

INTRODUCTION TO THE MINERALOGICAL SCIENCES

Peter Tropper

University of Innsbruck, Austria

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Summary

During the last 200 years, the scope of mineralogy has changed considerably from a merely descriptive discipline to a highly innovative field of science by incorporating ideas, techniques, and aspects of many contiguous areas such as physics, chemistry, material science, biology, archeology, and medicine. Modern mineralogy seeks to understand the links among mineral structure, properties, and processes in a range of potentially technologically useful solids. The constant requirement of human societies for new materials—ranging from building materials to pharmaceuticals—acted as a driving force for the diversity of mineralogical research and finally led to the innovations of the mineralogical sciences permeating many aspects of our daily life.

1. Introduction to Minerals and Mineralogy

1.1. Why Do We Study Minerals?

Undoubtedly, minerals are the fundamental elements of all rocks and consequently of Earth and other planets. The study of minerals and rocks provides the basis for the

understanding of geological processes, and therefore about the formation and evolution of Earth and other planetary bodies. The study of mineralogy not only increases our knowledge about Earth's history, it also provides invaluable information about Earth materials which are economically significant and thus are important to any modern industrial society. But before we step into specific aspects of the mineralogical sciences, we have to look at some basic principles of mineralogy, such as: what is a mineral?

1.2. Definition of a Mineral

A mineral is by definition a naturally occurring homogeneous solid with a definite, but not fixed, chemical composition and a highly ordered atomic arrangement. It may be formed by inorganic as well as organic processes. This means that synthetic compounds not known in nature cannot be called minerals or have mineral names in a strict sense. Most minerals are found on the surface of the Earth. However minerals may occur elsewhere, such as deep in Earth or in other planets, as long as a natural sample exists to describe.

This definition also states that in terms of homogeneity, minerals are chemically and physically homogeneous down to the atomic scale, to the smallest basic repeat unit of their structure. The term “definite composition” indicates that atoms or groups of atoms must occur in specific ratios in minerals, but this composition may vary within the mineral expressed by mineral solid solutions, for example, chemical zoning. The highly ordered arrangement indicates that a mineral is in a crystalline state. As per the definition, crystalline materials are three-dimensional periodic arrays which show a precise geometric arrangement of their atoms.

1.3. Naming of Minerals

Minerals are most commonly classified, on the basis of the presence of a major chemical component or anion complex, into chemical groups such as silicates, oxides, sulfides, carbonates, and phosphates. However, the naming of individual minerals is not based on such a logical scheme and therefore may cause a lot of confusion. There are many possibilities to name minerals: minerals may be named on the basis of some physical property or chemical aspect, they may also be named after a locality, a public figure, a mineralogist, or almost any other subject considered appropriate. An international committee—the Commission on New Minerals and Mineral Names of the International Mineralogical Association (IMA)—now reviews all mineral descriptions and judges the appropriateness of new mineral names as well as the scientific characterization of newly discovered minerals.

1.4. The Physical Properties of Minerals

The physical properties of minerals are the direct result of their chemical and structural characteristics. There are a few diagnostic properties that have been very important for the early mineralogists and miners, who had to recognize minerals with hardly any testing equipment. These diagnostic features are still useful today for the rapid recognition of a mineral:

- *Crystal form and habit*: The relationship of the crystal faces on the surface of minerals reflects the internal symmetry of the crystal structure. The crystal form consists therefore of a group of crystal faces, and the crystal habit denotes the external shape of a crystal.
- *Color and streak*: Color results from the absorption of certain wavelengths of light when passing through the crystal. The streak results from scratching a mineral on a ceramic tile. The color of the streak can be markedly different from the color of the mineral.
- *Hardness*: This property is usually tested by establishing which standard minerals are able to scratch the mineral in question. In 1812, Friedrich Mohs developed a standard scale from 1 to 10. The minerals of this scale are (in order from hardness 1 to 10): talc, gypsum, calcite, fluorite, apatite, feldspar, quartz, topaz, corundum, and diamond.
- *Tenacity*: This is the ability of a mineral to deform plastically under stress. Minerals may be brittle and not deform, or they may be ductile and deform readily.
- *Density*: This physical property is measured in grams per cubic centimeter (g cm^{-3}). Most silicates of light elements have densities in the range of 2.6 to 3.5 g cm^{-3} . Sulfides have typically 5 to 6 g cm^{-3} . Native metals range from 8 (iron) to 22 (osmium) g cm^{-3} .
- *Luster and transparency*: The way a mineral transmits or reflects light is also a diagnostic property. The transparency (ability for light to pass through a mineral) may be opaque, translucent, or transparent. The reflectance property is called “luster” and may be measured in a reflected light microscope.
- *Cleavage, fracture, and parting*: Because bonding is not of equal strength in all directions in most crystals, they will tend to break along certain directions. This gives them a fracture property that reflects the underlying structure and is frequently diagnostic.
- *Unique and other properties*: These properties include taste, magnetic properties, radioactivity, optical properties, electrical conductivity, chemical reactivity, and many more. The determination of the optical properties of minerals under the microscope became one of the most important mineral identification methods in the Earth sciences.

1.5. Classification of Minerals

Minerals are chemically divided into classes depending on the dominant anion or anionic group. The most common classifications are based on the classification of Dana's System of Mineralogy and the Mineralogische Tabellen of H. Strunz (1944). Dana's first edition of *A System of Mineralogy* in 1837 contained 352 minerals. Today more than 4000 naturally occurring minerals are known. Each year approximately 50 to 60 minerals are newly discovered.

The most important groups are:

1. *Native elements*: Approximately 20 elements occur in the native (pure) state in nature. These elements can be divided into 1) metals, 2) semimetals, and 3) nonmetals. The most fundamental group of minerals is native metals. Copper (Cu),

iron (Fe), gold (Au), platinum (Pt), and a few other metals can occur naturally as pure metals. Arsenic (As) and bismuth (Bi) occur as semimetals, and sulfur (S) and carbon (C)—which occurs either as graphite or as diamond—are nonmetals. These naturally occurring elements are called “native.” Apart from graphite they are extremely rare.

2. *Sulfides*: These are minerals in which a positively charged metal ion (called a “cation”) such as iron (Fe^{2+}), zinc (Zn^{2+}), or lead (Pb^{2+}) is bound to one or more negatively charged sulfur (S^{2-}) ions (called “anion”). Common examples are pyrite (FeS_2), sphalerite (ZnS), and galena (PbS). Many important metallic elements like cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), or molybdenum (Mo) naturally occur mainly as sulfides.
3. *Oxides*: In these minerals, oxygen (O^{2-}) is the anion. Examples are hematite (Fe_2O_3), magnetite (Fe_3O_4), rutile (TiO_2), corundum (Al_2O_3), spinel (MgAl_2O_4), and quartz (SiO_2). Important metals like tin, titanium, and chromium are mined from deposits of their respective oxide minerals.
4. *Hydroxides*: These minerals contain (OH^-) as the dominant polyanionic species. Examples are brucite, $\text{Mg}(\text{OH})_2$ and gibbsite, $\text{Al}(\text{OH})_3$.
5. *Halides*: These minerals include the halogen elements (F⁻, Cl⁻, Br⁻, I⁻) as the dominant anions and the alkali and alkaline Earth elements (Na^+ , K^+ , Ca^{2+}) as cations. Examples are rock salt (halite, NaCl) and fluorite (CaF_2).
6. *Carbonates*: In these minerals, a metal cation is bound to a carbonate (CO_3^{2-}) polyanion. The most common examples are calcite (CaCO_3), siderite (FeCO_3) and dolomite ($\text{CaMg}(\text{CO}_3)_2$).
7. *Sulfates*: In these minerals, a metal cation is bound to a sulfate (SO_4^{2-}) polyanion. A familiar example is gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). Most sulfates are highly soluble and occur mainly in dry climates as sedimentary minerals.
8. *Tungstates*: In these minerals, a metal cation is bound to a tungsten (WO_4^{2-}) polyanion. An example is scheelite (CaWO_4).
9. *Phosphates*: These minerals contain the (PO_4^{3-}) group as dominant polyanion. A common example is apatite ($\text{Ca}_5(\text{PO}_4)_3\text{OH}$), which is also a constituent of bones and teeth.
10. *Silicates*: This group of minerals contains (SiO_4^{4-}) as the dominant polyanion. In these minerals, Si is always surrounded by four oxygens—in the form of a tetrahedron (Figure 1). Because Si and O are the most abundant elements in Earth’s crust, this is the largest group of minerals. Many of these minerals are so abundant, that they are called “rock-forming” minerals. The most common examples are quartz (SiO_2) and feldspar ($(\text{Na,K})\text{AlSi}_3\text{O}_8$).

Additional standard mineralogical reference works listed in the Bibliography include texts on the compilation of all naturally occurring minerals and the rock-forming silicate minerals. Also of importance is the journal *Reviews in Mineralogy* (1974–recent) published by the American Mineralogical Society.

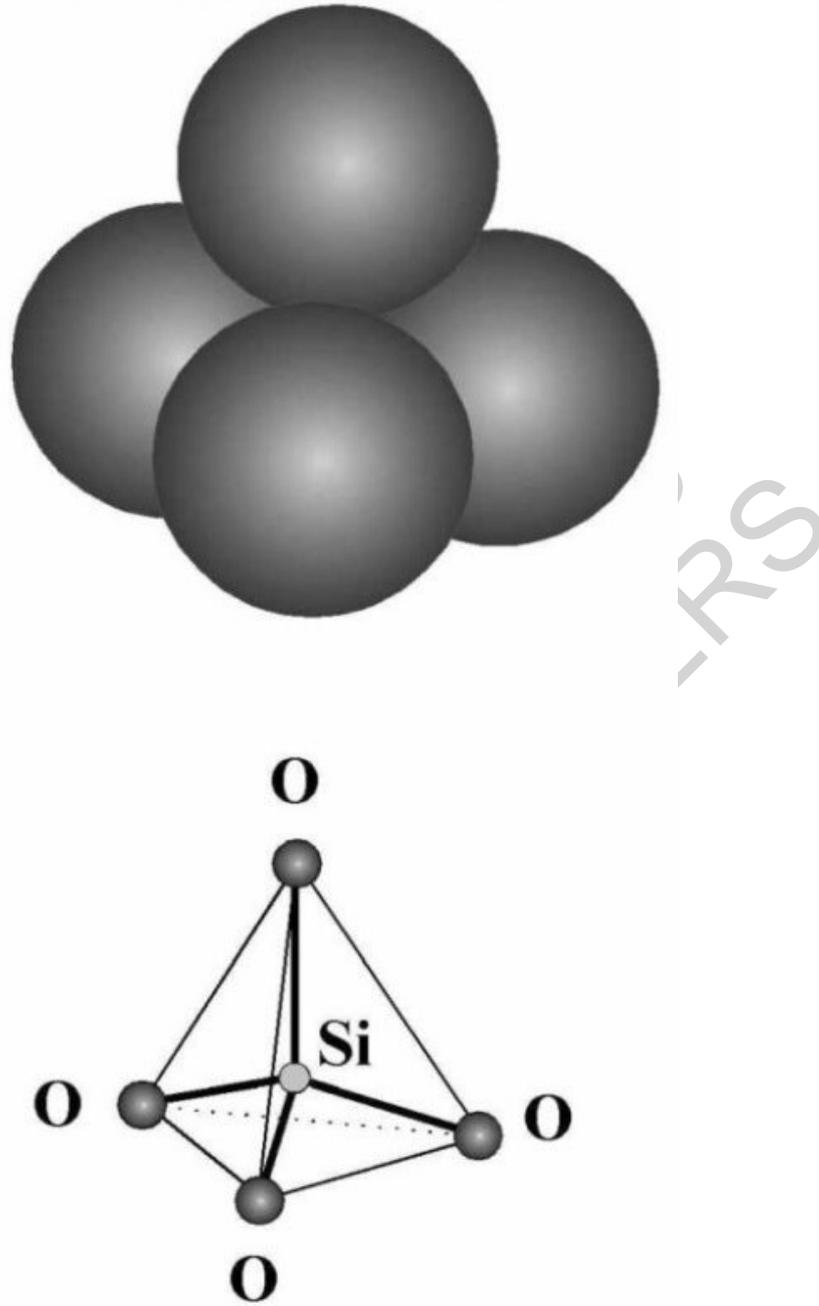


Figure 1. The SiO_4 tetrahedron. The upper image shows an actual image of tetrahedron. Since oxygen (1.38 \AA) has a larger atomic radius than silicon (0.26 \AA), the silicon atom will completely disappear in the middle of the tetrahedron. The lower image shows a schematic ball-and-stick model of the SiO_4 tetrahedron.

1.6. Mineral Occurrences and Environments

Many minerals are characteristic for certain geologic environments or processes, so they can also be classified after the most important geological environments into the following groups:

- *Igneous minerals*: These minerals must have high melting points and be crystallized from silicate melts at temperatures above 800 °C. They are found in solidified magma bodies (such as granites) and dikes and veins (such as pegmatites) within the Earth, or are brought to Earth's surface through volcanic eruptions, and therefore found in volcanic rocks. Typical volcanic minerals found at Hawaii or Mount Vesuvius are augite (pyroxene), leucite (feldspathoid), or tridymite, a high-temperature modification of quartz. Mineral deposits of chromium (Cr), tin (Sn), and copper (Cu), as well as of gemstones such as diamond or aquamarine (beryl) are typical results of igneous activity.
- *Metamorphic minerals*: Minerals in metamorphic rocks have crystallized from other, older minerals rather than from melts. The process where rocks are subjected to high pressures and temperatures, which finally leads to this recrystallization, is called "metamorphism." Metamorphism usually occurs because of geodynamic processes. The most important geodynamic process takes place when continental and oceanic plates on Earth's surface disintegrate or collide to form a mountain chain such as the Alps, the Rocky Mountains, or the Appalachian Mountains. This process is also called an "orogeny." Typical metamorphic minerals are the silicate minerals hornblende, serpentine, and garnet; pure elements such as graphite (which sometimes occurs as diamond); and the oxides ruby (Al_2O_3) and rutile (TiO_2).
- *Sedimentary minerals*: At the Earth's surface erosion takes place because of precipitation, temperature changes, and winds, which leads to the disintegration of rocks. The minerals become separated out of the rocks and are transported and finally deposited as sediments. Sedimentary minerals are usually very insoluble and therefore very resistant. Typical minerals are quartz and feldspar which are deposited in a rock called "sandstone." Minerals can also be partly or fully dissolved in surface waters, and other minerals (such as gypsum and rock salt deposits) may precipitate again under different conditions of temperature or pressure. Sedimentary minerals in a narrow sense are not those only just displaced by wind and water, but also those newly formed by precipitation in lakes and oceans. Many people also consider biogenic minerals as sedimentary minerals.
- *Hydrothermal minerals*: These minerals precipitate from hot aqueous solutions most commonly associated with the emplacement of igneous rocks and volcanic activity, and often form valuable metal deposits. Typical minerals include native elements like gold (Au) and silver (Ag), quartz, calcite, and sulfides.
- *Biogenic minerals*: Microorganisms can induce the precipitation of minerals from a fluid (water, cell plasma) to form skeletal structures. This process is called "microbial biomineralization." It may occur as a consequence of cell metabolism, and may lead to the formation of sedimentary rocks like clays, carbonates (for example, in reefs), and cherts.

2. Introduction to the Mineralogical Sciences

2.1. What is Mineralogy?

Mineralogy, which started out as a mostly descriptive discipline (see Section 1.4), has become an interdisciplinary natural science which combines aspects of physics, chemistry, and geology. Mineralogists try to understand the properties and formation of naturally and synthetically formed minerals and materials. Of particular interest are the physical properties, chemical composition, crystal structure, occurrence, and distribution of minerals, as well as the physical and chemical processes leading to the formation and destruction of minerals in nature. The objects studied by mineralogists include materials originating not only from Earth, but also from other planetary bodies such as the moon, the planets, and interstellar materials such as meteorites and cosmic dust. In addition to these natural products, mineralogists are looking increasingly into synthetic and technological materials that display similar properties to those observed in natural minerals.

Important fields of mineralogy dealing with synthetic compounds are experimental mineralogy and petrology and applied, often called “technical,” mineralogy. Both fields investigate the synthesis conditions and the stability of chemical compounds under physical conditions other than on Earth’s surface, such as high pressures and high temperatures. Whereas experimental mineralogy/petrology investigates all aspects of minerals under varying pressure and temperature conditions, applied mineralogy investigates chemical compounds that are relevant for industrial use, with the aim of tailoring the properties of these materials to achieve a maximum performance in industrial processes. Increasingly, mineralogists are also concerned with the care and conservation of archeological materials.

2.2. Historical Background of the Mineralogical Sciences

The history of mineralogy is as old as humankind. Special stones and gems were associated for example with magic and sacral meanings from prehistoric times on. The blue mineral *lapis lazuli* was greatly appreciated and sought after from Neolithic times onwards, as findings from Pakistan from 7000 BC show. Additional findings from the Middle East from Mesopotamia (Iran, Iraq) give evidence for a local gem industry, since cut pieces of lapis lazuli, turquoise, amethyst, and beryl were found. Very old evidence also comes from China, where pieces of *jade* were the most appreciated minerals, also from Neolithic times onwards.

The association of gems with magical virtues led people to consider gems in a manner that can be said to be absolutely scientific in line with the mental development of the age. This led to writings that are called “lapidaries” today. These lapidaries are works that deal with stones and their manifold properties. These texts did not at first come into being as well-defined works, but rather as collections of vague notions encountered especially in the poetry of India and Greece. The earliest known literature is the Indian *Vedas*, which dates from about 1100 BC. We are indebted to the Greek philosopher Theophrastus (372–287 BC) for the first written work on minerals, and to Pliny the elder (23–79 AD), who 400 years later recorded the mineralogical ideas of his time. The

topics of these lapidaries range from the magic and supernatural virtues of stones to their properties and their prices in the markets.

In the middle ages, most of the knowledge about gems came from the Arabic world, but minerals were still considered in an alchemistic context. If one were to select a single event signaling the emergence of mineralogy as a science, it would be the publication of *De Re Metallica* in 1556 by the German physician Georgius Agricola (1494–1555). This publication summarizes the mining practices and metallurgy technologies of this time. Another book, which also summarized the current knowledge about the mining technologies at that time is the *Schwazer Bergbuch* from Schwaz in Tyrol, which was also published in 1556.

From the seventeenth century onwards, mineralogists started to describe the outer shapes of crystals, and thus crystallography became the oldest branch of modern mineralogy. Technical developments in the seventeenth and eighteenth century led to the application of scientific instruments to crystallographic investigations (1780: contact goniometer to measure interfacial crystal angles) as well as analytical techniques to mineral analysis (1760: blowpipe analysis). In 1784, Rene J. Haüy (1743–1822) showed that crystals were built by stacking together tiny identical building blocks. In the early nineteenth century further technical advances led to the invention of the reflecting goniometer in 1809 by Wollaston (1766–1828). This provided highly accurate measurements on crystals and led to the development of crystallography as an exact science. During this time, a Swedish chemist named Berzelius (1779–1848) laid the foundation for the chemical classification of minerals. From 1830 onwards, the optical properties of minerals were studied with the polarization microscope, invented by Sorby (1826–1908). In the later part of the nineteenth century, Fedorov (1853–1919), Schönflies (1853–1928), and Barlow (1776–1862) developed theories for internal symmetry and order within crystals.

The most far-reaching discovery of the twentieth century was made by Max von Laue (1879–1960), Walter Friedrich (1883–1968), and Paul Knipping (1883–1935), showing that crystals could diffract X-rays—thus providing information about their atomic structure. In 1914, W. H. Bragg (1862–1942) and W. L. Bragg (1890–1971) performed the first crystal structure determinations. The advent of the “electron microprobe” in the early 1960s was a giant leap towards the *in situ* chemical analysis of minerals. In the 1970s the development of another electron beam instrument, the “transmission electron microscope,” allowed the magnification of the internal structure of minerals many millions of times, thus producing visual images of atomic structures. The mineralogical sciences were very aware of new analytical methods developed by physicists during the last years. These methods make use of high-energy sources other than X-rays, namely neutrons, electrons, and synchrotron radiation. The application of lasers led to the study of minerals with infrared (IR) and Raman spectroscopy.

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Biographical Sketch

Peter Tropper was born in 1968. He received his M.Sc. from the University of Graz, Austria (1986–1993) and a Ph.D. in Geology from the University of Michigan, USA (1993–1998). After a period in the civil service (1998–1999) he has been at the Institute of Mineralogy and Petrography at the University of Innsbruck.

His primary research interest is to combine field-oriented methods of petrology and structural geology of metamorphic rocks with experimental investigations on natural as well as synthetic phases. His research involves rocks from a wide range of metamorphic grades from the Eastern and Western Alps, ranging from rocks that underwent metamorphism under low P–T conditions to high P eclogite facies rocks and

high T rocks where partial melting already occurs. The experimental research interests thus involve 1) the investigation of the stability field of minerals in P–T–X space such as sodic amphiboles and titanites, 2) the change of their chemical compositions with P and T and its application to geothermobarometry, and 3) the extraction of thermodynamic data (a -X relations, ΔG_f) of rock-forming minerals.

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