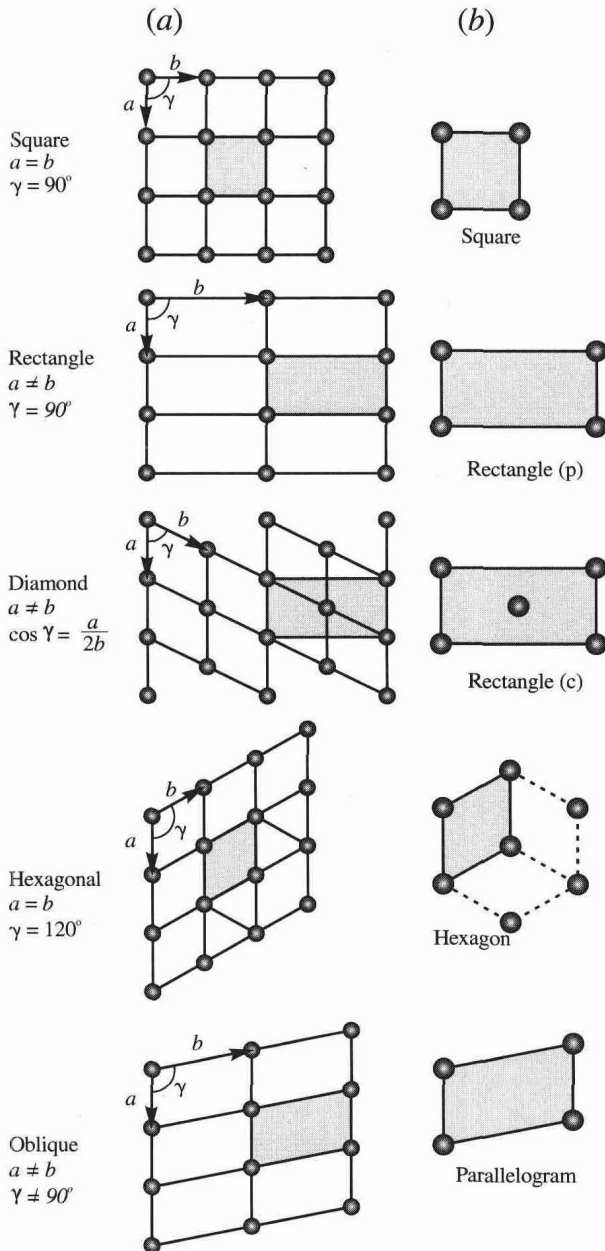


Figure 2.2 Plane lattices (a) and unit meshes (b). Only five different plane lattices can be produced by combinations of the dimensions of a and b and the angle γ . The four different unit meshes are shaded and are identified on the right. Note that both the rectangle and diamond lattice can be repeated on the page by using a rectangular unit mesh.

meshes (Figure 2.2b): square, rectangle (for both the rectangle and diamond plane lattices), rhombus (or a hexagon if desired), and parallelogram. Oblique, rectangular, hexagonal, and square plane lattices have **primitive** (p) unit meshes because lattice nodes occur only at their corners. The diamond plane lattice has a **centered** (c) unit mesh because a lattice node is at its center. Axes parallel to the edges of the unit mesh are labeled a and b , even if they are the same length. The angle between them is γ .

The type of translational symmetry described here is routinely used by craftsmen in building brick walls and laying ceramic tile on floors and walls, and it must be present in the pattern of wallpaper used to decorate homes. Bricks typically have a rectangular unit mesh and are most commonly laid using a centered rectangular lattice. Square ceramic tiles are laid on floors and walls using a square lattice; hexagonal ceramic tiles must be laid using a hexagonal lattice. Wallpaper typically uses either square, rectangular, or centered rectangular plane lattices so that the pattern on adjacent pieces of wallpaper will match. Oblique lattices are rarely used because surfaces such as walls and floors typically have square or rectangular shapes (Figure 2.3).

Space Lattices and Unit Cell

If the two-dimensional plane lattices are systematically repeated one above the other, to allow for a translation vector in the third dimension, the result is the formation of a **space lattice** (Figure 2.4a) in which lattice nodes are repeated in all three dimensions. The volume outlined by

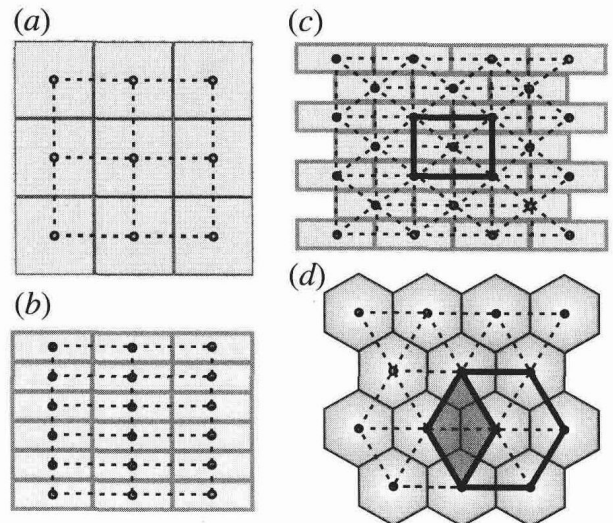


Figure 2.3 Plane lattices and unit meshes in everyday life. (a) Square ceramic tile laid in a square lattice. (b) Rectangular bricks laid in a rectangular lattice. (c) Rectangular bricks laid in a centered rectangular (diamond) lattice. The unit mesh includes pieces sufficient to make two bricks. (d) Hexagonal ceramic tile laid in a hexagonal lattice. The rhombic unit mesh includes pieces sufficient to make one tile.