Mineralogy

CONCEPTS
DESCRIPTIONS
DETERMINATIONS

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Mineralogy: Concepts, Descriptions, Determinations

Preface

This book is designed to satisfy the requirements of an undergraduate course in mineralogy. It is intended not only for the student who will later take more advanced work in the subject, but also (and perhaps more so) for the student for whom this is not only the first but also the last course in mineralogy. Emphasis is therefore given to general principles and to the significance of mineralogical data in interpreting geological phenomena, especially in the fields of petrology and economic geology.

A guiding principle in the writing of this book has been that each individual mineral—a phase in the earth's crust—documents the chemical and physical conditions that caused it to form at a specific place and at a particular time. Minerals are products of geological processes; from these products we can draw conclusions as to the nature of the processes themselves. An attractive feature of mineralogy is that we can use the laboratory to help us understand what we observe in the field. It is possible to reproduce most minerals in the laboratory under controlled conditions of temperature, pressure, and chemical environment. This enables elucidation of the stability range of different minerals, and hence the conditions under which the rocks containing them were formed.

These aims have placed special emphasis on certain aspects of the subject as it is treated here. The consideration of minerals as crystalline solids involves giving attention to both external form and internal structure and to their interdependence. The chemistry of minerals is regarded as a specialized part of solid state chemistry, requiring consideration of the relative sizes of atoms, the types of bonding, and the significance of these bonds in determining crystal structure; this leads to discussions of isomorphism, atomic substitution, and polymorphism in minerals. In the treatment of the physics of minerals we have emphasized the interrelations of physical properties, crystal structure, and chemical composition. The chapter on genesis (Chapter 5) goes beyond the occurrence and associations of minerals to a consideration of their origin: here we have placed emphasis on the correlation of geological observations with physicochemical principles and experimental data. Chapters 8 through 15 describe some 200 minerals in detail, and many others are mentioned incidentally. We believe that this number is adequate for a course in general mineralogy, although some uncommon minerals of great local significance may have been omitted. The determinative tables provide the student with a logical scheme for the examination of an unknown specimen and its ultimate identification.

Selected bibliographies appended to some chapters will, it is hoped, guide the student to the most useful literature in the subject and encourage him to read more widely on topics of special interest.

A course in mineralogy generally has two aims. One is to develop in the student the facility for identifying minerals, especially the more common ones; the other is to provide him with an understanding of the physics, chemistry, and genesis of minerals, so that he will be able to go beyond the identification of the minerals to consideration of their geological significance and the evidence they bear for the interpretation of earth history. It is hoped that this book is an adequate guide for such a course. As far as possible, the text develops the subject from first principles; however, it is assumed that the student is conversant with the basic principles of physics and chemistry, and with elementary plane trigonometry.

The individual chapters in Part I have been written in such a way that they may be read and discussed in any order. Some instructors may wish to begin a course with the chemistry or physics of minerals, others may begin with crystallography, others may wish to develop two or more topics concurrently. We believe that any of these schemes may be followed without inconvenience.

The decision to omit a detailed discussion of the optical properties of nonopaque minerals, and their application to mineral identification, was based on the realization that in most colleges special courses in optical mineralogy follow the course in general mineralogy, and that the average field geologist seldom has access to a petrographic microscope.

The text has benefited greatly from suggestions by many of our colleagues, and from the critical readings and comments of Professor A. O. Woodford, Dr. James Gilluly, Professor Chalmer Roy, Professor Arthur Howland, and, especially, Professor Adolf Pabst. To all of these persons we would express our appreciation and thanks. We are also greatly indebted to Roger Hayward who has contributed both artistic merit and scientific understanding to the task of illustrating this book.

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BRIAN MASON

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Notations and Abbreviations

CHEMICAL

Chemical elements	Na (appendix)
Anions	O^{-2}, SO_4^{-2}
Cations	Fe^2, K^1
Isotopes	U^{238}, Pb^{207}, He^4
Rare-earth elements	**R**
Smaller atoms (cations) in oxides, sulphides, halides	A, B
Larger atoms (anions) in sulphides, halides	X
Larger cations in sulphates, phosphates	A, B
Smaller cations in sulphates (S), phosphates (P, As, V)	X
Anion (OH, Cl, F) in sulphates, phosphates	Z
Large cation in silicates	W
Medium sized bivalent cations (and lithium) in sixfold coordination in silicates	X
Medium sized trivalent and quadrivalent cations in sixfold coordination in silicates	Y
Small cations in fourfold coordination in silicates	Z
Total weight of atoms in a unit cell	M
Number of formula units in a unit cell	Z

CRYSTALLOGRAPHIC

Crystal axes, unit cell dimensions	
Orthorhombic, monoclinic, triclinic	$a\ b\ c$
Tetragonal	$a_1\ a_2\ c$
Hexagonal	$a_1\ a_2\ a_3\ c$
Rhombohedral	a_r
Isometric	$a_1\ a_2\ a_3$
Unit cell interaxial angles	
Triclinic	$\alpha\ \beta\ \gamma$
Monoclinic	β
Rhombohedral	α
Unit cell interfacial angles (polar interaxial angles)	
Triclinic	$\lambda\ \mu\ \nu$
Monoclinic	μ
Polar axial elements (orthorhombic, monoclinic, triclinic)	$p_o, q_o, r_o = 1$ $p_1 = 1, q_1, r_1$ $p_2, q_2 = 1, r_2$
Polar axial elements (tetragonal, hexagonal)	$p_o, r_o = 1$
Gnomonic projection elements (*c* vertical)	
Triclinic	$p_o', q_o', x_o', y_o', \nu$
Monoclinic	p_o', q_o', x_o'
Two-circle goniometer crystal angles	V, H, φ, ρ
Interplanar spacing	d
Unit cell volume	V
Crystal face indices	(hkl)
Crystal form indices	$\{hkl\}$
Crystal zone axis (lattice row) indices	$[u\ v\ w]$
Symmetrically equivalent lattice rows	$[[u\ v\ w]]$
Primitive lattice	P
End-centered lattice	C, B, A
Body-centered lattice	I
Rhombohedral lattice	R
Face-centered lattice	F
Reflection plane of symmetry	m
Rotation axes of symmetry	2, 3, 4, 6

Center of symmetry	$\bar{1}$
Rotary inversion axes of symmetry	$\bar{2}$, $\bar{3}$, $\bar{4}$, $\bar{6}$
Rotation axes perpendicular to mirror planes	$2/m$, $3/m$, $4/m$, $6/m$

PHYSICAL

Angstrom unit (10^{-8} cm)	A
Specific gravity (density)	G
Pressure	
Atmospheres	atm
Kilograms per square centimeter	kg/cm^2
Hardness	H
Fusibility	F
Index of refraction (isotropic media)	n

PART I | Concepts

CHAPTER 1

Introduction

The Subject of Mineralogy

Mineralogy is the science of minerals, which are the naturally occurring elements and compounds making up the solid parts of the universe. We generally think of mineralogy in terms of the materials of the earth's crust. However, meteorites provide us with samples of minerals from outside the earth, and geophysical measurements furnish some indication of the nature of the minerals below the accessible crust. Mineralogy is a subdivision of geology, since minerals constitute the rocks of the earth's crust. Chemistry and mineralogy are also closely related, since minerals are chemical compounds; indeed, the terms *mineral chemistry* and *inorganic chemistry* have sometimes been used interchangeably. Crystallography began as a subdivision of mineralogy, being the study of the external form of naturally occurring crystals, but has developed into the study of all crystals, natural and artificial, and the investigation not only of external form but also of internal structure.

Inasmuch as mineralogy is the scientific study of minerals, we should start with a clear understanding of what the term "mineral" connotes. It is quite difficult to formulate a precise definition of a mineral, and, in fact, there is no general agreement on any such definition. We prefer to say: *A mineral is a naturally occurring homogeneous solid, inorganically formed, with a definite chemical composition and an ordered atomic arrangement.*

It may help our understanding to scrutinize this definition point by point. The qualification *naturally occurring* is essential because it is possible to reproduce most minerals in the chemical laboratory. For example, evaporating a solution of sodium chloride produces crystals indistinguishable from those of the mineral halite, but such laboratory produced crystals are not minerals. Replicas of most gemstones are made commercially, but they are referred to as synthetic ruby, synthetic spinel, and so on, to distinguish them from the natural minerals. On the other hand, substances that have formed naturally from man-made materials *are* considered to be minerals. An interesting case in point concerns a group of lead oxychloride minerals from Laurium, a town on the Greek coast some miles south of Athens. During the fourth and fifth centuries B.C. lead-bearing minerals were mined and smelted at Laurium and the slag dumped into the sea. These slags were reworked during the nineteenth century, and beautiful crystals of lead oxychlorides were found in cavities in the slag, evidently formed by the long-continued action of sea water on the lead compounds therein. The compounds in the slag itself are not considered to be minerals, but these lead oxychlorides are.

A mineral is a *homogeneous solid*, that is to say, it consists of a single solid phase—one kind of material only, which cannot be separated into simpler compounds by any physical method. The requirement that a mineral be solid eliminates liquids and gases from consideration. This may seem rather arbitrary; ice is a mineral (a very common one, especially at high altitudes) but water is not. Some mineralogists dispute this restriction and would include water (and native mercury, which is sometimes found associated with cinnabar) as a mineral.

The restriction of minerals to *inorganically formed* substances eliminates those homogeneous solids produced by animals and plants. Thus the shell of an oyster (and the pearl inside), though consisting of calcium carbonate indistinguishable chemically or physically from the mineral aragonite, is not usually considered to be a mineral. The human body, unfortunately, sometimes produces homogeneous solids in the form of stones in certain internal organs. These stones are often identical in all respects to natural minerals, but are not classified as minerals (although the Riksmuseum in Stockholm has on display in its mineral gallery the gallstone of a famous Swedish admiral of the seventeenth century). On the other hand, the restriction of "inorganically formed" does not eliminate the possibility of organic compounds being minerals. A few such substances (solid hydrocarbons, calcium oxalates, and other compounds) have been found in peat and coal, and distilled from the products of natural combustion.

The requirement of a *definite chemical composition* implies that a mineral is a chemical compound, and chemical compounds have a definite composition which is readily expressable by a formula. Mineral formulas may be simple or complex, depending upon the number of elements present and the proportions in which they are combined. It is important to distinguish between a *definite* and a *fixed* chemical composition; many minerals vary in composition (i.e., the composition is not fixed), but this variation is within definite limits.

An *ordered atomic arrangement* is the criterion of the crystalline state; another way of expressing this is to say that minerals are crystalline solids. Under favorable conditions of formation the ordered atomic arrangement may be expressed in the external crystal form—in fact, the presence of an ordered atomic arrangement in crystalline solids was deduced from the external regularity of crystals long before *x*-rays provided the means of demonstrating it. There are, however, a few exceptions to this requirement. Some minerals are *metamict;* when they were formed they had an ordered atomic arrangement which has since been partly or completely destroyed by radiation from uranium or thorium. A few minerals, the commonest being opal, are formed by the solidification of a colloidal gel and are noncrystalline initially; many such minerals become crystalline during geologic time.

The History of Mineralogy

The origins of mineralogy lie far back in prehistory. Long before the art of writing was developed men recognized natural pigments such as hematite (red) and manganese oxides (black) and used them in their cave paintings. Stone Age Man was well aware that the hardness and toughness of fibrous actinolite (nephrite jade) made it a superior material for adzes, and the distribution of nephrite tools indicates that a lively trade must have developed in this material, since these tools are found in places far removed from any possible source of the raw material. The mining and smelting of metallic minerals to produce iron, copper, bronze, lead, and silver probably dates back 4,000 years or more, although we have no written records to verify this.

One of the earliest writings on minerals was the book *On Stones* by Greek philosopher Theophrastus (*ca.* 372–287 B.C.). Pliny, in the first century A.D., recorded a great deal of natural history as it was understood by the Romans, and described a number of minerals that were mined as gemstones, as pigments, or as metallic ores. Little is known of developments during the next millennium, but the Renaissance in Europe brought with it an upswing of interest in science and technology. The classic works on minerals from this period were written by a German mining expert, Agricola, who published *De Re Metallica* (1556), and *De Natura Fossilium* (1546), in which he recorded the state of geology, mineralogy, mining, and metallurgy at that time. These works have been translated into English and are available in many libraries. After Agricola the next step in the development of mineralogy was provided by the Dane Niels Stensen (better known by the Latinized version of his name—Nicolaus Steno) who in 1669 showed that the interfacial angles of quartz crystals were constant, no matter what the shape and size of the crystals. He thereby drew attention to the significance of crystal form, which was to lead to the development of the whole science of crystallography.

Throughout the eighteenth century slow but steady progress in mineralogy was recorded. New minerals were recognized and described, and various attempts were made to achieve a rational classification of them. Most of the active workers in this endeavor were in Sweden and Germany, and the greatest teacher of the time was A. G. Werner (1750–1817), Professor at the Mining Academy in Freiberg, who attracted students from all parts of Europe. At this time mineralogy and chemistry were closely linked, since the chemists of the day worked largely with minerals as their raw materials. This resulted in the recognition of many new elements—cobalt, nickel, manganese, tungsten, molybdenum, uranium, and others. The significance of crystallography in the study of minerals was brought out largely by the work of the French scientist Haüy (1743–1822).

The early years of the nineteenth century saw rapid advances in mineralogy, following the enunciation of the atomic theory and the realization that minerals were chemical compounds with a definite composition. The invention of the reflecting goniometer also provided the means for much more precise measurements on crystals and an acceptable classification of crystal forms and crystal systems. The Swedish chemist Berzelius (1779–1848) and his pupils, especially Mitscherlich (1794–1863), studied the chemistry of minerals and enunciated the principles of their chemical classification.

Throughout the nineteenth century many new minerals were discovered and described, often as a result of the opening up of new mining districts in previously unexplored territories. The development of the polarizing microscope, and its application to the determination of the optical properties of minerals from about 1870 on, placed a new and powerful tool in the hands of the mineralogist.

The greatest development within the present century has been the demonstration by von Laue in 1912 that crystals diffract *x*-rays and that the diffraction patterns can be interpreted to give the actual positions of the atoms in the crystal. The mineralogist, previously limited to examining the external form and optical properties of his minerals, and to determining their chemical composition, could now proceed to investigate their internal structure. Since 1912 the structures of hundreds of minerals have been determined, but many still remain to be analyzed. In addition, improvements in technique have made it possible to detect extremely subtle differences between similar crystal structures. This whole field of research continues to be an exceedingly active branch of mineralogy.

The Literature of Mineralogy

The basic literature of mineralogy consists of individual papers describing original researches on minerals and published in scientific journals all over the world. The most important journals in the English-speaking countries are the *American Mineralogist*, published by the Mineralogical Society of America, and the *Mineralogical Magazine*, published by the Mineralogical Society in Great Britain. The latter society has also been responsible for a journal devoted to the abstracting of mineralogical papers wherever they appear; this journal, *Mineralogical Abstracts*, is now being expanded in its size and scope through the cooperative efforts of mineralogical societies in several countries. Another important journal of abstracts is the *Zentralblatt für Mineralogie*, published in Germany. *Chemical Abstracts*, published by the American Chemical Society, carries a section entitled "Mineralogical and Geological Chemistry."

A standard reference work in mineralogy has long been *Dana's System of Mineralogy*. The first edition of this book was written by J. D. Dana and published in 1837, and it aimed at a complete account of all minerals described up to that time. It was revised and brought up to date by successive editions in 1844, 1850, 1854, 1868, and 1892, and by supplements issued at intervals between each edition. Three supplements to the sixth edition (1892) have been published, in 1899, in 1909, and in 1915. Some years ago the colossal task of preparing a seventh edition was begun. It is now no longer possible to publish such a comprehensive work in one volume, and the seventh edition is appearing in three volumes, of which two have been published, in 1944 and in 1951; the third volume, dealing with the silicate minerals, has not yet appeared.

Two very comprehensive treatises on mineralogy, both in German, have been published. In some respects these are more detailed than *Dana's System of Mineralogy*. One is *Handbuch der Mineral-chemie*, by C. Doelter and co-workers, published 1911–1931. The other is *Handbuch der Mineralogie*, begun by C. Hintze and carried on after his death by other workers; the first volume appeared in 1897, the last in 1933, and supplementary parts covering new minerals and new data on previously described minerals are published from time to time.

The Importance of Minerals

From earliest times man has found important uses for minerals, and these uses have expanded tremendously with the expansion of science and industry. At first minerals were used as they were found: clay for bricks and pottery; flint, quartz, and jade for weapons or implements; oxides of iron and manganese as paints; turquois, garnet, amethyst, and other colored stones for ornaments;