Handbook of Mineralogy

Cory Bunn

Justice Bunker

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Mineralogy

Mineralogy is the study of chemistry, crystal structure, and physical (including optical) properties of minerals. Specific studies within mineralogy include the processes of mineral origin and formation, classification of minerals, their geographical distribution, as well as their utilization.

History

Early writing on mineralogy, especially on gemstones, comes from ancient Babylonia, the ancient Greco-Roman world, ancient and medieval China, and Sanskrit texts from ancient India and the ancient Islamic World. Books on the subject included the Naturalis Historia of Pliny the Elder, which not only described many different minerals but also explained many of their properties, and Kitab al Jawahir (Book of Precious Stones) by Muslim scientist Al Biruni. The German Renaissance specialist Georgius Agricola wrote works such as *De re metallica* (*On Metals*, 1556) and *De Natura Fossilium* (*On the Nature of Rocks*, 1546) which begin the scientific approach to the subject. Systematic scientific studies of minerals and rocks developed in post-Renaissance Europe. The modern study of mineralogy was founded on the principles of crystallography (the origins of geometric crystallography, itself, can be traced back to the mineralogy practiced in the eighteenth and nineteenth centuries) and to the microscopic study of rock sections with the invention of the microscope in the 17th century.

Modern mineralogy

Chalcocite, a copper ore mineral.

Historically, mineralogy was heavily concerned with taxonomy of the rock-forming minerals; to this end, the International Mineralogical Association is an organization whose members represent mineralogists in individual countries. Its activities include managing the naming of minerals (via the Commission of New Minerals and Mineral Names), location of known minerals, etc. As of 2004 there are over 4,000 species of mineral recognized by the IMA. Of these, perhaps 150 can be called "common," another 50 are "occasional," and the rest are "rare" to "extremely rare."

More recently, driven by advances in experimental technique (such as neutron diffraction) and available computational power, the latter of which has enabled extremely accurate atomic-scale simulations of the behaviour of crystals, the science has branched out to consider more general problems in the fields of inorganic chemistry and solid-state physics. It, however, retains a focus on the crystal structures commonly encountered in rock-forming minerals (such as the perovskites, clay minerals and framework silicates). In particular, the field has made great advances in the understanding of the relationship between the atomic-scale structure of minerals and their function; in nature, prominent examples would be accurate measurement and prediction of the elastic properties of minerals, which has led to new insight into seismological behaviour of rocks and depth-related discontinuities in seismograms of the Earth's mantle. To this end, in their focus on the connection between atomic-scale phenomena and macroscopic properties, the **mineral sciences** (as they are now commonly known) display perhaps more of an overlap with materials science than any other discipline.

Physical mineralogy

Physical mineralogy is the specific focus on physical attributes of minerals. Description of physical attributes is the simplest way to identify, classify, and categorize minerals, and they include:

- crystal structure
- crystal habit
- twinning
- cleavage
- luster
- color
- streak
- hardness
- specific gravity

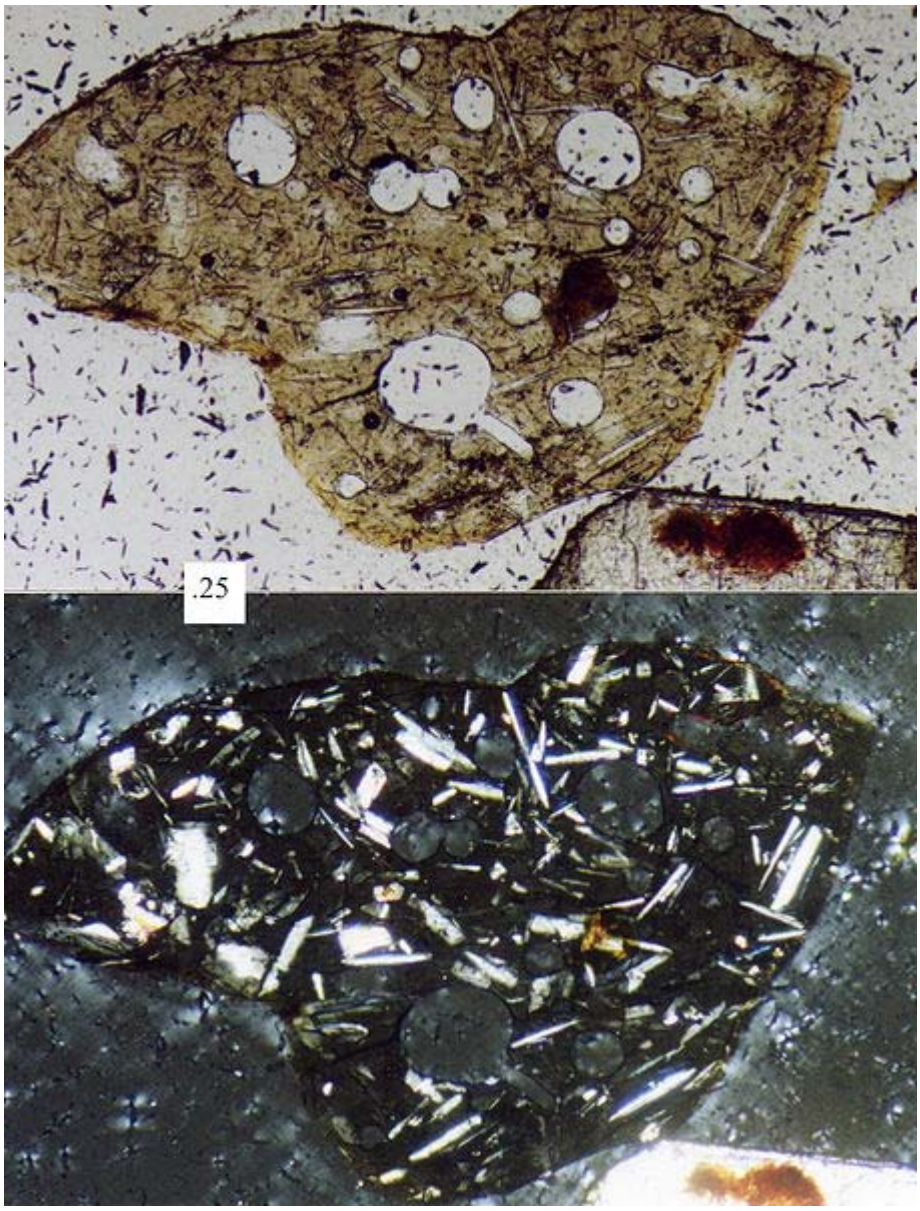
Chemical mineralogy

Chemical mineralogy focuses on the chemical composition of minerals in order to identify, classify, and categorize them, as well as a means to find beneficial uses from them. There are a few minerals which are classified as whole elements, including sulfur, copper, silver, and gold, yet the vast majority of minerals are chemical compounds, some more complex than others. In terms of major chemical divisions of minerals, most are placed within the isomorphous groups, which are based on analogous chemical composition and similar crystal forms. A good example of isomorphism classification would be the calcite group, containing the minerals calcite, magnesite, siderite, rhodochrosite, and smithsonite.

Biomineralogy

Biomineralogy is a cross-over field between mineralogy, paleontology and biology. It is the study of how plants and animals stabilize minerals under biological control, and the sequencing of mineral replacement of those minerals after deposition. It uses techniques from chemical mineralogy, especially isotopic studies, to determine such things as growth forms in living plants and animals as well as things like the original mineral content of fossils.

Optical mineralogy



Photomicrograph of a volcanic lithic fragment (sand grain); upper picture is plane-polarized light, bottom picture is cross-polarized light, scale box at left-center is 0.25 millimeter.

Optical mineralogy is a specific focus of mineralogy that applies sources of light as a means to identify and classify minerals. All minerals which are not part of the cubic system are double refracting, where ordinary light passing through them is broken up into two plane polarized rays that travel at different velocities and refracted at different angles. Mineral substances belonging to the cubic system pertain only one index of refraction. Hexagonal and tetragonal mineral substances have two indices, while orthorhombic, monoclinic, and triclinic substances have three indices of refraction. With opaque ore minerals, reflected light from a microscope is needed for identification.

Crystal structure

X-rays are used to determine the atomic arrangements of minerals and so to identify and classify them. The arrangements of atoms define the crystal structures of the minerals. Some very fine-grained minerals, such as clays, commonly can be identified most readily by their crystal structures. The structure of a mineral also offers a precise way of establishing isomorphism. With knowledge of atomic arrangements and compositions, one may deduce why minerals have specific physical properties , and one may calculate how those properties change with pressure and temperature.

Formation environments

The environments of mineral formation and growth are highly varied, ranging from slow crystallization at the high temperature and pressures of igneous melts deep within the Earth's crust to the low temperature precipitation from a saline brine at the Earth's surface.

Various possible methods of formation include:

- sublimation from volcanic gases
- deposition from aqueous solutions and hydrothermal brines
- crystallization from an igneous magma or lava
- recrystallization due to metamorphic processes and metasomatism
- crystallization during diagenesis of sediments
- formation by oxidation and weathering of rocks exposed to the atmosphere or within the soil environment.

Descriptive mineralogy

Descriptive mineralogy summarizes results of studies performed on mineral substances. It is the scholarly and scientific method of recording the identification, classification, and categorization of minerals, their properties, and their uses. Classifications for descriptive mineralogy includes:

- native elements
- sulfides
- oxides and hydroxides
- halides
- carbonates, nitrates and borates
- sulfates, chromates, molybdates and tungstates
- phosphates, arsenates and vanadates
- silicates
- organic minerals

Determinative mineralogy

Determinative mineralogy is the actual scientific process of identifying minerals, through data gathering and conclusion. When new minerals are discovered, a standard procedure of scientific analysis is followed, including measures to identify a mineral's formula, its crystallographic data, its optical data, as well as the general physical attributes determined and listed.

Uses

Minerals are essential to various needs within human society, such as minerals used as ores for essential components of metal products used in various commodities and machinery, essential components to building materials such as limestone, marble, granite, gravel, glass, plaster, cement, etc. Minerals are also used in fertilizers to enrich the growth of agricultural crops.

Collecting

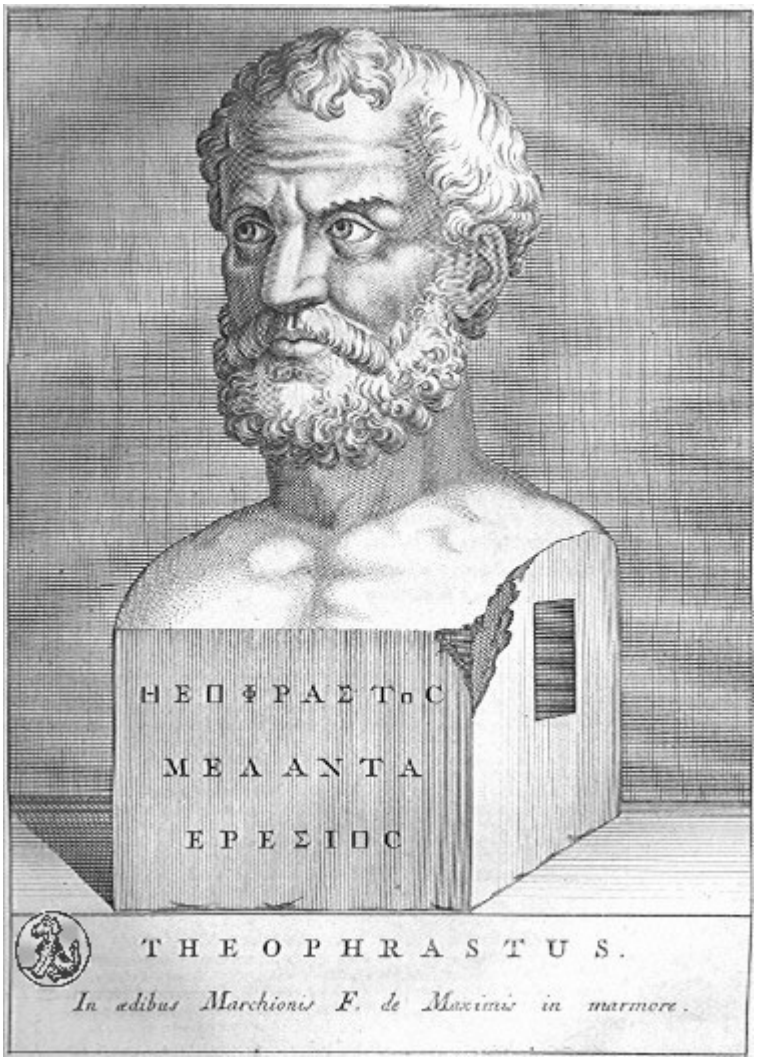
Mineral collecting is also a recreational study and collection hobby, with clubs and societies representing the field. Museums, such as the Smithsonian National Museum of Natural History Hall of Geology, Gems, and Minerals and the Natural History Museum of Los Angeles County, have popular collections of mineral specimens on permanent display.

Chapter-2

History of Mineralogy

Early writing on mineralogy, especially on gemstones, comes from ancient Babylonia, the ancient Greco-Roman world, ancient and medieval China, and Sanskrit texts from ancient India. Books on the subject included the Naturalis Historia of Pliny the Elder which not only described many different minerals but also explained many of their properties. The German Renaissance specialist Georgius Agricola wrote works such as *De re metallica* (*On Metals*, 1556) and *De Natura Fossilium* (*On the Nature of Rocks*, 1546) which begin the scientific approach to the subject. Systematic scientific studies of minerals and rocks developed in post-Renaissance Europe. The modern study of mineralogy was founded on the principles of crystallography and microscopic study of rock sections with the invention of the microscope in the 17th century.

Europe and the Middle East



Theophrastus

The ancient Greek writers Aristotle (384–322 BC) and Theophrastus (370-285 BC) were the first in the Western tradition to write of minerals and their properties, as well as metaphysical explanations for them. The Greek philosopher Aristotle wrote his *Meteorologica*, and in it theorized that all the known substances were composed of water, air, earth, and fire, with the properties of dryness, dampness, heat, and cold. The Greek philosopher and botanist Theophrastus wrote his *De Mineralibus*, which accepted Aristotle's view, and divided minerals into two categories: those affected by heat and those affected by dampness.

The metaphysical emanation and exhalation (*anathumiaseis*) theory of the Greek philosopher Aristotle included early speculation on earth sciences including mineralogy. According to his theory, while metals were supposed to be congealed by means of moist exhalation, dry gaseous exhalation (*pneumatodestera*) was the efficient material cause of

minerals found in the earth's soil. He postulated these ideas by using the examples of moisture on the surface of the earth (a moist vapor 'potentially like water'), while the other was from the earth itself, pertaining to the attributes of hot, dry, smoky, and highly combustible ('potentially like fire'). Aristotle's metaphysical theory from times of antiquity had wide-ranging influence on similar theory found in later medieval Europe, as the historian Berthelot notes:

The theory of exhalations was the point of departure for later ideas on the generation of metals in the earth, which we meet with Proclus, and which reigned throughout the middle ages.

Fibrous asbestos on muscovite

Ancient Greek terminology of minerals has also stuck through the ages with widespread usage in modern times. For example, the Greek word asbestos (meaning 'inextinguishable', or 'unquenchable'), for the unusual mineral known today containing

fibrous structure. The ancient historians Strabo (63 BC-19 AD) and Pliny the Elder (23-79 AD) both wrote of asbestos, its qualities, and its origins, with the Hellenistic belief that it was of a type of vegetable. Pliny the Elder listed it as a mineral common in India, while the historian Yu Huan (239-265 AD) of China listed this 'fireproof cloth' as a product of ancient Rome or Arabia (Chinese: Daqin). Although documentation of these minerals in ancient times does not fit the manner of modern scientific classification, there was nonetheless extensive written work on early mineralogy.

Pliny the Elder

octahedral shape of diamond.

Baltic amber necklace with trapped insects

For example, Pliny devoted 5 entire volumes of his work Naturalis Historia (77 AD) to the classification of "earths, metals, stones, and gems". He not only describes many minerals not known to Theophrastus, but discusses their applications and properties. He is the first to correctly recognise the origin of amber for example, as the fossilized remnant of tree resin from the observation of insects trapped in some samples. He laid the basis of crystallography by discussing crystal habit, especially the octahedral shape of diamond. His discussion of mining methods is unrivalled in the ancient world, and includes, for example, an eye-witness account of gold mining in northern Spain, an account which is fully confirmed by modern research.

However, before the more definitive foundational works on mineralogy in the 16th century, the ancients recognized no more than roughly 350 minerals to list and describe.

Jabir and Avicenna

With philosophers such as Proclus, the theory of Neoplatonism also spread to the Islamic world during the Middle Ages, providing a basis for metaphyiscal ideas on mineralogy in the medieval Middle East as well. The medieval Islamic scientists expanded upon this as well, including the Persian scientist Ibn Sina (ابوعلی سینا/پورسینا) (980-1037 AD), also known as *Avicenna*, who rejected alchemy and the earlier notion of Greek metaphysics that metallic and other elements could be transformed into one another. However, what was largely accurate of the ancient Greek and medieval metaphysical ideas on mineralogy was the slow chemical change in composition of the earth's crust. There was also the Islamic alchemist and scientist Jabir ibn Hayyan (721-815 AD), who was the first to bring the experimental method into alchemy. Aided by Greek mathematics and Islamic mathematics, he discovered the syntheses for hydrochloric acid, nitric acid, distillation and crystallization (the latter two being essential for the understanding of modern mineralogy).

Georgius Agricola, 'Father of Mineralogy'

Agricola, author of De re metallica

In the early 16th century AD, the writings of the German scientist Georg Bauer, pen-name Georgius Agricola (1494-1555 AD), in his *Bermannus, sive de re metallica dialogus* (1530) is considered to be the official establishment of mineralogy in the modern sense of its study. He wrote the treatise while working as a town physician and making observations in Joachimsthal, which was then a center for mining and metallurgic smelting industries. In 1544, he published his written work *De ortu et causis subterraneorum*, which is considered to be the foundational work of modern physical geology. In it (much like Ibn Sina) he heavily criticized the theories laid out by the ancient Greeks such as Aristotle. His work on mineralogy and metallurgy continued with the publication of *De veteribus et novis metallis* in 1546, and culminated in his best known works, the *De re metallica* of 1556. It was an impressive work outlining applications of mining, refining, and smelting metals, alongside discussions on geology of ore bodies, surveying, mine construction, and ventilation. He praises Pliny the Elder for his pioneering work Naturalis Historia and makes extensive references to his discussion of minerals and mining methods. For the next two centuries this written work remained the authoritative text on mining in Europe.

Agricola had many various theories on mineralogy based on empirical observation, including understanding of the concept of ore channels that were formed by the circulation of ground waters ('succi') in fissures subsequent to the deposition of the surrounding rocks. As will be noted below, the medieval Chinese previously had conceptions of this as well.

For his works, Agricola is posthumously known as the "Father of Mineralogy".

After the foundational work written by Agricola, it is widely agreed by the scientific community that the *Gemmarum et Lapidum Historia* of Anselmus de Boodt (1550–1632) of Bruges is the first definitive work of modern mineralogy. The German mining chemist J.F. Henckel wrote his *Flora Saturnisans* of 1760, which was the first treatise in Europe to deal with geobotanical minerals, although the Chinese had mentioned this in earlier treatises of 1421 and 1664. In addition, the Chinese writer Du Wan made clear references to weathering and erosion processes in his *Yun Lin Shi Pu* of 1133, long before Agricola's work of 1546.

China and the Far East

In ancient China, the oldest literary listing of minerals dates back to at least the 4th century BC, with the *Ji Ni Zi* book listing twenty four of them. Chinese ideas of metaphysical mineralogy span back to at least the ancient Han Dynasty (202 BC-220 AD). From the 2nd century BC text of the *Huai Nan Zi*, the Chinese used ideological Taoist terms to describe meteorology, precipitation, different types of minerals, metallurgy, and alchemy. Although the understanding of these concepts in Han times was Taoist in nature, the theories proposed were similar to the Aristotelian theory of mineralogical exhalations (noted above). By 122 BC, the Chinese had thus formulated the theory for metamorphosis of minerals, although it is noted by historians such as Dubs that the tradition of alchemical-mineralogical Chinese doctrine stems back to the School of Naturalists headed by the philosopher Zou Yan (305 BC-240 BC). Within the broad categories of rocks and stones (shi) and metals and alloys (jin), by Han times the Chinese had hundreds (if not thousands) of listed types of stones and minerals, along with theories for how they were formed.

In the 5th century AD, Prince Qian Ping Wang of the Liu Song Dynasty wrote in the encyclopedia *Tai-ping Yu Lan* (circa 444 AD, from the lost book *Dian Shu*, or *Management of all Techniques*):

The most precious things in the world are stored in the innermost regions of all. For example, there is orpiment. After a thousand years it changes into realgar. After another thousand years the realgar becomes transformed into yellow gold.

In ancient and medieval China, mineralogy became firmly tied to empirical observations in pharmaceutics and medicine. For example, the famous horologist and mechanical engineer Su Song (1020-1101 AD) of the Song Dynasty (960-1279 AD) wrote of mineralogy and pharmacology in his *Ben Cao Tu Jing* of 1070. In it he created a

systematic approach to listing various different minerals and their use in medicinal concoctions, such as all the variously known forms of mica that could be used to cure various ills through digestion. Su Song also wrote of the subconchoidal fracture of native cinnabar, signs of ore beds, and provided description on crystal form. Similar to the ore channels formed by circulation of ground water mentioned above with the German scientist Agricola, Su Song made similar statements concerning copper carbonate, as did the earlier *Ri Hua Ben Cao* of 970 AD with copper sulfate.

The Yuan Dynasty scientist Zhang Si-xiao (died 1332 AD) provided a groundbreaking treatise on the conception of ore beds from the circulation of ground waters and rock fissures, two centuries before Georgius Agricola would come to similar conclusions. In his *Suo-Nan Wen Ji*, he applies this theory in describing the deposition of minerals by evaporation of (or precipitation from) ground waters in ore channels.

In addition to alchemical theory posed above, later Chinese writers such as the Ming Dynasty physician Li Shizhen (1518-1593 AD) wrote of mineralogy in similar terms of Aristotle's metaphysical theory, as the latter wrote in his pharmaceutical treatise *Běncǎo Gāngmù*. Another figure from the Ming era, the famous geographer Xu Xiake (1587–1641) wrote of mineral beds and mica schists in his treatise. However, while European literature on mineralogy became wide and varied, the writers of the Ming and Qing dynasties wrote little of the subject (even compared to Chinese of the earlier Song era). The only other works from these two eras worth mentioning were the *Shi Pin* (Hierarchy of Stones) of Yu Jun in 1617, the *Guai Shi Lu* (Strange Rocks) of Song Luo in 1665, and the *Guan Shi Lu* (On Looking at Stones) in 1668. However, one figure from the Song era that is worth mentioning above all is Shen Kuo.

Theories of Shen Kuo

Shen Kuo (1031-1095))

The medieval Chinese Song Dynasty statesman and scientist Shen Kuo (1031-1095 AD) wrote of his land formation theory involving concepts of mineralogy. In his *Meng Xi Bi Tan*, Shen formulated a hypothesis for the process of land formation (geomorphology); based on his observation of marine fossil shells in a geological stratum in the Taihang Mountains hundreds of miles from the Pacific Ocean. He inferred that the land was formed by erosion of the mountains and by deposition of silt, and described soil erosion, sedimentation and uplift. In an earlier work of his (circa 1080), he wrote of a curious fossil of a sea-orientated creature found far inland. It is also of interest to note that the contemporary author of the *Xi Chi Cong Yu* attributed the idea of particular places under the sea where serpents and crabs were petrified to one Wang Jinchen. With Shen Kuo's writing of the discovery of fossils, he formulated a hypothesis for the shifting of geographical climates throughout time. This was due to hundreds of petrified bamboos found underground in the dry climate of northern China, once an enormous landslide upon the bank of a river revealed them. Shen theorized that in pre-historic times, the

climate of Yanzhou must have been very rainy and humid like southern China, where bamboos are suitable to grow.

In a similar way, the historian Joseph Needham likened Shen's account with the Scottish scientist Roderick Murchison (1792–1871), who was inspired to become a geologist after observing a providential landslide. In addition, Shen's description of sedimentary deposition predated that of James Hutton, who wrote his groundbreaking work in 1802 (considered the foundation of modern geology). The influential philosopher Zhu Xi (1130–1200) wrote of this curious natural phenomena of fossils as well, and was known to have read the works of Shen Kuo. In comparison, the first mentioning of fossils found in the West was made nearly two centuries later with Louis IX of France in 1253 AD, who discovered fossils of marine animals (as recorded in Joinville's records of 1309 AD).

Chapter-3

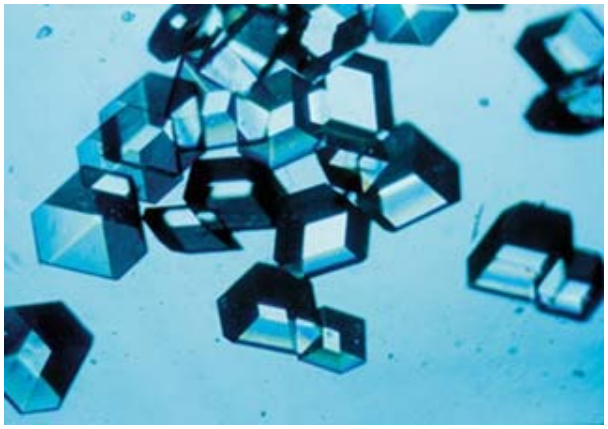
Physical Mineralogy

Physical mineralogy is the specific focus on physical attributes of minerals. Description of physical attributes is the simplest way to identify, classify, and categorize minerals, and they include:

Crystal Structure

In mineralogy and crystallography, **crystal structure** is a unique arrangement of atoms or molecules in a crystalline liquid or solid. A crystal structure is composed of a pattern, a set of atoms arranged in a particular way, and a lattice exhibiting long-range order and symmetry. Patterns are located upon the points of a lattice, which is an array of points repeating periodically in three dimensions. The points can be thought of as forming identical tiny boxes, called unit cells, that fill the space of the lattice. The lengths of the edges of a unit cell and the angles between them are called the *lattice parameters.* The symmetry properties of the crystal are embodied in its space group.

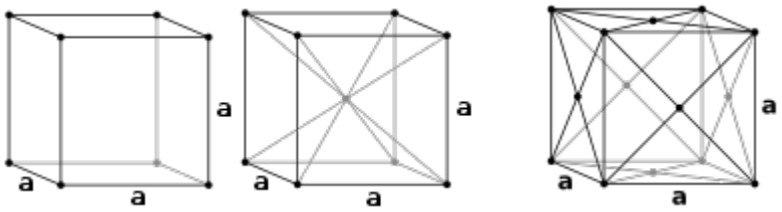
A crystal's structure and symmetry play a role in determining many of its physical properties, such as cleavage, electronic band structure, and optical transparency.



Insulin crystals.

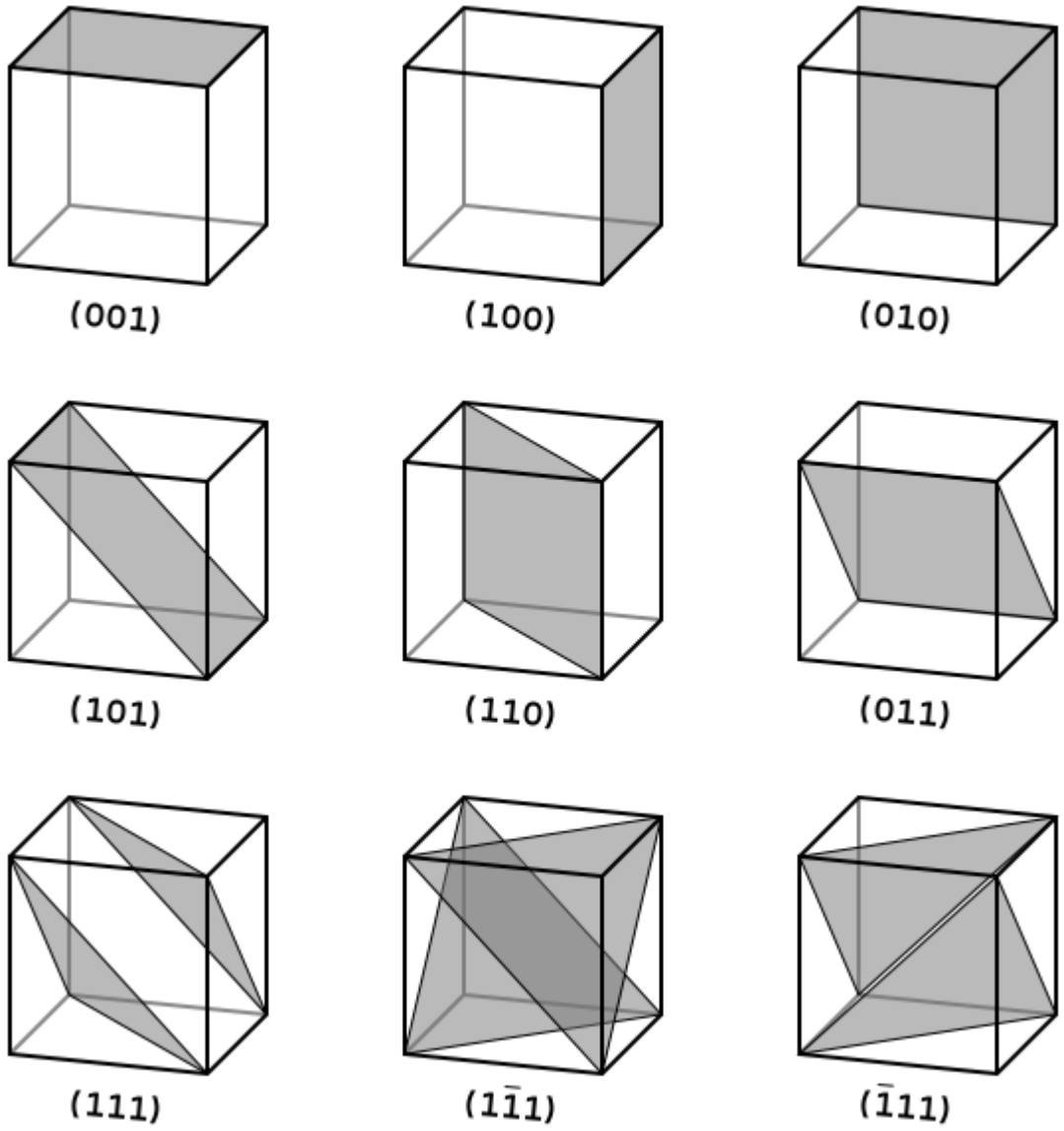
Unit cell

The crystal structure of a material or the arrangement of atoms within a given type of crystal structure can be described in terms of its unit cell. The unit cell is a tiny box containing one or more atoms, a spatial arrangement of atoms. The unit cells stacked in three-dimensional space describe the bulk arrangement of atoms of the crystal. The crystal structure has a three dimensional shape. The unit cell is given by its lattice parameters, the length of the cell edges and the angles between them, while the positions of the atoms inside the unit cell are described by the set of atomic positions (x_i, y_i, z_i) measured from a lattice point.



Simple cubic (P) Body-centered cubic (I)Face-centered cubic (F)

Miller indices



Planes with different Miller indices in cubic crystals

Vectors and atomic planes in a crystal lattice can be described by a three-value Miller index notation (ℓmn). The ℓ, m and n directional indices are separated by 90°, and are thus orthogonal. In fact, the ℓ component is mutually perpendicular to the m and n indices.

By definition, (ℓmn) denotes a plane that intercepts the three points a_1/ℓ, a_2/m, and a_3/n, or some multiple thereof. That is, the Miller indices are proportional to the *inverses* of the intercepts of the plane with the unit cell (in the basis of the lattice vectors). If one or more

of the indices is zero, it simply means that the planes do not intersect that axis (i.e. the intercept is "at infinity").

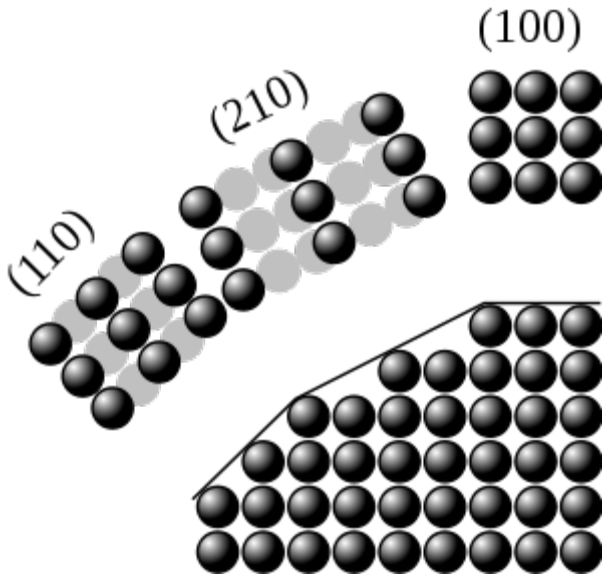
Considering only (ℓmn) planes intersecting one or more lattice points (the *lattice planes*), the perpendicular distance *d* between adjacent lattice planes is related to the (shortest) reciprocal lattice vector orthogonal to the planes by the formula:

$$d = 2\pi / |\mathbf{g}_{\ell mn}|$$

Planes and directions

The crystallographic directions are fictitious lines linking nodes (atoms, ions or molecules) of a crystal. Similarly, the crystallographic planes are fictitious *planes* linking nodes. Some directions and planes have a higher density of nodes. These high density planes have an influence on the behavior of the crystal as follows:

- Optical properties: Refractive index is directly related to density (or periodic density fluctuations).
- Adsorption and reactivity: Physical adsorption and chemical reactions occur at or near surface atoms or molecules. These phenomena are thus sensitive to the density of nodes.
- Surface tension: The condensation of a material means that the atoms, ions or molecules are more stable if they are surrounded by other similar species. The surface tension of an interface thus varies according to the density on the surface.



Dense crystallographic planes

- Microstructural defects: Pores and crystallites tend to have straight grain boundaries following higher density planes.

- Cleavage: This typically occurs preferentially parallel to higher density planes.

- Plastic deformation: Dislocation glide occurs preferentially parallel to higher density planes. The perturbation carried by the dislocation (Burgers vector) is along a dense direction. The shift of one node in a more dense direction requires a lesser distortion of the crystal lattice.

In the rhombohedral, hexagonal, and tetragonal systems, the **basal plane** is the plane perpendicular to the principal axis.

Cubic structures

For the special case of simple cubic crystals, the lattice vectors are orthogonal and of equal length (usually denoted *a*); similarly for the reciprocal lattice. So, in this common case, the Miller indices (ℓmn) and [ℓmn] both simply denote normals/directions in Cartesian coordinates. For cubic crystals with lattice constant *a*, the spacing *d* between adjacent (ℓmn) lattice planes is (from above):

$$d_{\ell mn} = \frac{a}{\sqrt{\ell^2 + m^2 + n^2}}$$

Because of the symmetry of cubic crystals, it is possible to change the place and sign of the integers and have equivalent directions and planes:

- Coordinates in *angle brackets* such as <100> denote a *family* of directions which are equivalent due to symmetry operations, such as [100], [010], [001] or the negative of any of those directions.

- Coordinates in *curly brackets* or *braces* such as {100} denote a family of plane normals which are equivalent due to symmetry operations, much the way angle brackets denote a family of directions.

For face-centered cubic (fcc) and body-centered cubic (bcc) lattices, the primitive lattice vectors are not orthogonal. However, in these cases the Miller indices are conventionally defined relative to the lattice vectors of the cubic supercell and hence are again simply the Cartesian directions.

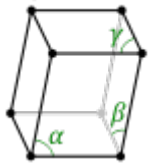
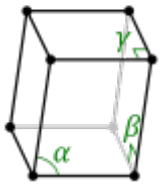
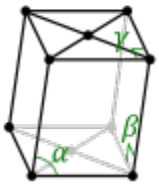
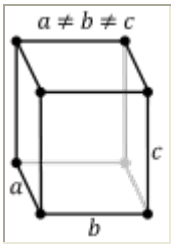
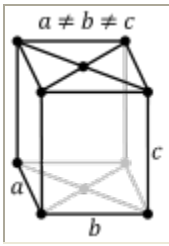
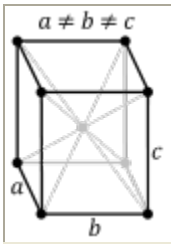
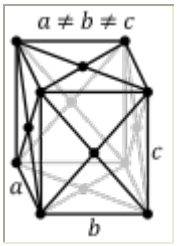
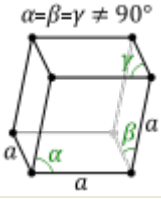
Classification

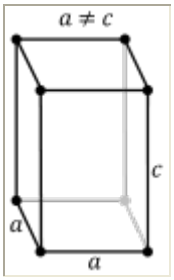
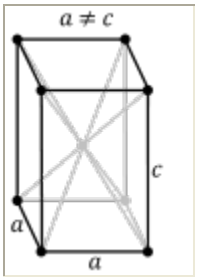
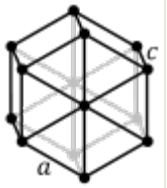
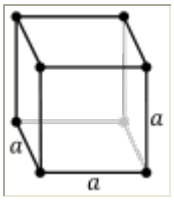
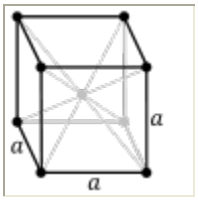
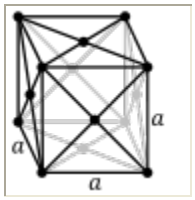
The defining property of a crystal is its inherent symmetry, by which we mean that under certain 'operations' the crystal remains unchanged. For example, rotating the crystal 180° about a certain axis may result in an atomic configuration which is identical to the original configuration. The crystal is then said to have a twofold rotational symmetry

about this axis. In addition to rotational symmetries like this, a crystal may have symmetries in the form of mirror planes and translational symmetries, and also the so-called "compound symmetries" which are a combination of translation and rotation/mirror symmetries. A full classification of a crystal is achieved when all of these inherent symmetries of the crystal are identified.

Lattice systems

These lattice systems are a grouping of crystal structures according to the axial system used to describe their lattice. Each lattice system consists of a set of three axes in a particular geometrical arrangement. There are seven lattice systems. They are similar to but not quite the same as the seven crystal systems and the six crystal families.

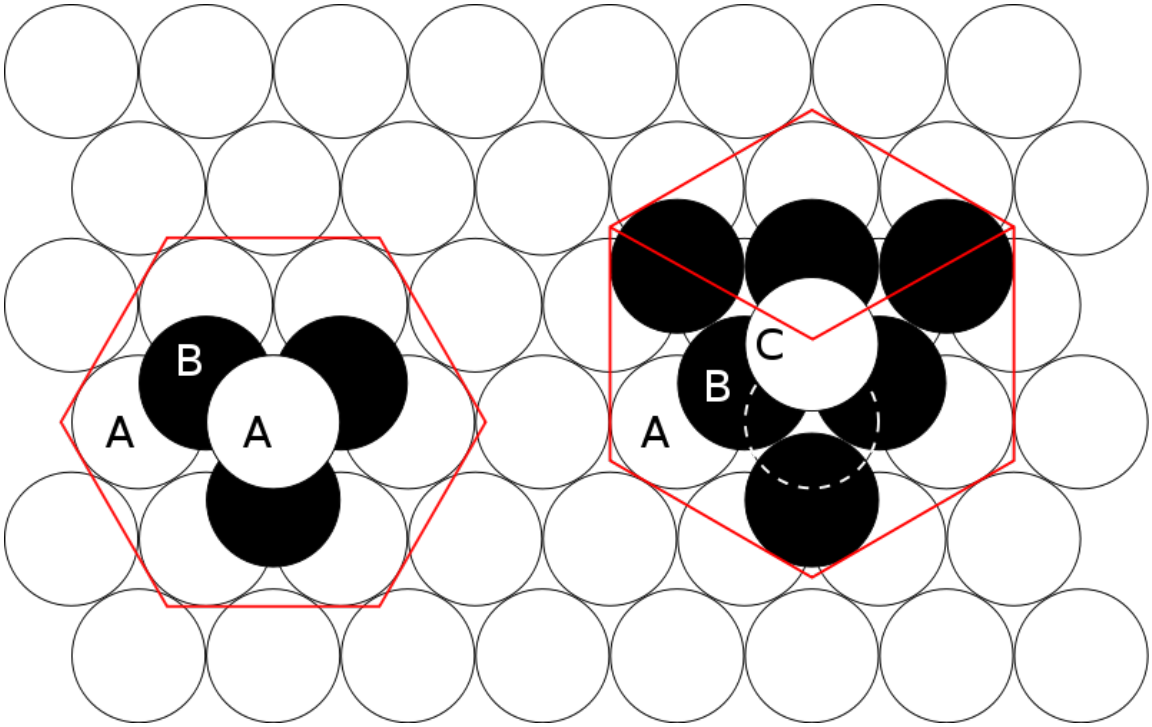
The 7 lattice systems (From least to most symmetric)	**The 14 Bravais Lattices**				**Examples**
1. triclinic (none)	$\alpha, \beta, \gamma \neq 90°$ 				
2. monoclinic (1 diad)	simple	base-centered			
	$\alpha \neq 90°$ $\beta, \gamma = 90°$ 	$\alpha \neq 90°$ $\beta, \gamma = 90°$ 			
3. orthorhombic (3 perpendicular diads)	simple	base-centered	body-centered	face-centered	
	$a \neq b \neq c$ 	$a \neq b \neq c$ 	$a \neq b \neq c$ 	$a \neq b \neq c$ 	
4. rhombohedral (1 triad)	$\alpha=\beta=\gamma \neq 90°$ 				

5. tetragonal (1 tetrad)	simple	body-centered
		
6. hexagonal (1 hexad)		
7. cubic (4 triads)	simple (SC)	body-centered (bcc) face-centered (fcc)
		 

The simplest and most symmetric, the cubic (or isometric) system, has the symmetry of a cube, that is, it exhibits four threefold rotational axes oriented at 109.5° (the tetrahedral angle) with respect to each other. These threefold axes lie along the body diagonals of the cube. The other six lattice systems, are hexagonal, tetragonal, rhombohedral (often confused with the trigonal crystal system), orthorhombic, monoclinic and triclinic.

Atomic coordination

By considering the arrangement of atoms relative to each other, their coordination numbers (or number of nearest neighbors), interatomic distances, types of bonding, etc., it is possible to form a general view of the structures and alternative ways of visualizing them.



HCP lattice (left) and the fcc lattice (right).

Close packing

The principles involved can be understood by considering the most efficient way of packing together equal-sized spheres and stacking close-packed atomic planes in three dimensions. For example, if plane A lies beneath plane B, there are two possible ways of placing an additional atom on top of layer B. If an additional layer was placed directly over plane A, this would give rise to the following series :

...**ABABABAB**....

This type of crystal structure is known as **hexagonal close packing (hcp)**.

If however, all three planes are staggered relative to each other and it is not until the fourth layer is positioned directly over plane A that the sequence is repeated, then the following sequence arises:

...**ABCABCABC**...

This type of crystal structure is known as **cubic close packing (ccp)**

The unit cell of the ccp arrangement is the face-centered cubic (fcc) unit cell. This is not immediately obvious as the closely packed layers are parallel to the {111} planes of the fcc unit cell. There are four different orientations of the close-packed layers.

The **packing efficiency** could be worked out by calculating the total volume of the spheres and dividing that by the volume of the cell as follows:

$$\frac{4 \times 1.33\pi r^3}{16\sqrt{2}r^3} = 0.7405$$

The 74% packing efficiency is the maximum density possible in unit cells constructed of spheres of only one size. Most crystalline forms of metallic elements are hcp, ccp or bcc (body-centered cubic). The coordination number of hcp and fcc is 12 and its atomic packing factor (APF) is the number mentioned above, 0.74.

Bravais lattices

When the crystal systems are combined with the various possible lattice centerings, we arrive at the Bravais lattices. They describe the geometric arrangement of the lattice points, and thereby the translational symmetry of the crystal. In three dimensions, there are 14 unique Bravais lattices which are distinct from one another in the translational symmetry they contain. All crystalline materials recognized until now (not including quasicrystals) fit in one of these arrangements. The fourteen three-dimensional lattices, classified by crystal system, are shown above. The Bravais lattices are sometimes referred to as *space lattices*.

The crystal structure consists of the same group of atoms, the *basis*, positioned around each and every lattice point. This group of atoms therefore repeats indefinitely in three dimensions according to the arrangement of one of the 14 Bravais lattices. The characteristic rotation and mirror symmetries of the group of atoms, or unit cell, is described by its crystallographic point group.

Point groups

The crystallographic point group or *crystal class* is the mathematical group comprising the symmetry operations that leave at least one point unmoved and that leave the appearance of the crystal structure unchanged. These symmetry operations include

- *Reflection*, which reflects the structure across a *reflection plane*
- *Rotation*, which rotates the structure a specified portion of a circle about a *rotation axis*
- *Inversion*, which changes the sign of the coordinate of each point with respect to a *center of symmetry* or *inversion point*
- *Improper rotation*, which consists of a rotation about an axis followed by an inversion.

Rotation axes (proper and improper), reflection planes, and centers of symmetry are collectively called *symmetry elements*. There are 32 possible crystal classes. Each one can be classified into one of the seven crystal systems.

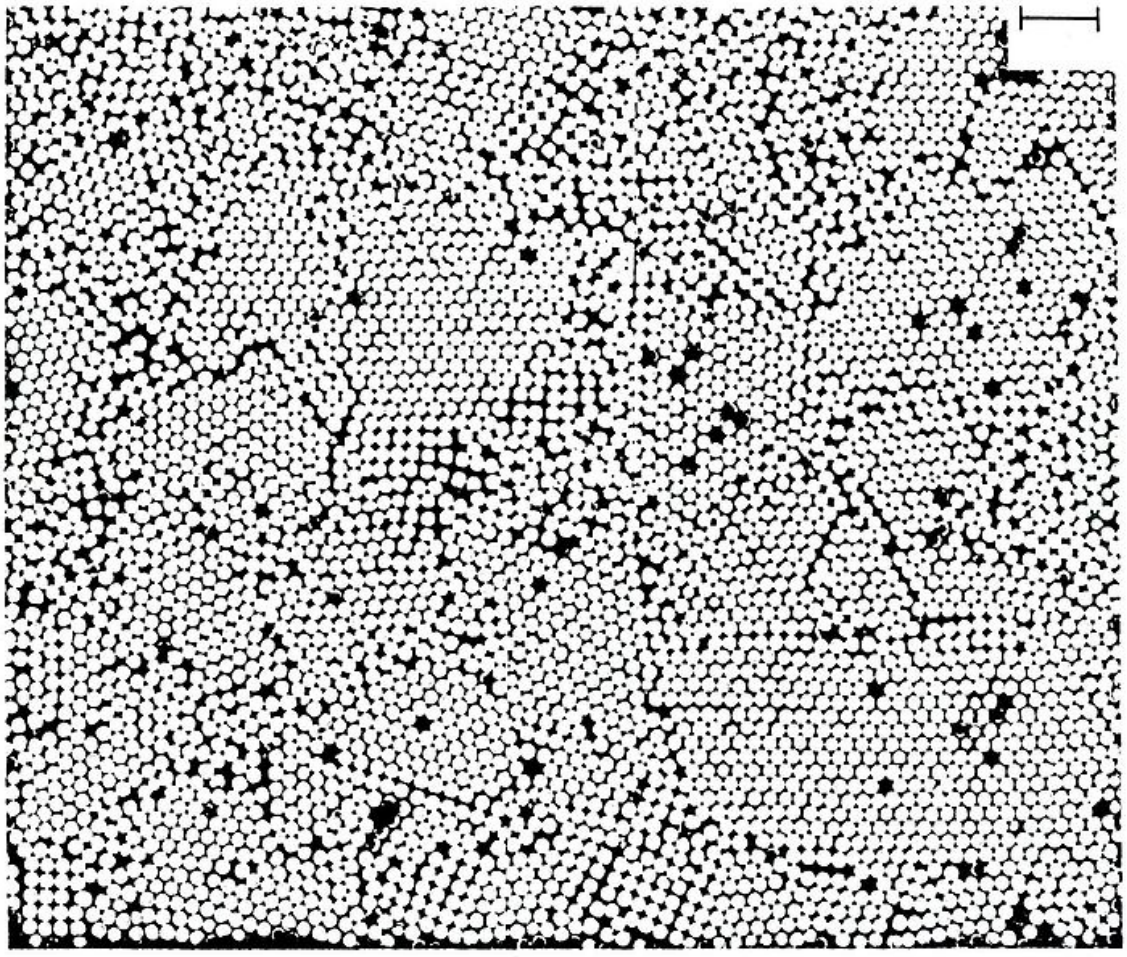
Space groups

The space group of the crystal structure is composed of the translational symmetry operations in addition to the operations of the point group. These include:

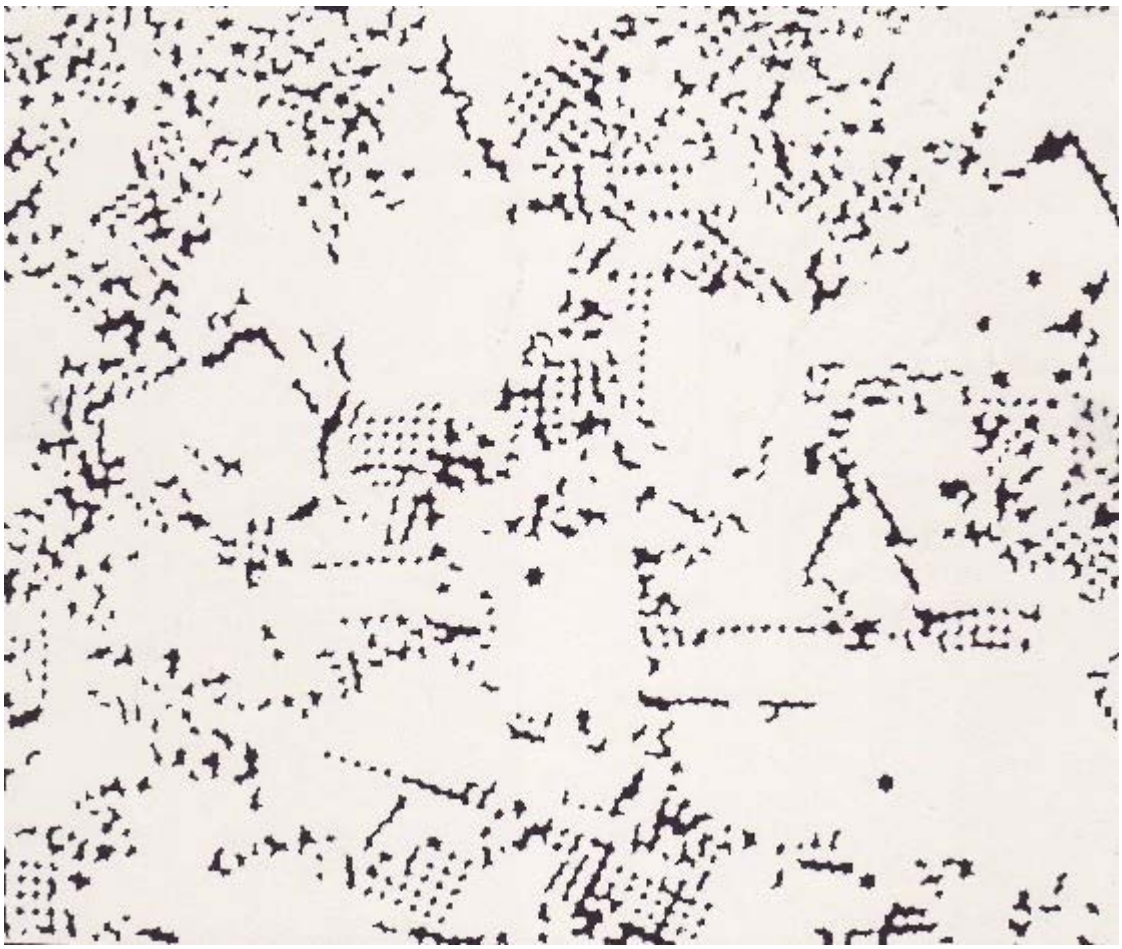
- Pure *translations* which move a point along a vector
- *Screw axes*, which rotate a point around an axis while translating parallel to the axis
- *Glide planes*, which reflect a point through a plane while translating it parallel to the plane.

There are 230 distinct space groups.

Grain boundaries



SEM micrograph of surface of a colloidal crystal. Structure and morphology consists of ordered crystallites, grains or domains of particles as well as interdomain lattice defects in the form of grain boundaries.



Highlighted image of surface of a colloidal crystal. Emphasis on microstructural defects to illustrate the defect/domain morphology typical of an elemental crystal.

Grain boundaries are interfaces where crystals of different orientations meet. A grain boundary is a single-phase interface, with crystals on each side of the boundary being identical except in orientation. The term "crystallite boundary" is sometimes, though rarely, used. Grain boundary areas contain those atoms that have been perturbed from their original lattice sites, dislocations, and impurities that have migrated to the lower energy grain boundary.

Treating a grain boundary geometrically as an interface of a single crystal cut into two parts, one of which is rotated, we see that there are five variables required to define a grain boundary. The first two numbers come from the unit vector that specifies a rotation axis. The third number designates the angle of rotation of the grain. The final two numbers specify the plane of the grain boundary (or a unit vector that is normal to this plane).

Grain boundaries disrupt the motion of dislocations through a material, so reducing crystallite size is a common way to improve strength, as described by the Hall-Petch relationship. Since grain boundaries are defects in the crystal structure they tend to

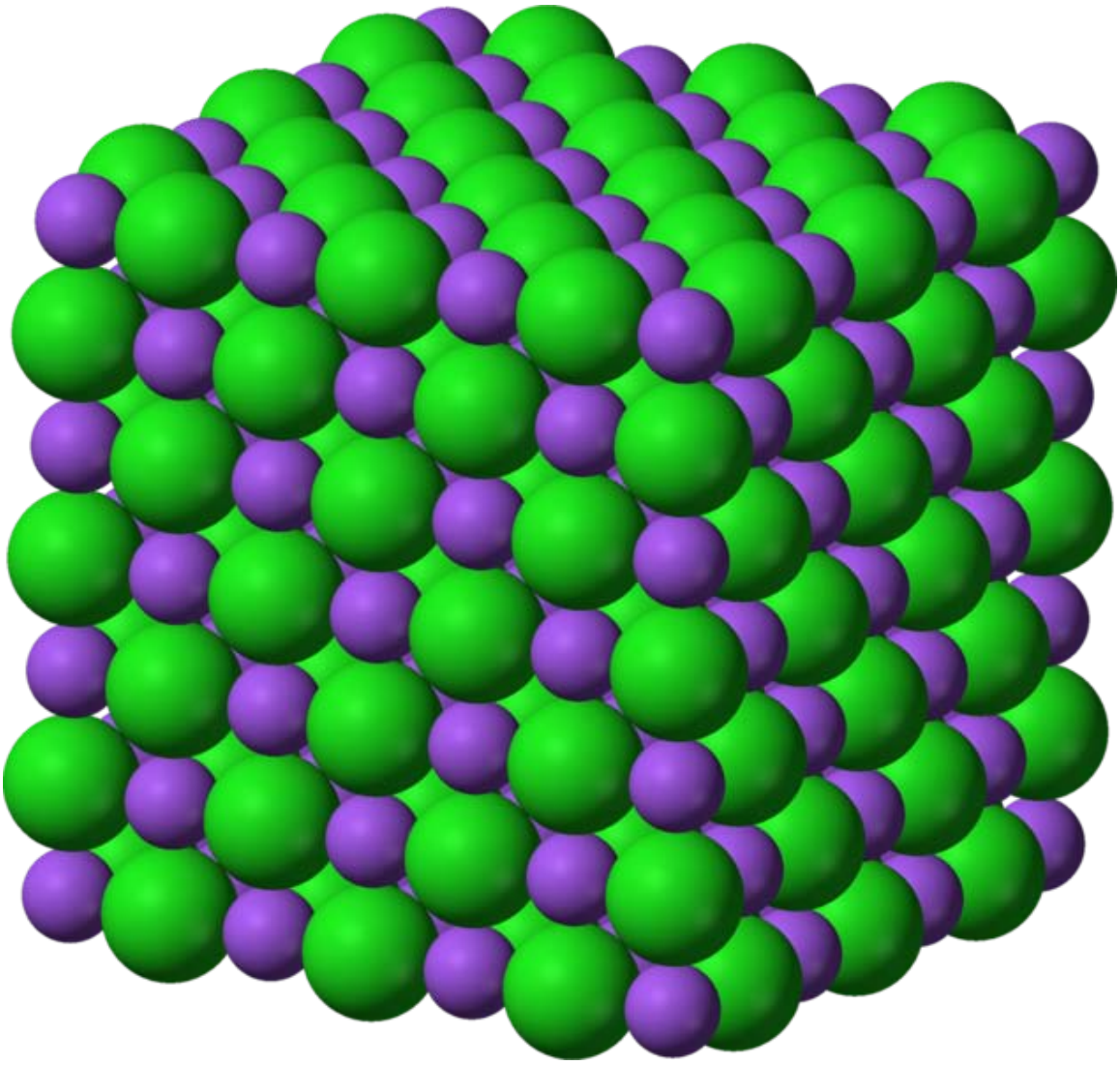
decrease the electrical and thermal conductivity of the material. The high interfacial energy and relatively weak bonding in most grain boundaries often makes them preferred sites for the onset of corrosion and for the precipitation of new phases from the solid. They are also important to many of the mechanisms of creep.

Grain boundaries are generally only a few nanometers wide. In common materials, crystallites are large enough that grain boundaries account for a small fraction of the material. However, very small grain sizes are achievable. In nanocrystalline solids, grain boundaries become a significant volume fraction of the material, with profound effects on such properties as diffusion and plasticity. In the limit of small crystallites, as the volume fraction of grain boundaries approaches 100%, the material ceases to have any crystalline character, and thus becomes an amorphous solid.

Defects and impurities

Real crystals feature defects or irregularities in the ideal arrangements described above and it is these defects that critically determine many of the electrical and mechanical properties of real materials. When one atom substitutes for one of the principal atomic components within the crystal structure, alteration in the electrical and thermal properties of the material may ensue. Impurities may also manifest as spin impurities in certain materials. Research on magnetic impurities demonstrates that substantial alteration of certain properties such as specific heat may be affected by small concentrations of an impurity, as for example impurities in semiconducting ferromagnetic alloys may lead to different properties as first predicted in the late 1960s. Dislocations in the crystal lattice allow shear at lower stress than that needed for a perfect crystal structure.

Prediction of structure



Crystal structure of sodium chloride (table salt)

The difficulty of predicting stable crystal structures based on the knowledge of only the chemical composition has long been a stumbling block on the way to fully computational materials design. Now, with more powerful algorithms and high-performance computing, structures of medium complexity can be predicted using such approaches as evolutionary algorithms, random sampling, or metadynamics.

The crystal structures of simple ionic solids (e.g. NaCl or table salt) have long been rationalized in terms of Pauling's rules, first set out in 1929 by Linus Pauling, referred to by many since as the "father of the chemical bond". Pauling also considered the nature of the interatomic forces in metals, and concluded that about half of the five d-orbitals in the transition metals are involved in bonding, with the remaining nonbonding d-orbitals

being responsible for the magnetic properties. He therefore was able to correlate the number of d-orbitals in bond formation with the bond length as well as many of the physical properties of the substance. He subsequently introduced the metallic orbital, an extra orbital necessary to permit uninhibited resonance of valence bonds among various electronic structures.

In the resonating valence bond theory, the factors that determine the choice of one from among alternative crystal structures of a metal or intermetallic compound revolve around the energy of resonance of bonds among interatomic positions. It is clear that some modes of resonance would make larger contributions (be more mechanically stable than others), and that in particular a simple ratio of number of bonds to number of positions would be exceptional. The resulting principle is that a special stability is associated with the simplest ratios or "bond numbers": 1/2, 1/3, 2/3, 1/4, 3/4, etc. The choice of structure and the value of the axial ratio (which determines the relative bond lengths) are thus a result of the effort of an atom to use its valency in the formation of stable bonds with simple fractional bond numbers.

After postulating a direct correlation between electron concentration and crystal structure in beta-phase alloys, Hume-Rothery analyzed the trends in melting points, compressibilities and bond lengths as a function of group number in the periodic table in order to establish a system of valencies of the transition elements in the metallic state. This treatment thus emphasized the increasing bond strength as a function of group number. The operation of directional forces were emphasized in one article on the relation between bond hybrids and the metallic structures. The resulting correlation between electronic and crystalline structures is summarized by a single parameter, the weight of the d-electrons per hybridized metallic orbital. The “d-weight” calculates out to 0.5, 0.7 and 0.9 for the fcc, hcp and bcc structures respectively. The relationship between d-electrons and crystal structure thus becomes apparent.

Polymorphism

Quartz is one of the several thermodynamically stable crystalline forms of silica, SiO_2. The most important forms of silica include: α-quartz, β-quartz, tridymite, cristobalite, coesite, and stishovite.

Polymorphism refers to the ability of a solid to exist in more than one crystalline form or structure. According to Gibbs' rules of phase equilibria, these unique crystalline phases will be dependent on intensive variables such as pressure and temperature. Polymorphism can potentially be found in many crystalline materials including polymers, minerals, and metals, and is related to allotropy, which refers to elemental solids. The complete morphology of a material is described by polymorphism and other variables such as crystal habit, amorphous fraction or crystallographic defects. Polymorphs have different stabilities and may spontaneously convert from a metastable form (or thermodynamically

unstable form) to the stable form at a particular temperature. They also exhibit different melting points, solubilities, and X-ray diffraction patterns.

One good example of this is the quartz form of silicon dioxide, or SiO_2. In the vast majority of silicates, the Si atom shows tetrahedral coordination by 4 oxygens. All but one of the crystalline forms involve tetrahedral SiO_4 units linked together by shared vertices in different arrangements. In different minerals the tetrahedra show different degrees of networking and polymerization. For example, they occur singly, joined together in pairs, in larger finite clusters including rings, in chains, double chains, sheets, and three-dimensional frameworks. The minerals are classified into groups based on these structures. In each of its 7 thermodynamically stable crystalline forms or polymorphs of crystalline quartz, only 2 out of 4 of each the edges of the SiO_4 tetrahedra are shared with others, yielding the net chemical formula for silica: SiO_2.

Another example is elemental tin (Sn), which is malleable near ambient temperatures but is brittle when cooled. This change in mechanical properties due to existence of its two major allotropes, α- and β-tin. The two allotropes that are encountered at normal pressure and temperature, α-tin and β-tin, are more commonly known as *gray tin* and *white tin* respectively. Two more allotropes, γ and σ, exist at temperatures above 161 °C and pressures above several GPa. White tin is metallic, and is the stable crystalline form at or above room temperature. Below 13.2 °C, tin exists in the gray form, which has a diamond cubic crystal structure, similar to diamond, silicon or germanium. Gray tin has no metallic properties at all, is a dull-gray powdery material, and has few uses, other than a few specialized semiconductor applications. Although the α-β transformation temperature of tin is nominally 13.2 °C, impurities (e.g. Al, Zn, etc.) lower the transition temperature well below 0 °C, and upon addition of Sb or Bi the transformation may not occur at all.

Physical properties

Twenty of the 32 crystal classes are so-called piezoelectric, and crystals belonging to one of these classes (point groups) display piezoelectricity. All piezoelectric classes lack a center of symmetry. Any material develops a dielectric polarization when an electric field is applied, but a substance which has such a natural charge separation even in the absence of a field is called a polar material. Whether or not a material is polar is determined solely by its crystal structure. Only 10 of the 32 point groups are polar. All polar crystals are pyroelectric, so the 10 polar crystal classes are sometimes referred to as the pyroelectric classes.

There are a few crystal structures, notably the perovskite structure, which exhibit ferroelectric behavior. This is analogous to ferromagnetism, in that, in the absence of an electric field during production, the ferroelectric crystal does not exhibit a polarization. Upon the application of an electric field of sufficient magnitude, the crystal becomes permanently polarized. This polarization can be reversed by a sufficiently large counter-charge, in the same way that a ferromagnet can be reversed. However, it is important to note that, although they are called ferroelectrics, the effect is due to the crystal structure (not the presence of a ferrous metal).

Crystal habit

Pyrite sun (or dollar) in laminated shale matrix. Between tightly spaced layers of shale, the aggregate was forced to grow in a laterally compressed, radiating manner. Under normal conditions, pyrite would form cubes or pyritohedrons

In mineralogy, shape and size give rise to descriptive terms applied to the typical appearance, or **habit** of crystals.

The many terms used by mineralogists to describe crystal habits are useful in communicating what specimens of a particular mineral often look like. Recognizing numerous habits helps a mineralogist to identify a large number of minerals. Some habits are distinctive of certain minerals, although most minerals exhibit many differing habits (the development of a particular habit is determined by the details of the conditions during the mineral formation/crystal growth). Crystal habit may mislead the inexperienced as a mineral's internal crystal system can be hidden or disguised.

Factors influencing a crystal's habit include: a combination of two or more crystal forms; trace impurities present during growth; crystal twinning and growth conditions (i.e., heat,

pressure, space). Minerals belonging to the same crystal system do not necessarily exhibit the same habit. Some habits of a mineral are unique to its variety and locality: For example, while most sapphires form elongate barrel-shaped crystals, those found in Montana form stout *tabular* crystals. Ordinarily, the latter habit is seen only in ruby. Sapphire and ruby are both varieties of the same mineral; corundum.

Some minerals may replace other existing minerals while preserving the original's habit: this process is called pseudomorphous replacement. A classic example is tiger's eye quartz, crocidolite asbestos replaced by silica. While quartz typically forms *euhedral* (well-formed), *prismatic* (elongate, prism-like) crystals, in tiger's eye the original *fibrous* habit of crocidolite is preserved.

List of crystal habits

Habit	Description	Example
Acicular	Needle-like, slender and/or tapered	Rutile in quartz
Amygdaloidal	Almond-shaped	Heulandite
Anhedral	Poorly formed, external crystal faces not developed	Olivine
Bladed	Blade-like, slender and flattened	Kyanite
Botryoidal or globular	Grape-like, hemispherical masses	Smithsonite, Hemimorphite, Adamite and Variscite.
Columnar	Similar to fibrous: Long, slender prisms often with parallel growth	Calcite
Coxcomb	Aggregated flaky or tabular crystals closely spaced.	Barite
Dendritic or arborescent	Tree-like, branching in one or more direction from central point	Magnesite in opal
Dodecahedral	Dodecahedron, 12-sided	Garnet
Drusy or encrustation	Aggregate of minute crystals coating a surface	Uvarovite, quartz
Enantiomorphic	Mirror-image habit and optical characteristics; right- and left-handed crystals	Quartz
Equant, stout, stubby or blocky	Length, width, and breadth roughly equal	Zircon
Euhedral	Well-formed, external crystal faces developed	Spinel
Fibrous or columnar	Extremely slender prisms	Tremolite
Filiform or capillary	Hair-like or thread-like, extremely fine	Natrolite
Foliated or micaceous	Layered structure, parting into thin	Mica

	sheets	
Granular	Aggregates of anhedral crystals in matrix	Scheelite
Hemimorphic	Doubly terminated crystal with two differently shaped ends.	Hemimorphite
Mamillary	Breast-like: surface formed by intersecting partial spherical shapes	Malachite
Massive or compact	Shapeless, no distinctive external crystal shape	Serpentine
Nodular or tuberose	Deposit of roughly spherical form with irregular protuberances	Geodes
Octahedral	Octahedron, eight-sided (two pyramids base to base)	Diamond
Plumose	Fine, feather-like scales	Mottramite
Prismatic	Elongate, prism-like: crystal faces parallel to c-axis well-developed	Tourmaline
Pseudo-hexagonal	hexagonal appearance due to cyclic twinning	Aragonite
Pseudomorphous	Occurring in the shape of another mineral through pseudomorphous replacement	Tiger's eye
Radiating or divergent	Radiating outward from a central point	Pyrite suns
Reniform or colloform	Similar to mamillary: intersecting kidney-shaped masses	Hematite
Reticulated	Acicular crystals forming net-like intergrowths	Cerussite
Rosette	Platy, radiating rose-like aggregate	Gypsum
Sphenoid	Wedge-shaped	Sphene
Stalactitic	Forming as stalactites or stalagmites; cylindrical or cone-shaped	Rhodochrosite
Stellate	Star-like, radiating	Pyrophyllite
Striated/striations	Surface growth lines parallel or perpendicular to a crystallographic axis	Pyrite
Subhedral	External crystal faces only partially developed	
Tabular or lamellar	Flat, tablet-shaped, prominent pinnacoid	Ruby
Wheat sheaf	Aggregates resembling hand-reaped wheat sheaves	Zeolites

Crystal Twinning

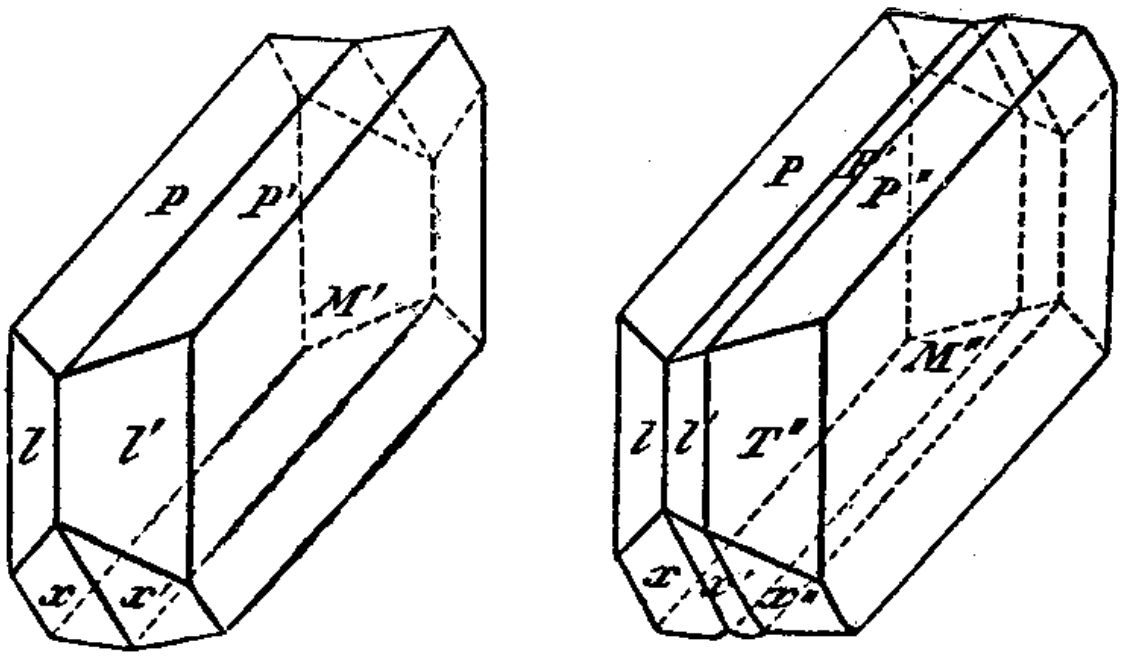


Diagram of twinned crystals of Albite. On the more perfect cleavage, which is parallel to the basal plane (P), is a system of fine striations, parallel to the second cleavage (M).

Crystal twinning occurs when two separate crystals share some of the same crystal lattice points in a symmetrical manner. The result is an intergrowth of two separate crystals in a variety of specific configurations. A twin boundary or composition surface separates the two crystals. Crystallographers classify twinned crystals by a number of twin laws. These twin laws are specific to the crystal system. The type of twinning can be a diagnostic tool in mineral identification.

Penetration twinning in orthoclase, Carlsbad law

Simple twinned crystals may be *contact twins* or *penetration twins*. Contact twins share a single composition surface often appearing as mirror images across the boundary. Plagioclase, quartz, gypsum, and spinel often exhibit contact twinning. In penetration twins the individual crystals have the appearance of *passing through* each other in a symmetrical manner. Orthoclase, staurolite, pyrite, and fluorite often show penetration twinning.

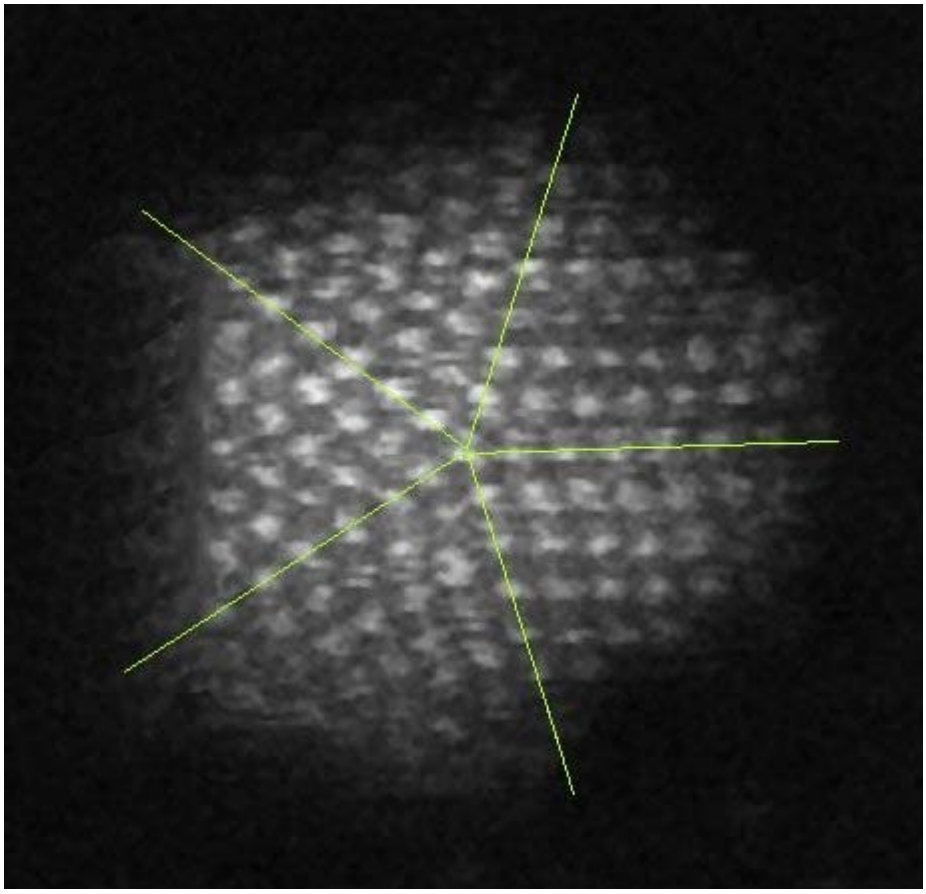
If several twin crystal parts are aligned by the same twin law they are referred to as multiple or repeated twins. If these multiple twins are aligned in parallel they are called *polysynthetic twins*. When the multiple twins are not parallel they are *cyclic twins*. Albite, calcite, and pyrite often show polysynthetic twinning. Closely spaced polysynthetic twinning is often observed as striations or fine parallel lines on the crystal face. Rutile, aragonite, cerussite, and chrysoberyl often exhibit cyclic twinning, typically in a radiating pattern.

Twinned pyrite crystal group

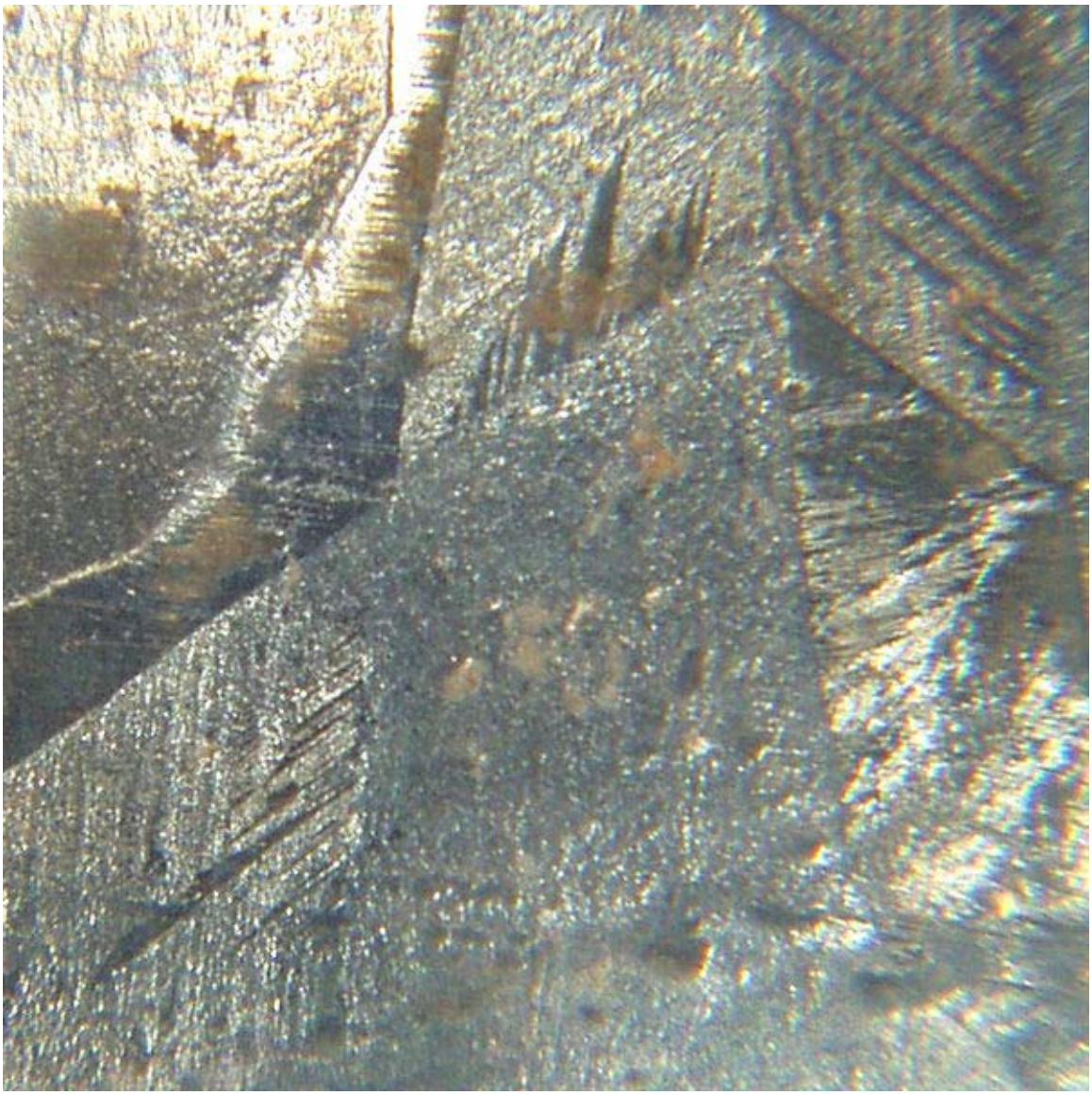
There are three modes of formation of twinned crystals. *Growth twins* are the result of an interruption or change in the lattice during formation or growth due to a possible deformation from a larger substituting ion. *Annealing* or *Transformation twins* are the result of a change in crystal system during cooling as one *form* becomes unstable and the crystal structure must re-organize or *transform* into another more stable form. *Deformation* or *gliding twins* are the result of stress on the crystal after the crystal has formed. Deformation twinning is a common result of regional metamorphism.

Crystals that grow adjacent to each other may be aligned to resemble twinning. This *parallel growth* simply reduces system energy and is not twinning.

Twin boundaries



Five-fold twinning in a gold nanoparticle (electron microscope image).



Galvanized surface with macroscopic crystalline features. Twin boundaries are visible as striations within each crystallite, most prominently in the bottom-left and top-right.

Twin boundaries occur when two crystals of the same type intergrow, so that only a slight misorientation exists between them. It is a highly symmetrical interface, often with one crystal the mirror image of the other; also, atoms are shared by the two crystals at regular intervals. This is also a much lower-energy interface than the grain boundaries that form when crystals of arbitrary orientation grow together.

Twin boundaries are partly responsible for shock hardening and for many of the changes that occur in cold work of metals with limited slip systems or at very low temperatures. They also occur due to martensitic transformations: the motion of twin boundaries is

responsible for the pseudoelastic and shape-memory behavior of nitinol, and their presence is partly responsible for the hardness due to quenching of steel.

Deformation twins

Of the three common crystalline structures BCC, FCC, and HCP, the HCP structure is the most likely to form deformation twins when strained, mainly due to the lack of slip systems in this structure.

Cleavage (crystal)

Green fluorite with prominent cleavage.

Cleavage, in mineralogy, is the tendency of crystalline materials to split along definite crystallographic structural planes. These planes of relative weakness are a result of the regular locations of atoms and ions in the crystal, which create smooth repeating surfaces that are visible both in the microscope and to the naked eye.

Types of cleavage

Cleavage forms parallel to crystallographic planes:

Biotite with basal cleavage.

- Basal or pinacoidal cleavage occurs parallel to the base of a crystal. This orientation is given by the {001} plane in the crystal lattice, and is the same as the

{0001} plane in Bravais-Miller indices, which are often used for rhombohedral and hexagonal crystals. Basal cleavage is exhibited by the mica group and by graphite.

- Cubic cleavage occurs on the {001} planes, parallel to the faces of a cube for a crystal with cubic symmetry. This is the source of the cubic shape seen in crystals of ground table salt, the mineral halite. The mineral galena also typically exhibits perfect cubic cleavage.

- Octahedral cleavage occurs on the {111} crystal planes, forming octahedra shapes for a crystal with cubic symmetry. Diamond and fluorite exhibit perfect octahedral cleavage. Octahedral cleavage is seen in common semiconductors. For lower-symmetry crystals, there will be a smaller number of {111} planes.

- Dodecahedral cleavage occurs on the {110} crystal planes forming dodecahedra for a crystal with cubic symmetry. For lower-symmetry crystals, there will be a smaller number of {110} planes.

- Rhombohedral cleavage occur parallel to the {1011} faces of a rhombohedron. Calcite and other carbonate minerals exhibit perfect rhombohedral cleavage.

- Prismatic cleavage is cleavage parallel to a vertical prism {110}. Cerussite, tremolite and spodumene exhibit prismatic cleavage.

Parting

Crystal parting occurs when minerals break along planes of structural weakness due to external stress or along twin composition planes. Parting breaks are very similar in appearance to cleavage, but only occur due to stress. Examples include magnetite which shows octahedral parting, the rhombohedral parting of corundum and basal parting in pyroxenes.

Uses

Cleavage is a traditional physical property used in mineral identification both in hand specimen and microscopic examination of rock and mineral studies. As an example, the angles between the prismatic cleavage planes for the pyroxenes (88-92°) and the amphiboles (56-124°) are diagnostic.

Crystal cleavage is of technical importance in the electronics industry and in the cutting of gemstones.

Precious stones are generally cleaved by impact as in diamond cutting.

Synthetic single crystals of semiconductor materials are generally sold as thin wafers which are much easier to cleave. Simply pressing a silicon wafer against a soft surface

and scratching its edge with a diamond scribe is usually enough to cause cleavage; however, when dicing a wafer to form chips, a procedure of scoring and breaking is often followed for greater control. Elemental semiconductors (Si, Ge, and diamond) are diamond cubic, a space group for which octahedral cleavage is observed. This means that some orientations of wafer allow near-perfect rectangles to be cleaved. Most other commercial semiconductors (GaAs, InSb, etc.) can be made in the related zinc blende structure, with similar cleavage planes.

Lustre (mineralogy)

Lustre (or **luster**) is a description of the way light interacts with the surface of a crystal, rock, or mineral. For example, a diamond is said to have an *adamantine* lustre and pyrite is said to have a *metallic* lustre. The term is also used to describe other items with a particular sheen (for example, fabric, especially silk and satin, or metals).

The word *lustre* traces its origins back to the Latin word *lux*, meaning "light", and generally implies radiance, gloss, or brilliance.

Terminology

A broad range of terms are used to describe the lustre of minerals. Lustre varies over a wide continuum, and so there are no rigid boundaries between the different terms. (For this reason, different sources can often describe the same mineral differently. This ambiguity is further complicated by the fact that lustre can vary widely within a particular mineral species.) The terms are frequently combined to describe intermediate types of lustre (for example, a "vitreous greasy" lustre).

Adamantine lustre

Cut diamonds

Adamantine minerals possess a superlative lustre, which is most notably seen in diamond. Such minerals are transparent or translucent, and have a high refractive index (of 1.9 or more). Minerals with a true adamantine lustre are uncommon, with examples being cerussite and zircon.

Minerals with a lesser (but still relatively high) degree of lustre are referred to as **subadamantine**, with some examples being garnet and corundum.

Dull lustre

Kaolinite

Dull (or **earthy**) minerals exhibit little to no lustre, due to coarse granulations which scatter light in all directions, approximating a Lambertian reflector. An example is kaolinite. A distinction is sometimes drawn between dull minerals and earthy minerals, with the latter being coarser, and having even less lustre.

Greasy lustre

Moss opal

Greasy minerals resemble fat or grease. A greasy lustre often occurs in minerals containing a great abundance of microscopic inclusions, with examples including opal and cordierite. Many minerals with a greasy lustre are also greasy to the touch.

Metallic lustre

Pyrite

Metallic (or **splendent**) minerals have the lustre of polished metal (and with ideal surfaces will act like a mirror). Examples include galena, pyrite and magnetite.

Pearly lustre

Muscovite

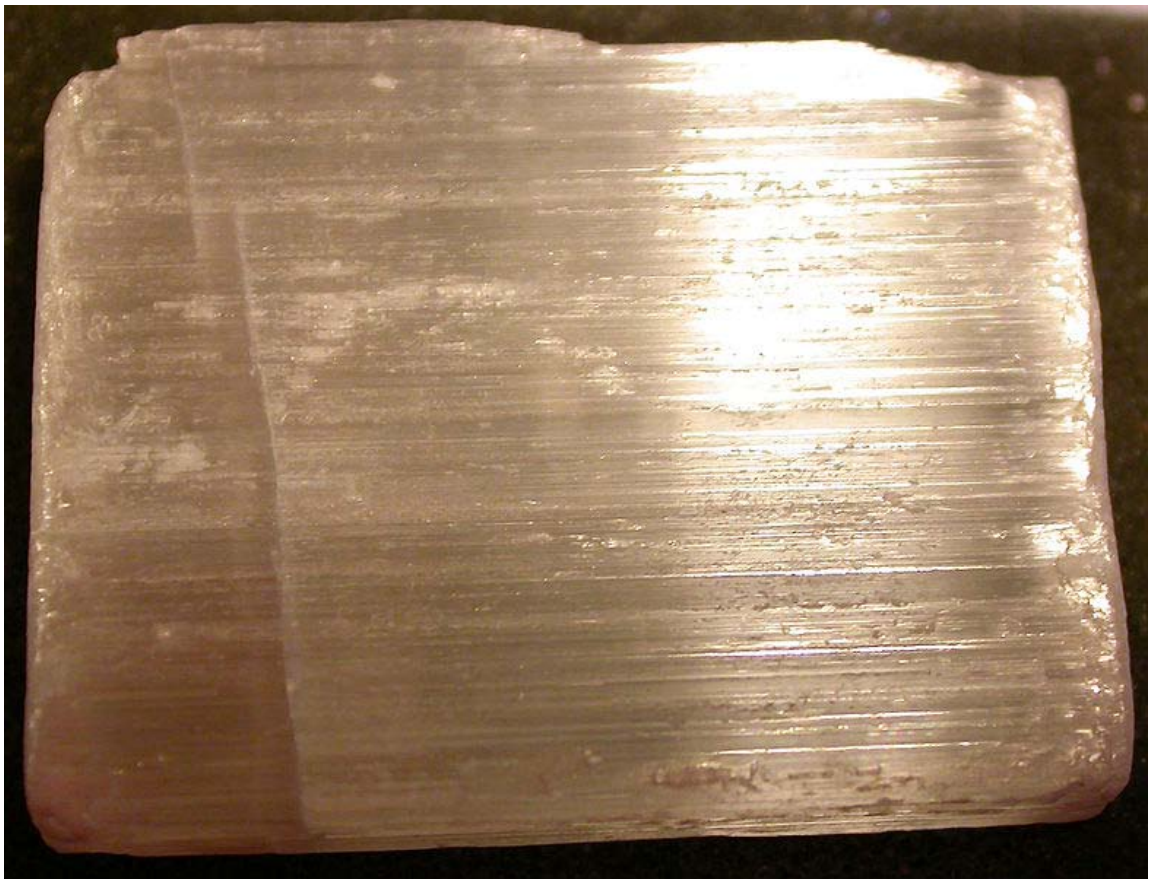
Pearly minerals consist of thin transparent co-planar sheets. Light reflecting from these layers give them a lustre reminiscent of pearls. Such minerals possess perfect cleavage, with examples including muscovite and stilbite.

Resinous lustre

Amber

Resinous minerals have the appearance of resin, chewing gum or (smooth surfaced) plastic. A principal example is amber, which is a form of fossilized resin.

Silky lustre



Satin spar variety of gypsum

Silky minerals have a parallel arrangement of extremely fine fibres, giving them a lustre reminiscent of silk. Examples include asbestos, ulexite and the satin spar variety of gypsum. A **fibrous** lustre is similar, but has a coarser texture.

Submetallic lustre

Sphalerite

Submetallic minerals have similar lustre to metal, but are duller and less reflective. A submetallic lustre often occurs in near-opaque minerals with very high refractive indices, such as sphalerite, cinnabar and cuprite.

Vitreous lustre

Quartz

Vitreous minerals have the lustre of glass. This type of lustre is one of the most commonly seen, and occurs in transparent or translucent minerals with relatively low refractive indices. Common examples include calcite, quartz, topaz, beryl, tourmaline and fluorite, among others.

Waxy lustre

Jade

Waxy minerals have a lustre resembling wax. Examples include jade and chalcedony.

Optical phenomena

Asterism

Sapphire cabochon

Asterism is the display of a star-shaped luminous area. It is seen in some sapphires and rubies, where it is caused by impurities of rutile. It can also occur in garnet, diopside and spinel.

Aventurescence

Aventurine

Aventurescence (or **aventurization**) is a reflectance effect like that of glitter. It arises from minute, preferentially oriented mineral platelets within the material. These platelets are so numerous that they also influence the material's body colour. In aventurine quartz chrome-bearing fuchsite makes for a green stone, and various iron oxides make for a red stone.

Chatoyancy

Tiger's eye

Chatoyant minerals display luminous bands, which appear to move as the specimen is rotated. Such minerals are composed of parallel fibers (or contain fibrous voids or inclusions), which reflect light into a direction perpendicular to their orientation, thus forming narrow bands of light. The most famous examples are tiger's eye and cymophane, but the effect may also occur in other minerals such as aquamarine, moonstone and tourmaline.

Schiller

Labradorite

Schiller, from German for "twinkle", is a term used to describe the metallic iridescence originating from below the surface of a stone, that occurs when light is reflected between layers of minerals. It is seen in moonstone and labradorite and is very similar to adularescence and aventurescence.

Color-change

Alexandrite

Color-change Alexandrite is a variety of chrysoberyl and the most well-known of color-change gemstones. Other gems also occur in color-change varieties, including (but not limited to) sapphire, garnet, spinel. Alexandrite displays a color change dependent upon light, along with strong pleochroism. The gem results from small scale replacement of aluminium by chromium oxide, which is responsible for alexandrite's characteristic green to red color change. Alexandrite from the Ural Mountains in Russia is green by daylight and red by incandescent light. Other varieties of alexandrite may be yellowish or pink in daylight and a columbine or raspberry red by incandescent light. The optimum or "ideal" color change would be fine emerald green to fine purplish red, but this is exceedingly rare.

Streak (mineralogy)

Hematite with a red streak on a porcelain fuse

The **streak** (also called **powder color**) of a mineral is the color of the powder produced when it is dragged across an unweathered surface. Unlike the apparent color of a mineral, which for most minerals can vary considerably, the trail of finely ground powder generally has a more consistent characteristic color, and is thus an important diagnostic tool in mineral identification. If no streak seems to be made, the mineral's streak is said to be white or colorless. Streak is particularly important as a diagnostic for opaque and colored materials. It is less useful for silicate minerals, most of which have a white streak and are too hard to powder easily.

The apparent color can vary widely because of trace impurities or a disturbed macroscopic crystal structure. Small amounts of an impurity that strongly absorbs a particular wavelength can radically change the wavelengths of light that are reflected by the specimen, and thus change the apparent color. However, when the specimen is dragged to produce a streak, it is broken into randomly oriented microscopic crystals, and small impurities do not greatly affect the absorption of light.

The surface across which the mineral is dragged is called a "streak plate," and is generally made of unglazed porcelain tile. In the absence of a streak plate, the unglazed

underside of a porcelain bowl or vase or the back of a glazed tile will work. Sometimes a streak is more easily or accurately described by comparing it with the "streak" made by another streak plate.

Because the trail left behind results from the mineral being crushed into powder, a streak can only be made of minerals softer than the streak plate, around 7 on the Mohs scale of mineral hardness. In case of harder minerals, the color of the powder can be determined by filing or crushing with a hammer a small sample, which is then usually rubbed on a streak plate. Most minerals that are harder have an unhelpful white streak.

Some minerals leave a streak similar to their natural color, such as cinnabar and azurite. Other minerals leave surprising colors, such as fluorite, which always has a white streak, although it can appear in purple, blue, yellow, or green crystals. Hematite, which is black in appearance, leaves a red streak which accounts for its name, which comes from the Greek word "haima," meaning "blood." Galena, which can be similar in appearance to hematite, is easily distinguished by its gray streak.

Mohs scale of mineral hardness

The **Mohs scale of mineral hardness** characterizes the scratch resistance of various minerals through the ability of a harder material to scratch a softer material. It was created in 1812 by the German mineralogist Friedrich Mohs and is one of several definitions of hardness in materials science. The method of comparing hardness by seeing which minerals can scratch others, however, is of great antiquity, having first been mentioned by Theophrastus in his treatise *On Stones*, *circa* 300 BC, followed by Pliny the Elder in his *Naturalis Historia*, *circa* 77 AD.

Minerals

The Mohs scale of mineral hardness is based on the ability of one natural sample of matter to scratch another. The samples of matter used by Mohs are all minerals. Minerals are pure substances found in nature. Rocks are made up of one or more minerals. As the hardest known naturally occurring substance when the scale was designed, diamonds are at the top of the scale. The hardness of a material is measured against the scale by finding the hardest material that the given material can scratch, and/or the softest material that can scratch the given material. For example, if some material is scratched by apatite but not by fluorite, its hardness on the Mohs scale would fall between 4 and 5.

The Mohs scale is a purely ordinal scale. For example, corundum (9) is twice as hard as topaz (8), but diamond (10) is almost four times as hard as corundum. The table below shows comparison with absolute hardness measured by a sclerometer, with pictorial examples.

Since the invention of the scale, there have been reports of materials harder than the highest mineral on the scale, diamond; so the Mohs scale may be changed in the future.

Mohs hardness	Mineral	Absolute hardness	Image
1	Talc ($Mg_3Si_4O_{10}(OH)_2$)	1	
2	Gypsum ($CaSO_4 \cdot 2H_2O$)	3	
3	Calcite ($CaCO_3$)	9	
4	Fluorite (CaF_2)	21	
5	Apatite ($Ca_5(PO_4)_3(OH^-,Cl^-,F^-)$)	48	
6	Orthoclase Feldspar ($KAlSi_3O_8$)	72	
7	Quartz (SiO_2)	100	
8	Topaz ($Al_2SiO_4(OH^-,F^-)_2$)	200	
9	Corundum (Al_2O_3)	400	

10	Diamond (C)	1600	

On the Mohs scale, a pencil "lead" (graphite) has a hardness of 1; a fingernail, 2.2–2.5; a copper penny, 3.2–3.5; a pocketknife 5.1; a knife blade, 5.5; window glass plate, 5.5; and a steel file, 6.5. A streak plate (unglazed porcelain) has a hardness of 7.0. Using these ordinary materials of known hardness can be a simple way to approximate the position of a mineral on the scale.

Intermediate hardness

The table below incorporates additional substances that may fall between levels:

Hardness	Substance or mineral
0.2–0.3	caesium, rubidium
0.5–0.6	lithium, sodium, potassium
1	talc, graphite
1.5	gallium, strontium, indium, tin, barium, thallium, lead
2	hexagonal boron nitride, calcium, selenium, cadmium, sulfur, tellurium, bismuth
2.5 to 3	magnesium, gold, silver, aluminium, zinc, lanthanum, cerium
3	calcite, copper, arsenic, antimony, thorium, dentin
4	fluorite, iron, nickel
4 to 4.5	platinum, steel
5	apatite, cobalt, zirconium, palladium, tooth enamel
5.5	beryllium, molybdenum, hafnium
6	orthoclase, titanium, manganese, germanium, niobium, rhodium, uranium
6 to 7	glass, fused quartz, iron pyrite, silicon, ruthenium, iridium, tantalum
7	quartz, vanadium, osmium, rhenium
7.5 to 8	hardened steel, tungsten, emerald
8	topaz, cubic zirconia
8.5	chrysoberyl, chromium
9-9.5	corundum, silicon carbide (carborundum), tungsten carbide, titanium carbide, stishovite
9.5–10	rhenium diboride, tantalum carbide, titanium diboride, boron
10	diamond
>10	nanocrystalline diamond (hyperdiamond, ultrahard fullerite)

Specific gravity

Specific gravity is ratio of the density (mass of a unit volume) of a substance to the density (mass of the same unit volume) of a reference substance. *Apparent* specific gravity is the ratio of the weight of a volume of the substance to the weight of an equal volume of the reference substance. The reference substance is nearly always water. Temperature and pressure must be specified for both the sample and the reference. Pressure is nearly always 1 atm equal to 101.325 kPa. Where it is not it is more usual to specify the density directly. Temperatures for both sample and reference vary from industry to industry. In British brewing practice the specific gravity as specified above is multiplied by 1000. Specific gravity is commonly used in industry as a simple means of obtaining information about the concentration of solutions of various materials such as brines, sugar solutions (syrups, juices, honeys, brewers wort, must etc.) and acids. In the sequel we shall assume that the reference substance is always water.

Details

Specific gravity, as it is the ratio of either densities or weights, is a dimensionless quantity. As an expression of relative mass or weight of equal volumes of sample and reference the specific gravity of the reference (water)is 1 (or 1000 in British brewing) if and only if the reference and sample temperatures are the same (see below). Substances with a specific gravity of 1 are neutrally buoyant, those with SG greater than one are denser than water, and so (ignoring surface tension effects) will sink in it, and those with an SG of less than one are less dense than water, and so will float. In scientific work the relationship of mass to volume is usually expressed directly in terms of the density (mass per unit volume) of the substance under study. It is in industry where specific gravity finds wide application, often for historical reasons.

True specific gravity, can be expressed mathematically as:

$$SG_{true} = \frac{V\rho_{sample}}{V\rho_{H_2O}} = \frac{gV\rho_{sample}}{gV\rho_{H_2O}} = \frac{w_{V,sample}}{w_{V,H_2O}} = \frac{\rho_{sample}}{\rho_{H_2O}}$$

where V is the volume of sample and water, $\rho_{\mathrm{sample}}$is the density of the sample, $\rho_{\mathrm{H_2O}}$is the density of water,g is the local acceleration due to gravity and w_V represents a weight obtained in vaccuo.

The apparent specific gravity is simply the ratio of the weights of equal volumes of sample and water in air:

$$SG_{apparent} = \frac{w_{A,sample}}{w_{A,H_2O}}$$

The density of water varies with temperature and pressure as does the density of the sample so that it is necessary to specify the temperatures and pressures at which the

densities or weights were determined. It is nearly always the case that measurements are made at nominally 1 atmosphere (1013.25 mb ± the variations caused by changing weather patterns) but as specific gravity usually refers to highly incompressible aqueous solutions or other incompressible substances (such as petroleum products) variations in density caused by pressure are usually neglected at least where apparent specific gravity is being measured. For true (*in vacuo*) specific gravity calculations air pressure must be considered (see below). Temperatures are specified by the notation (T_s / T_r) with T_s representing the temperature at which the sample's density was determined and T_r the temperature at which the reference (water) density is specified. For example SG (20°C/4°C) would be understood to mean that the density of the sample was determined at 20 °C and of the water at 4°C. Taking into account different sample and reference temperatures we note that while $SG_{H_2O} = 1.000000$(20°C/20°C) it is also the case that $SG_{H_2O} = 0.998203/0.998840 = 0.998363$(20°C/4°C). Here temperature is being specified using the current ITS-90 scale and the densities used here. On the previous IPTS-68 scale the densities at 20 °C and 4 °C are, respectively, 0.9982071 and 0.9999720 resulting in an SG (20°C/4°C) value for water of 0.9982343.

As the principal use of specific gravity measurements in industry is determination of the concentrations of substances in aqueous solutions and these are found in tables of SG vs concentration it is extremely important that the analyst enter the table with the correct form of specific gravity. For example, in the brewing industry, the Plato table, which lists sucrose concentration by weight against true SG, were originally (20°C/4°C) i.e. based on measurements of the density of sucrose solutions made at laboratory temperature (20 °C) but referenced to the density of water at 4 °C which is very close to the temperature at which water has its maximum density of $\rho_{\mathrm{H_2O}}$equal to 0.999972 g·cc^{-3} or SI units (or 62.43 lb$_m$·ft^{-3} in United States customary units). The ASBC table in use today in North America, while it is derived from the original Plato table is for apparent specific gravity measurements at (20°C/20°C) on the IPTS-68 scale where the density of water is 0.9982071 g·cc^{-3}. In the sugar, soft drink, honey, fruit juice and related industries sucrose concentration by weight is taken from a table prepared by A. Brix which uses SG (17.5°C/17.5°CC). As a final example, the British SG units are based on reference and sample temperatures of 60F and are thus (15.56°C/15.56°C).

Given the specific gravity of a substance, its actual density can be calculated by rearranging the above formula:

$$\rho_{\mathrm{substance}} = \mathrm{SG} \times \rho_{\mathrm{H_2O}}$$

Occasionally a reference substance other than water is specified (for example, air), in which case specific gravity means density relative to that reference.

Specific gravity is, by definition, dimensionless and therefore independent on the system of units used (e.g. slugs·ft^{-3} or kg·m^{-3}). However, the two densities must be converted to the same units before carrying out the numerical ratio calculation.

Measurement: apparent and true specific gravity

Pycnometer

Specific gravity can be measured in a number of ways. The following illustration involving the use of the pycnometer is instructive. A pycnometer is simply a bottle which can be precisely filled to a specific, but not necessarily accurately known volume, V. Placed upon a balance of some sort it will exert a force

$$F_b = g(m_b - \rho_a \frac{m_b}{\rho_b})$$

where m_b is the mass of the bottle and g the gravitational acceleration at the location at which the measurements are being made. ρ_a is the density of the air at the ambient pressure and ρ_b is the density of the material of which the bottle is made (usually glass) so that the second term is the mass of air displaced by the glass of the bottle whose weight, by Archimedes Principle must be subtracted. The bottle is, of course, filled with air but as that air displaces an equal amount of air the weight of that air is canceled by the weight of the air displaced. Now we fill the bottle with the reference fluid e.g. pure water. The force exerted on the pan of the balance becomes:

$$F_w = g(m_b - \rho_a \frac{m_b}{\rho_b} + V\rho_w - V\rho_a)$$

If we subtract the force measured on the empty bottle from this (or tare the balance before making the water measurement) we obtain.

$$F_{w,n} = gV(\rho_w - \rho_a)$$

where the subscript n indicated that this force is net of the force of the empty bottle. The bottle is now emptied, thoroughly dried and refilled with the sample. The force, net of the empty bottle, is now:

$$F_{s,n} = gV(\rho_s - \rho_a)$$

where ρ_s is the density of the sample. The ratio of the sample and water forces is:

$$SG_A = \frac{gV(\rho_s - \rho_a)}{gV(\rho_w - \rho_a)} = \frac{(\rho_s - \rho_a)}{(\rho_w - \rho_a)}$$

This is called the Apparent Specific Gravity, denoted by subscript A, because it is what we would obtain if we took the ratio of net weighings in air from an analytical balance or used a hydrometer (the stem displaces air). Note that the result does not depend on the calibration of the balance. The only requirement on it is that it read linearly with force. Nor does SG_A depend on the actual volume of the pycnometer.

Further manipulation and finally substitution of SG_V,the true specific gravity,(the subscript V is used because this is often referred to as the specific gravity *in vacuo*) for $\frac{\rho_s}{\rho_w}$ gives the relationship between apparent and true specific gravity.

$$SG_A = \frac{\frac{\rho_s}{\rho_w} - \frac{\rho_a}{\rho_w}}{1 - \frac{\rho_a}{\rho_w}} = \frac{SG_V - \frac{\rho_a}{\rho_w}}{1 - \frac{\rho_a}{\rho_w}}$$

In the usual case we will have measured weights and want the true specific gravity. This is found from

$$SG_V = SG_A - \frac{\rho_a}{\rho_w}(SG_A - 1)$$

Since the density of dry air at 1013.25 mb at 20 °C is 0.001205 g·cm^{-3} and that of water is 0.998203 g·cm^{-3} we see that the difference between true and apparent specific gravities for a substance with specific gravity (20°C/20°C) of about 1.100 would be 0.000120. Where the specific gravity of the sample is close to that of water (for example dilute ethanol solutions) the correction is even smaller.

Digital density meter

In modern laboratories precise measurements of specific gravity are made using oscillating U-tube meters. These are capable of measurement to 5 to 6 places beyond the decimal point and are used in the brewing, distilling, pharmaceutical, petroleum and other industries. The instruments measure the actual mass of fluid contained in a fixed volume at temperatures between 0 and 80 °C but as they are microprocessor based can calculate apparent or true specific gravity and contain tables relating these to the strengths of common acids, sugar solutions etc.

Chapter-4

Optical Mineralogy

A petrographic microscope, which is a optical microscope fitted with cross-polarizing lenses, a conoscopic lens, and compensators (plates of anisotropic materials; gypsum plates and quartz wedges are common), for crystallographic analysis.

Optical mineralogy is the study of minerals and rocks by measuring their optical properties. Most commonly, rock and mineral samples are prepared as thin sections or grain mounts for study in the laboratory with a petrographic microscope. Optical mineralogy is used to identify the mineralogical composition of geological materials in order to help reveal their origin and evolution.

Some of the properties and techniques used include:

- Refractive index
- Birefringence

- Michel-Lévy Interference colour chart
- Pleochroism
- Extinction angle
- Conoscopic interference pattern (Interference figure)
- Becke line test
- Optical relief
- Sign of elongation (Length fast vs. length slow)
- Wave plate

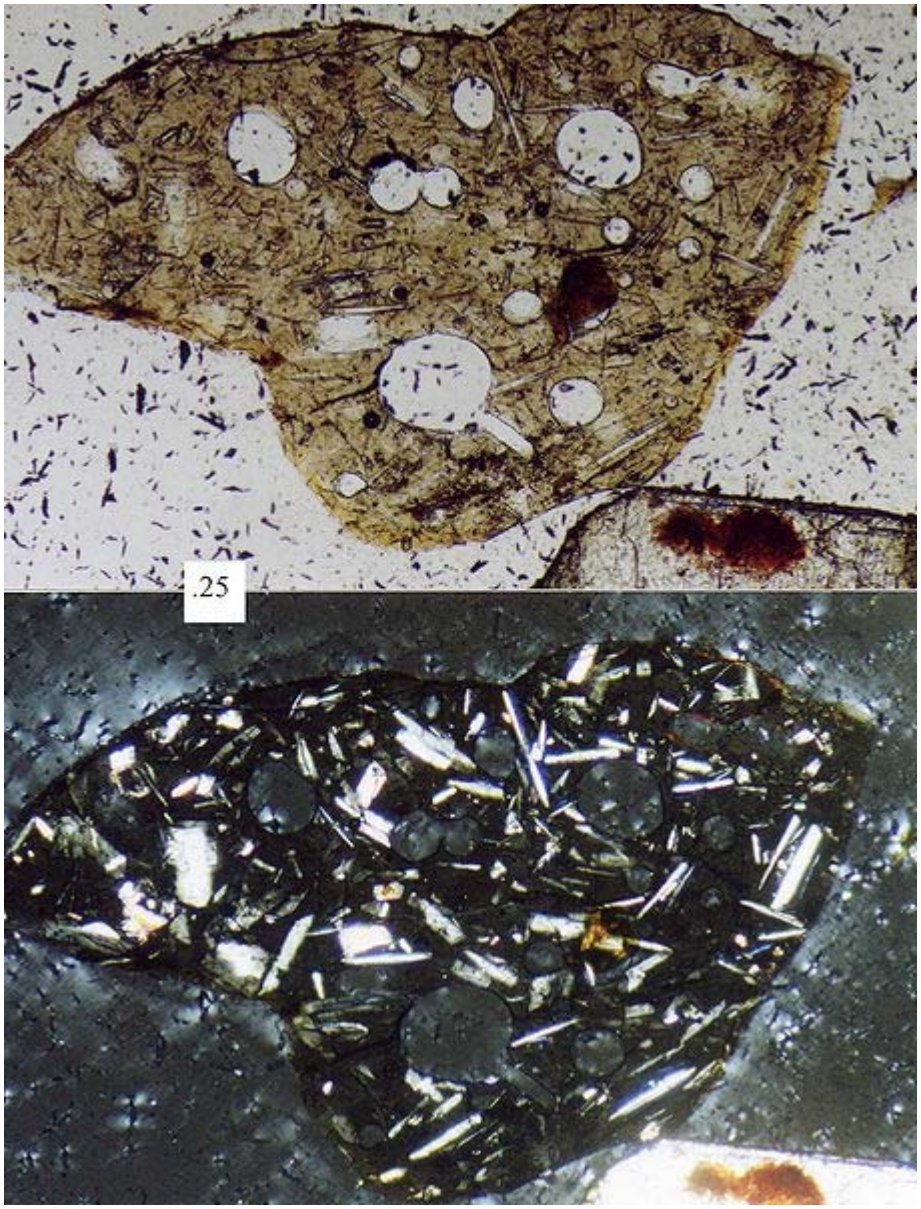
History

William Nicol, whose name is associated with the creation of the Nicol prism, seems to have been the first to prepare thin slices of mineral substances, and his methods were applied by Henry Thronton Maire Witham (1831) to the study of plant petrifactions. This method, of such far-reaching importance in petrology, was not at once made use of for the systematic investigation of rocks, and it was not until 1858 that Henry Clifton Sorby pointed out its value. Meanwhile the optical study of sections of crystals had been advanced by Sir David Brewster and other physicists and mineralogists and it only remained to apply their methods to the minerals visible in rock sections.

Sections

A rock-section should be about one-thousandth of an inch (30 micrometres) in thickness, and is relatively easy to make. A thin splinter of the rock, about 1 centimetre may be taken; it should be as fresh as possible and free from obvious cracks. By grinding it on a plate of planed steel or cast iron with a little fine carborundum it is soon rendered flat on one side and is then transferred to a sheet of plate glass and smoothed with the very finest emery till all minute pits and roughnesses are removed and the surface is a uniform plane. The rock-chip is then washed, and placed on a copper or iron plate which is heated by a spirit or gas lamp. A microscopic glass slip is also warmed on this plate with a drop of viscous natural Canada balsam on its surface. The more volatile ingredients of the balsam are dispelled by the heat, and when that is accomplished the smooth, dry, warm rock is pressed firmly into contact with the glass plate so that the film of balsam intervening may be as thin as possible and free from air-bubbles. The preparation is allowed to cool and then the rock chip is again ground down as before, first with carborundum and, when it becomes transparent, with fine emery till the desired thickness is obtained. It is then cleaned, again heated with a little more balsam, and covered with a cover glass. The labor of grinding the first surface may be avoided by cutting off a smooth slice with an iron disk armed with crushed diamond powder. A second application of the slitter after the first face is smoothed and cemented to the glass will in expert hands leave a rock-section so thin as to be already transparent. In this way the preparation of a section may require only twenty minutes.

Microscope



Photomicrograph of a volcanic lithic fragment (sand grain); upper picture is plane-polarized light, bottom picture is cross-polarized light, scale box at left-center is 0.25 millimeter.

The microscope employed is usually one which is provided with a rotating stage beneath which there is a polarizer, while above the objective or the eyepiece an analyzer is mounted; alternatively the stage may be fixed and the polarizing and analyzing prisms may be capable of simultaneous rotation by means of toothed wheels and a connecting-rod. If ordinary light and not polarized light is desired, both prisms may be withdrawn from the axis of the instrument; if the polarizer only is inserted the light transmitted is plane polarized; with both prisms in position the slide is viewed in cross-polarized light,

also known as "crossed nicols." A microscopic rock-section in ordinary light, if a suitable magnification (say 30) be employed, is seen to consist of grains or crystals varying in color, size and shape.

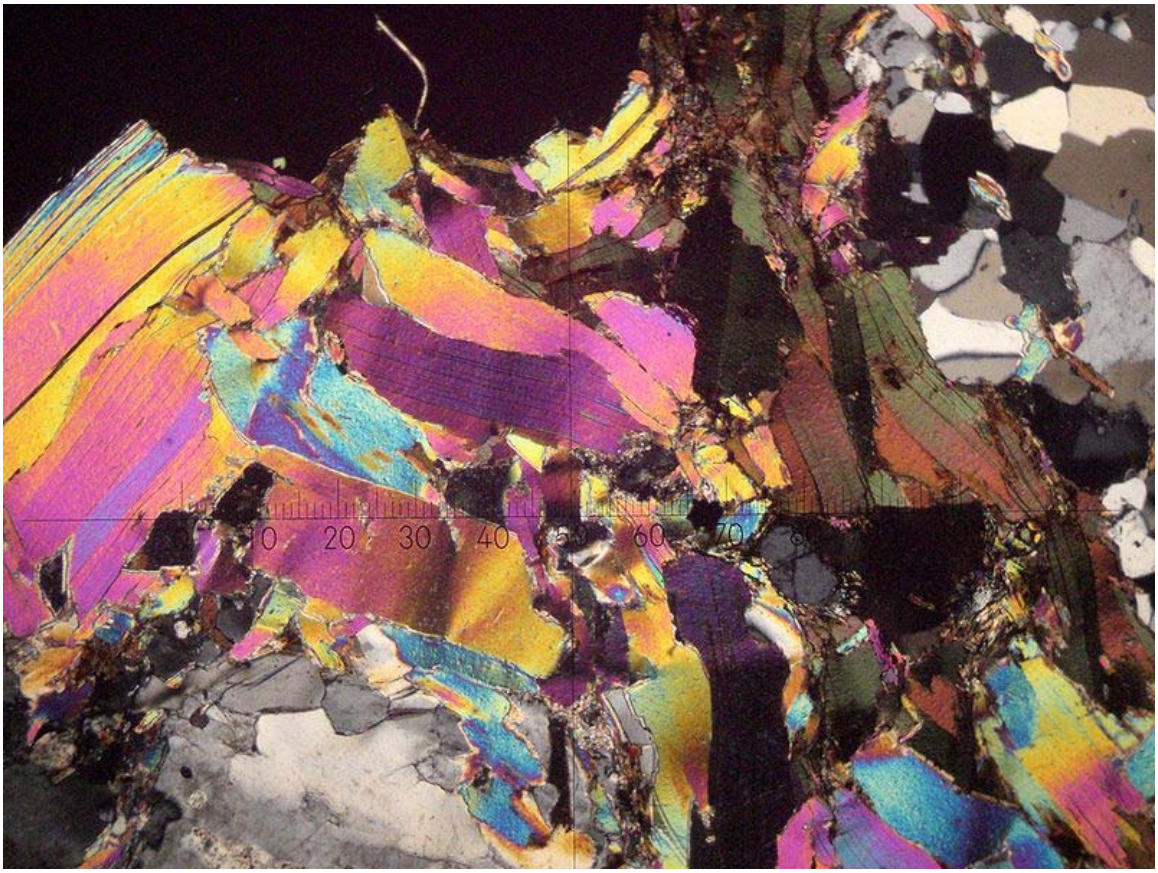
Characters of minerals

Some minerals are colorless and transparent (quartz, calcite, feldspar, muscovite, etc.), others are yellow or brown (rutile, tourmaline, biotite), green (diopside, hornblende, chlorite), blue (glaucophane), pink (garnet), etc. The same mineral may present a variety of colors, in the same or different rocks, and these colors may be arranged in zones parallel to the surfaces of the crystals. Thus tourmaline may be brown, yellow, pink, blue, green, violet, grey, or colorless, but every mineral has one or more characteristic, most common tints. The shapes of the crystals determine in a general way the outlines of the sections of them presented on the slides. If the mineral has one or more good cleavages they will be indicated by systems of cracks. The refractive index is also clearly shown by the appearance of the section, which are rough, with well-defined borders if they have a much stronger refraction than the medium in which they are mounted. Some minerals decompose readily and become turbid and semi-transparent (e.g. feldspar); others remain always perfectly fresh and clear (e.g. quartz), others yield characteristic secondary products (such as green chlorite after biotite). The inclusions in the crystals (both solid and fluid) are of great interest; one mineral may enclose another, or may contain spaces occupied by glass, by fluids or by gases.

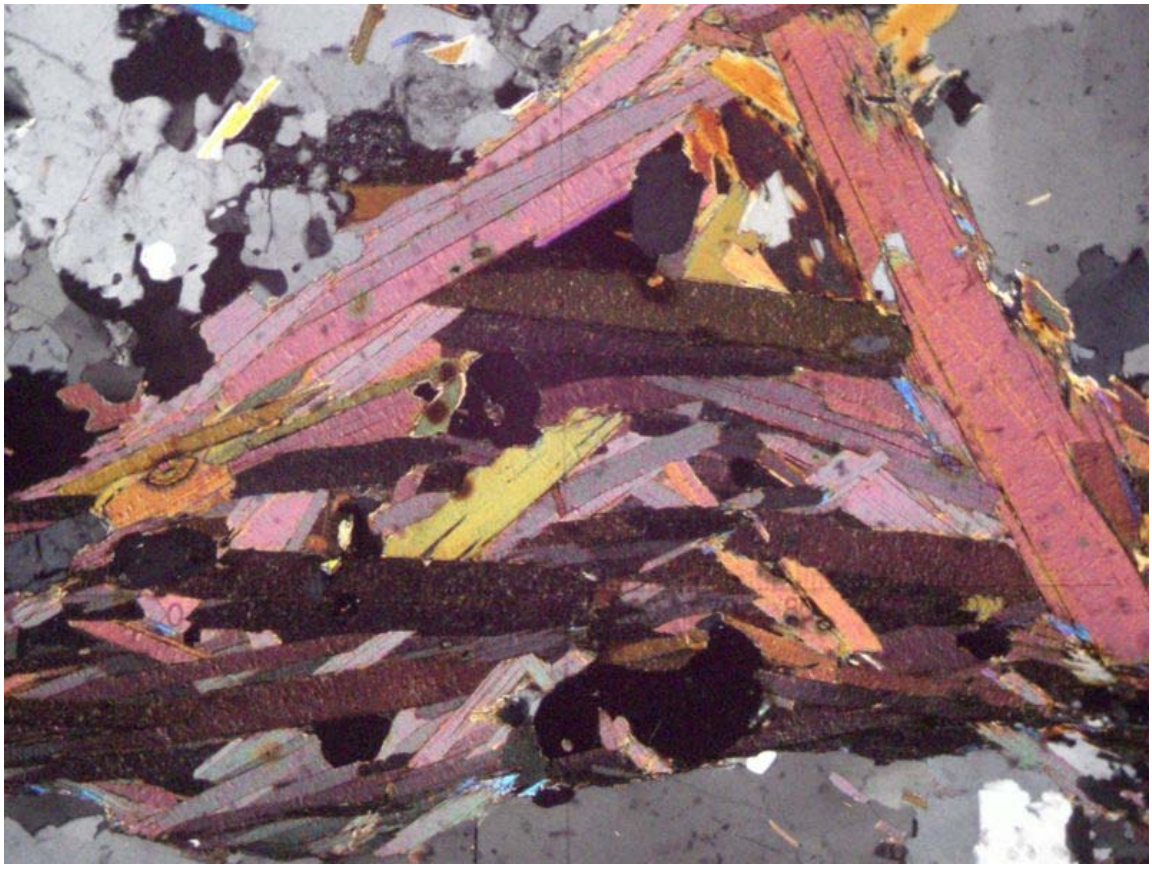
Microstructure

Lastly the structure of the rock, that is to say, the relation of its components to one another, is usually clearly indicated, whether it be fragmented or massive; the presence of glassy matter in contradistinction to a completely crystalline or "holo-crystalline" condition; the nature and origin of organic fragments; banding, foliation or lamination; the pumiceous or porous structure of many lavas; these and many other characters, though often not visible in the hand specimens of a rock, are rendered obvious by the examination of a microscopic section. Many refined methods of observation may be introduced, such as the measurement of the size of the elements of the rock by the help of micrometers; their relative proportions by means of a glass plate ruled in small squares; the angles between cleavages or faces seen in section by the use of the rotating graduated stage, and the estimation of the refractive index of the mineral by comparison with those of different mounting media.

Pleochroism



Thin section of Muscovite grains



Biotite grains showing strong pleochroism during rotation

Pleochroism is an optical phenomenon in which mineral grains within a rock appear to be different colors when observed at different angles under a polarizing petrographic microscope.

Background

Pleochroism is caused by the double refraction of light by a mineral. Light of different polarizations is bent different amounts by the crystal, and therefore follows different paths through the crystal. The components of a divided light beam follow different paths within the mineral and travel at different speeds, and each path will absorb different colors of light. When the mineral is observed at some angle, light following some combination of paths and polarizations will be present, each of which will have had light of different colors absorbed. At another angle, the light passing through the crystal will be composed of another combination of light paths and polarizations, each with their own color. The light passing through the mineral will therefore have different colors when it is viewed from different angles, making the stone seem to be of different colors.

Tetragonal, trigonal and hexagonal minerals can only show two colors and are called dichroic. Orthorhombic, monoclinic and triclinic crystals show three and are trichroic. Isometric minerals cannot exhibit pleochroism. Tourmaline is notable for exhibiting

strong pleochroism. Gems are sometimes cut and set either to display pleochroism or to hide it, depending on the colors and their attractiveness.

In mineralogy

Pleochroism is an extremely useful tool in mineralogy for mineral identification, since minerals that are otherwise very similar often have very different pleochroic color schemes. In such cases, a thin section of the mineral is used and examined under polarized transmitted light with a petrographic microscope.

Double refraction

If the analyzer be now inserted in such a position that it is crossed relatively to the polarizer the field of view will be dark where there are no minerals, or where the light passes through isotropic substances such as glass, liquids and cubic crystals. All other crystalline bodies, being doubly refracting, will appear bright in some position as the stage is rotated. The only exception to this rule is provided by sections which are perpendicular to the optic axes of birefringent crystals; these remain dark or nearly dark during a whole rotation, and as will be seen later, their investigation is of special importance.

Extinction

The doubly refracting mineral sections, however, will in all cases appear black in certain positions as the stage is rotated. They are said to go "extinct" when this takes place. If we note these positions we may measure the angle between them and any cleavages, faces or other structures of the crystal by means of the rotating stage. These angles are characteristic of the system to which the mineral belongs and often of the mineral species itself. To facilitate measurement of extinction angles various kinds of eyepieces have been devised, some having a stereoscopic calcite plate, others with two or four plates of quartz cemented together; these are often found to give more exact results than are obtained by observing merely the position in which the mineral section is most completely dark between crossed nicols.

The mineral sections when not extinguished are not only bright but are colored and the colors they show depend on several factors, the most important of which is the strength of the double refraction. If all the sections are of the same thickness as is nearly true of well-made slides, the minerals with strongest double refraction yield the highest polarization colors. The order in which the colors are arranged in what is known as Newton's scale, the lowest being dark grey, then grey, white, yellow, orange, red, purple, blue and so on. The difference between the refractive indexes of the ordinary and the extraordinary ray in quartz is .009, and in a rock-section about 1/500 of an inch thick this mineral gives grey and white polarization colours; nepheline with weaker double refraction gives dark grey; augite on the other hand will give red and blue, while calcite with the stronger double refraction will appear pinkish or greenish white. All sections of the same mineral, however, will not have the same color; it was stated above that sections perpendicular to

an optic axis will be nearly black, and, in general, the more nearly any section approaches this direction the lower its polarization colors will be. By taking the average, or the highest color given by any mineral, the relative value of its double refraction can be estimated; or if the thickness of the section be precisely known the difference between the two refractive indexes can be ascertained. If the slides be thick the colors will be on the whole higher than in thin slides.

It is often important to find out whether of the two axes of elasticity (or vibration traces) in the section is that of greater elasticity (or lesser refractive index). The quartz wedge or selenite plate enables us to do this. Suppose a doubly refracting mineral section so placed that it is "extinguished"; if now is rotated through 45 degrees it will be brightly illuminated. If the quartz wedge be passed across it so that the long axis of the wedge is parallel to the axis of elasticity in the section the polarization colors will rise or fall. If they rise the axes of greater elasticity in the two minerals are parallel; if they sink the axis of greater elasticity in the one is parallel to that of lesser elasticity in the other. In the latter case by pushing the wedge sufficiently far complete darkness or compensation will result. Selenite wedges, selenite plates, mica wedges and mica plates are also used for this purpose. A quartz wedge also may be calibrated by determining the amount of double refraction in all parts of its length. If now it be used to produce compensation or complete extinction in any doubly refracting mineral section, we can ascertain what is the strength of the double refraction of the section because it is obviously equal and opposite to that of a known part of the quartz wedge.

A further refinement of microscopic methods consists of the use of strongly convergent polarized light (konoscopic methods). This is obtained by a wide angled achromatic condenser above the polarizer, and a high power microscopic objective. Those sections are most useful which are perpendicular to an optic axis, and consequently remain dark on rotation. If they belong to uniaxial crystals they show a dark cross or convergent light between crossed nicols, the bars of which remain parallel to the wires in the field of the eyepiece. Sections perpendicular to an optic axis of a biaxial mineral under the same conditions show a dark bar which on rotation becomes curved to a hyperbolic shape. If the section is perpendicular to a "bisectrix" a black cross is seen which on rotation opens out to form two hyperbolas, the apices of which are turned towards one another. The optic axes emerge at the apices of the hyperbolas and may be surrounded by colored rings, though owing to the thinness of minerals in rock sections these are only seen when the double refraction of the mineral is strong. The distance between the axes as seen in the field of the microscope depends partly on the axial angle of the crystal and partly on the numerical aperture of the objective. If it is measured by means of eye-piece micrometer, the optic axial angle of the mineral can be found by a simple calculation. The quartz wedge, quarter mica plate or selenite plate permit the determination of the positive or negative character of the crystal by the changes in the color or shape of the figures observed in the field. These operations are precisely similar to those employed by the mineralogist in the examination of plates cut from crystals. It is sufficient to point out that the petrological microscope in its modern development is an optical instrument of great precision, enabling us to determine physical constants of crystallized substances as

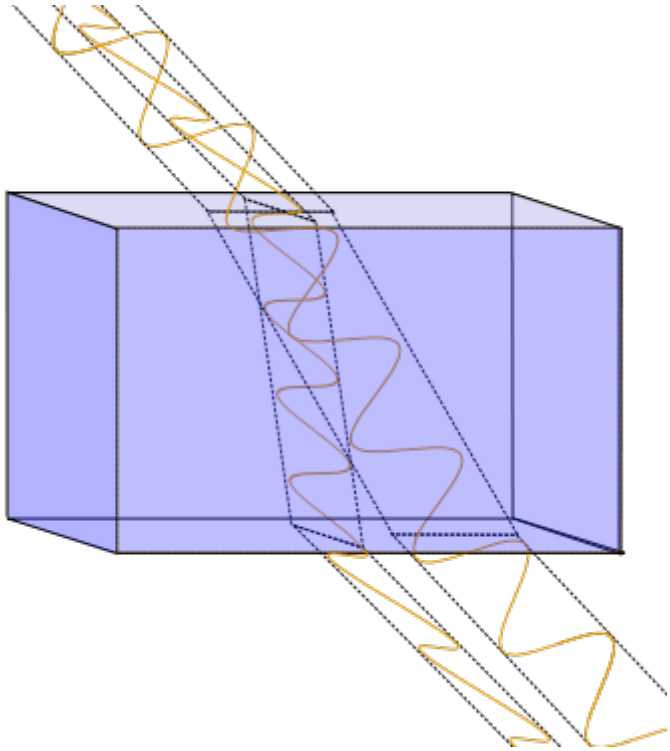
well as serving to produce magnified images like the ordinary microscope. A great variety of accessory apparatus has been devised to fit it for these special uses.

Examination of rock powders

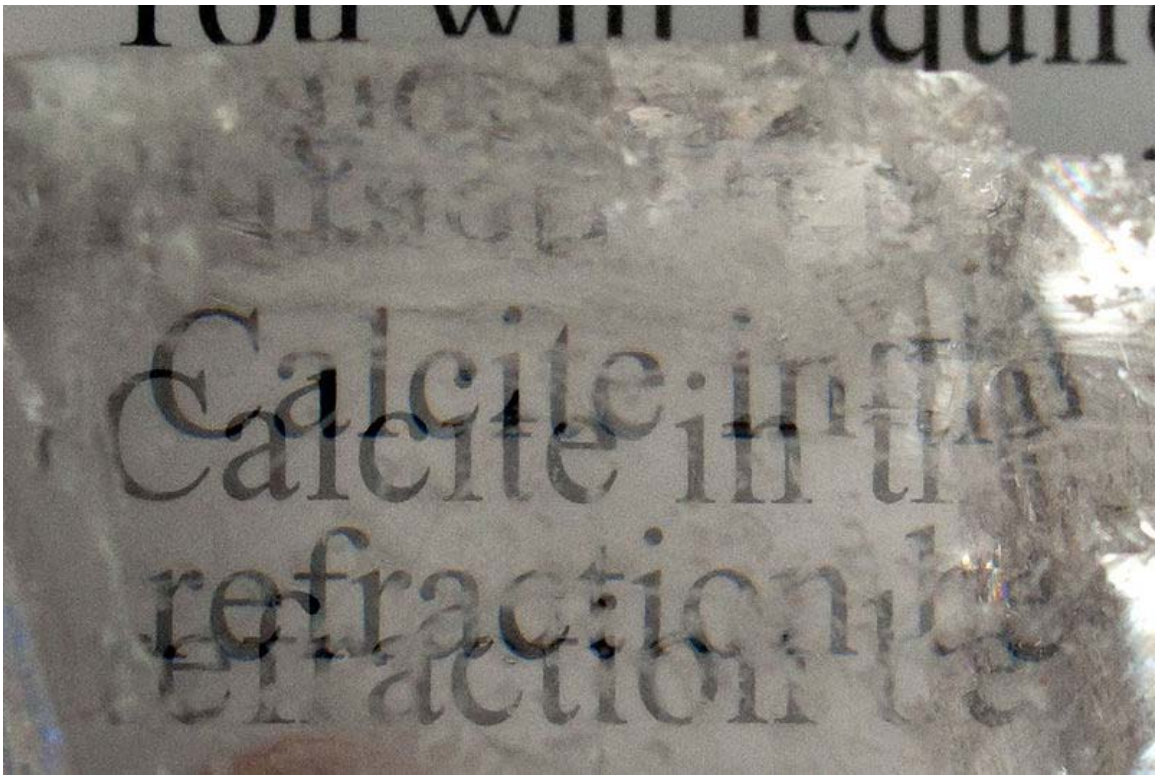
Although rocks are now studied principally in microscopic sections the investigation of fine crushed rock powders, which was the first branch of microscopic petrology to receive attention, is by no means discontinued. The modern optical methods are perfectly applicable to transparent mineral fragments of any kind. Minerals are almost as easily determined in powder as in section, but it is otherwise with rocks, as the structure or relation of the components to one another, which is an element of great importance in the study of the history and classification or rocks, is almost completely destroyed by grinding them to powder.

Properties and Techniques

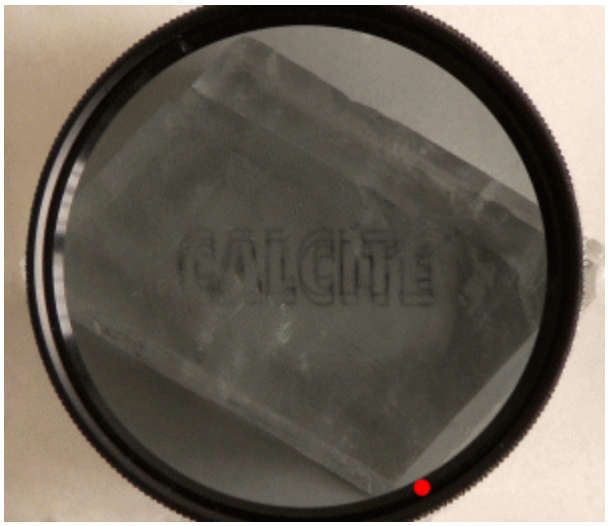
Birefringence



Displacement of light rays with perpendicular polarization through a birefringent material.



A calcite crystal laid upon a paper with all letters showing the double refraction



A calcite crystal seen through a polarizing filter

Birefringence, or **double refraction**, is the decomposition of a ray of light (and other electromagnetic radiation) into two rays (the **ordinary ray** and the **extraordinary ray**) when it passes through certain types of material, such as calcite crystals or boron nitride, depending on the polarization of the light. This effect can occur only if the structure of the material is anisotropic (directionally dependent). If the material has a single axis of

anisotropy or optical axis, (i.e. it is uniaxial) birefringence can be formalized by assigning two different refractive indices to the material for different polarizations. The birefringence magnitude is then defined by

$$\Delta n = n_e - n_o$$

where n_e and n_o are the refractive indices for polarizations parallel (**extraordinary**) and perpendicular (**ordinary**) to the axis of anisotropy respectively.

The reason for birefringence is the fact that in anisotropic media the electric field vector $\vec{E}$ and the dielectric displacement $\vec{D}$ can be nonparallel (namely for the extraordinary polarisation), although being linearly related.

Birefringence can also arise in magnetic, not dielectric, materials, but substantial variations in magnetic permeability of materials are rare at optical frequencies. Liquid crystal materials as used in Liquid Crystal Displays (LCDs) are also birefringent.

Creation

While birefringence is often found naturally (especially in crystals), there are several ways to create it in optically isotropic materials.

- Birefringence results when isotropic materials are deformed such that the isotropy is lost in one direction (i.e., stretched or bent). Example
- Applying an electric field can induce molecules to line up or behave asymmetrically, introducing anisotropy and resulting in birefringence.
- Applying a magnetic field can cause a material to be **circularly birefringent**, with different indices of refraction for oppositely-handed circular polarizations
- Self alignment of highly polar molecules such as lipids and some surfactants will generate highly birefringent thin films

Examples of uniaxial birefringent materials

Uniaxial materials, at 590 nm

Material	n_o	n_e	Δn
beryl $Be_3Al_2(SiO_3)_6$	1.602	1.557	-0.045
calcite $CaCO_3$	1.658	1.486	-0.172
calomel Hg_2Cl_2	1.973	2.656	+0.683
ice H_2O	1.309	1.313	+0.004

lithium niobate $LiNbO_3$	2.272	2.187	-0.085
magnesium fluoride MgF_2	1.380	1.385	+0.006
quartz SiO_2	1.544	1.553	+0.009
ruby Al_2O_3	1.770	1.762	-0.008
rutile TiO_2	2.616	2.903	+0.287
peridot $(Mg, Fe)_2SiO_4$	1.690	1.654	-0.036
sapphire Al_2O_3	1.768	1.760	-0.008
sodium nitrate $NaNO_3$	1.587	1.336	-0.251
tourmaline (complex silicate)	1.669	1.638	-0.031
zircon, high $ZrSiO_4$	1.960	2.015	+0.055
zircon, low $ZrSiO_4$	1.920	1.967	+0.047

Many plastics are birefringent, because their molecules are 'frozen' in a stretched conformation when the plastic is moulded or extruded. For example, cellophane is a cheap birefringent material, and Polaroid sheets are commonly used to examine for orientation in birefringent plastics like polystyrene and polycarbonate. Birefringent materials are used in many devices which manipulate the polarization of light, such as wave plates, polarizing prisms, and Lyot filters.

There are many birefringent crystals: birefringence was first described in calcite crystals by the Danish scientist Rasmus Bartholin in 1669.

Birefringence can be observed in amyloid plaque deposits such as are found in the brains of Alzheimer's patients. Modified proteins such as immunoglobulin light chains abnormally accumulate between cells, forming fibrils. Multiple folds of these fibers line up and take on a beta-pleated sheet conformation. Congo red dye intercalates between the folds and, when observed under polarized light, causes birefringence.

Cotton (Gossypium hirsutum) fiber is birefringent because of high levels of cellulosic material in the fiber's secondary cell wall.

Slight imperfections in optical fiber can cause birefringence, which can cause distortion in fiber-optic communication. The imperfections can be geometrically based, or a result of photoelastic effects from loading on the optical fiber.

Silicon carbide, also known as Moissanite, is strongly birefringent.

The refractive indices of several (uniaxial) birefringent materials are listed to the right (at wavelength ~ 590 nm)

Fast and slow rays

Effective refractive indices in uniaxial materials

Propagation direction	**Ordinary ray**		**Extraordinary ray**	
	Polarization	**n_{eff}**	**Polarization**	**n_{eff}**
z	*xy*-plane	n_o	n/a	n/a
xy-plane	*xy*-plane	n_o	*z*	n_e
xz-plane	*y*	n_o	*xz*-plane	$n_e < n < n_o$
other	analogous to *xz*-plane			

For a given propagation direction, there are generally two perpendicular polarizations for which the medium behaves as if it had a single effective refractive index. In a uniaxial material, rays with these polarizations are called the extraordinary and the ordinary ray (*e* and *o* rays), corresponding to the extraordinary and ordinary refractive indices. In a biaxial material, there are three refractive indices α, β, and γ, yet only two rays, which are called the fast and the slow ray. The slow ray is the ray that has the highest effective refractive index.

For a uniaxial material with the *z* axis defined to be the optical axis, the effective refractive indices are as in the table on the right. For rays propagating in the *xz* plane, the effective refractive index of the *e* polarization varies continuously between n_o and n_e, depending on the angle with the *z* axis. The effective refractive index can be constructed from the Index ellipsoid.

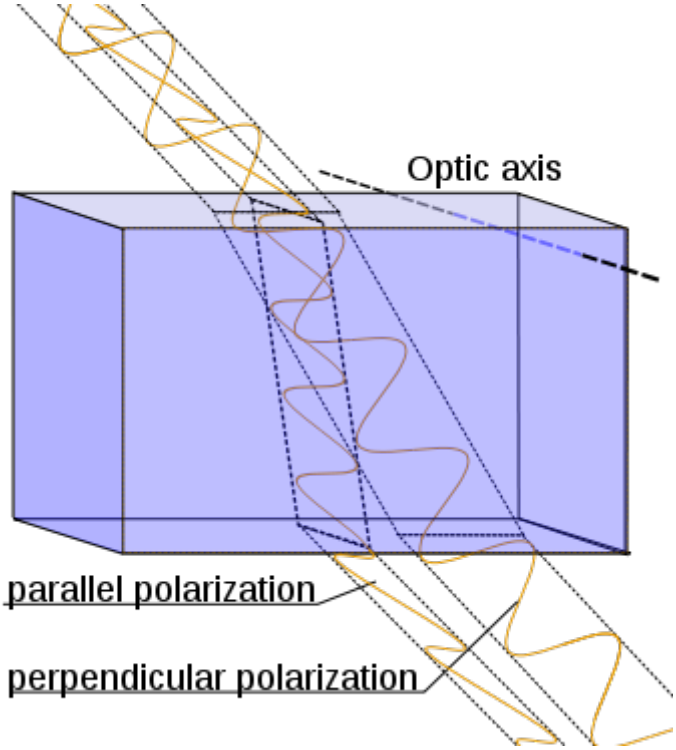
Biaxial birefringence

Biaxial materials, at 590 nm

Material	n_α	n_β	n_γ
borax	1.447	1.469	1.472
epsom salt $MgSO_4 \cdot 7(H_2O)$	1.433	1.455	1.461
mica, biotite	1.595	1.640	1.640
mica, muscovite	1.563	1.596	1.601
olivine $(Mg, Fe)_2SiO_4$	1.640	1.660	1.680
perovskite $CaTiO_3$	2.300	2.340	2.380
topaz	1.618	1.620	1.627
ulexite	1.490	1.510	1.520

Biaxial birefringence, also known as **trirefringence**, describes an anisotropic material that has more than one axis of anisotropy. For such a material, the refractive index tensor **n**, will in general have three distinct eigenvalues that can be labeled n_α, n_β and n_γ.

Positive or negative



Rays passing through a positively birefringent material. The optical axis is perpendicular to the direction of the rays, so the ray polarized perpendicularly to the optic axis has a greater refractive index than the ray polarized parallel to it.

Uniaxial birefringent materials are classified as positively (or negatively) birefringent when, for light directed perpendicularly to the optic axis, the refractive index of light polarized parallel to the optic axis is greater (or smaller, respectively,) than light polarized perpendicularly to the optic axis. In other words, the polarization of the slow (or fast) wave is parallel to the optical axis when the birefringence of the crystal is positive (or negative, respectively).

Biaxial crystals are defined as positively (or negatively) birefringent when the slow ray (or fast ray, respectively) bisects the acute angle formed by the optical axes.

In practice, when using an optical compensator that emits red light, a crystal with positive birefringence appears blue when its long dimension is parallel to the slow axis of the compensator. In contrast, a crystal with negative birefringence appears yellow when its long dimension is parallel to the slow axis of the compensator, and the slow ray of the compensator is oriented perpendicularly to the long axis of the crystal. The reason for these phenomena is that the wavelength of emitted light is shifted higher in positively birefringent crystals, because the slow ray of the crystal is parallel to the slow axis of the compensator, while for negatively birefringent crystals the wavelength of emitted light is shifted lower, because the fast ray of the crystal is parallel to the slow axis of the compensator. The order of colors resulting from the use of compensators in a polarized

light system differs from that of a typical spectrum, instead having an order including yellow-orange-red-violet-blue.

Measurement

Birefringence and related optical effects (such as optical rotation and linear or circular dichroism) can be measured by measuring the changes in the polarization of light passing through the material. These measurements are known as polarimetry.

Birefringence of lipid bilayers can be measured using dual polarisation interferometry. This provides a measure of the degree of order within these fluid layers and how this order is disrupted when the layer interacts with other biomolecules.

A common feature of optical microscopes is a pair of crossed polarizing filters. Between the crossed polarizers, a birefringent sample will appear bright against a dark (isotropic) background.

For a fixed composition such as calcium carbonate, a crystal such as calcite or its polymorphs, the index of refraction depends on the direction of light through the crystal structure. The refraction also depends on composition, and can be calculated using the Gladstone-Dale relation.

Applications

A calcite crystal laid upon a paper with some letters showing the double refraction

Birefringence is widely used in optical devices, such as liquid crystal displays, light modulators, color filters, wave plates, optical axis gratings, etc. It also plays an important role in second harmonic generation and many other nonlinear processes.

It is also utilized in medical diagnostics. For example, needle aspiration of fluid from a gouty joint will reveal negatively birefringent urate crystals. Calcium pyrophosphate crystals, in contrast, show weak positive birefringence. In ophthalmology, scanning laser polarimetry utilises the birefringence of the retinal nerve fibre layer to indirectly quantify its thickness, which is of use in the assessment and monitoring of glaucoma. Birefringence characteristics in sperm heads allow for the selection of spermatozoa for intracytoplasmic sperm injection. Likewise, *zona imaging* uses birefringence on oocytes to select the ones with highest chances of successful pregnancy. Birefringence of particles biopsied from pulmonary nodules indicates silicosis.

Birefringent filters are also used as spatial low-pass filters in electronic cameras, where the thickness of the crystal is controlled to spread the image in one direction, thus increasing the spot-size. This is essential to the proper working of all television and electronic film cameras, to avoid spatial aliasing, the folding back of frequencies higher than can be sustained by the pixel matrix of the camera.

Elastic birefringence

Another form of birefringence is observed in anisotropic elastic materials. In these materials, shear waves split according to similar principles as the light waves discussed above. The study of birefringent shear waves in the earth is a part of seismology. Birefringence is also used in optical mineralogy to determine the chemical composition, and history of minerals and rocks.

Stress induced birefringence

Color pattern of a plastic box with 'frozen' in mechanical stress placed between two crossed polarizers.

Isotropic solids do not exhibit birefringence. However, when they are under mechanical stress, birefringence results. The stress can be applied externally or is 'frozen' in after a birefringent plastic ware is cooled after it is manufactured using injection molding. When such a sample is placed between two crossed polarizers, colour patterns can be observed due to stress induced birefringence. The reason is that polarization of a light ray is usually rotated after passing through a birefingent material and the amount of rotation is dependent on wavelength.

Mathematical description

More generally, birefringence can be defined by considering a dielectric permittivity and a refractive index that are tensors. Consider a plane wave propagating in an anisotropic medium, with a relative permittivity tensor **ε**, where the refractive index **n**, is defined by $n \cdot n = \epsilon$. If the wave has an electric vector of the form:

$$\mathbf{E} = \mathbf{E_0} \exp i(\mathbf{k} \cdot \mathbf{r} - \omega t) \quad (2)$$

where **r** is the position vector and *t* is time, then the wave vector **k** and the angular frequency ω must satisfy Maxwell's equations in the medium, leading to the equations:

$$-\nabla \times \nabla \times \mathbf{E} = \frac{1}{c^2}(\epsilon \cdot \frac{\partial^2 \mathbf{E}}{\partial t^2}) \quad (3a)$$

$$\nabla \cdot (\epsilon \cdot \mathbf{E}) = 0 \quad (3b)$$

where *c* is the speed of light in a vacuum. Substituting eqn. 2 in eqns. 3a-b leads to the conditions:

$$|\mathbf{k}|^2 \mathbf{E_0} - (\mathbf{k} \cdot \mathbf{E_0})\mathbf{k} = \frac{\omega^2}{c^2}(\epsilon \cdot \mathbf{E_0}) \quad (4a)$$

$$\mathbf{k} \cdot (\epsilon \cdot \mathbf{E_0}) = 0 \quad (4b)$$

For the matrix product $(\epsilon \cdot \mathbf{E})$often a separate name is used, the *dielectric displacement vector* $\mathbf{D}$. So essentially birefringence concerns the general theory of linear relationships between these two vectors in anisotropic media.

To find the allowed values of **k**, $\mathbf{E}_0$ can be eliminated from eq 4a. One way to do this is to write eqn 4a in Cartesian coordinates, where the *x*, *y* and *z* axes are chosen in the directions of the eigenvectors of **ε**, so that

$$\epsilon = \begin{bmatrix} n_x^2 & 0 & 0 \\ 0 & n_y^2 & 0 \\ 0 & 0 & n_z^2 \end{bmatrix} \quad (4c)$$

Hence eqn 4a becomes

$$(-k_y^2 - k_z^2 + \frac{\omega^2 n_x^2}{c^2})E_x + k_x k_y E_y + k_x k_z E_z = 0 \quad (5a)$$

$$k_x k_y E_x + (-k_x^2 - k_z^2 + \frac{\omega^2 n_y^2}{c^2})E_y + k_y k_z E_z = 0 \quad (5b)$$

$$k_x k_z E_x + k_y k_z E_y + (-k_x^2 - k_y^2 + \frac{\omega^2 n_z^2}{c^2})E_z = 0 \quad (5c)$$

where E_x, E_y, E_z, k_x, k_y and k_z are the components of $\mathbf{E}_0$ and **k**. This is a set of linear equations in E_x, E_y, E_z, and they have a non-trivial solution if their determinant is zero:

$$\det\begin{bmatrix}(-k_y^2-k_z^2+\frac{\omega^2 n_x^2}{c^2}) & k_xk_y & k_xk_z \\ k_xk_y & (-k_x^2-k_z^2+\frac{\omega^2 n_y^2}{c^2}) & k_yk_z \\ k_xk_z & k_yk_z & (-k_x^2-k_y^2+\frac{\omega^2 n_z^2}{c^2})\end{bmatrix}=0 \quad (6)$$

Multiplying out eqn (6), and rearranging the terms, we obtain

$$\frac{\omega^4}{c^4}-\frac{\omega^2}{c^2}\left(\frac{k_x^2+k_y^2}{n_z^2}+\frac{k_x^2+k_z^2}{n_y^2}+\frac{k_y^2+k_z^2}{n_x^2}\right)+\left(\frac{k_x^2}{n_y^2n_z^2}+\frac{k_y^2}{n_x^2n_z^2}+\frac{k_z^2}{n_x^2n_y^2}\right)(k_x^2+k_y^2+k_z^2)=0 \quad (7)$$

In the case of a uniaxial material, where $n_x=n_y=n_o$ and $n_z=n_e$ say, eqn 7 can be factorised into

$$\left(\frac{k_x^2}{n_o^2}+\frac{k_y^2}{n_o^2}+\frac{k_z^2}{n_o^2}-\frac{\omega^2}{c^2}\right)\left(\frac{k_x^2}{n_e^2}+\frac{k_y^2}{n_e^2}+\frac{k_z^2}{n_o^2}-\frac{\omega^2}{c^2}\right)=0\,. \quad (8)$$

Each of the factors in eqn 8 defines a surface in the space of vectors **k** — the **surface of wave normals**. The first factor defines a sphere and the second defines an ellipsoid. Therefore, for each direction of the wave normal, two wavevectors **k** are allowed. Values of **k** on the sphere correspond to the **ordinary rays** while values on the ellipsoid correspond to the **extraordinary rays**.

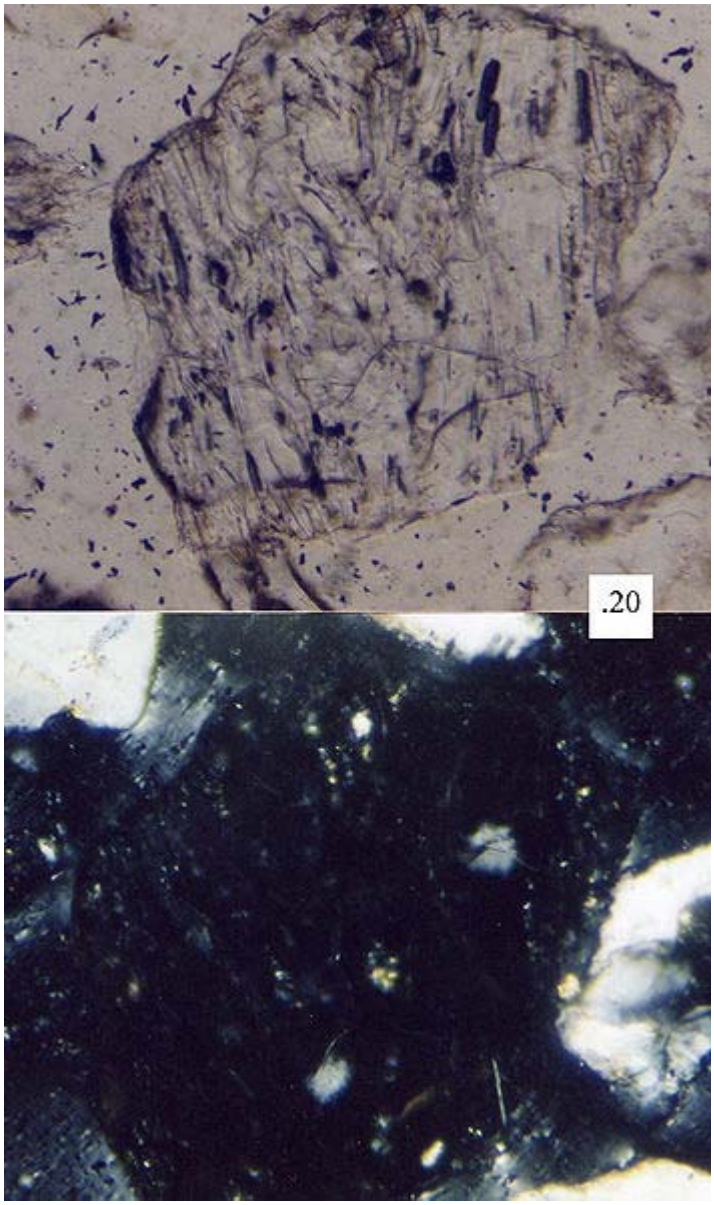
For a biaxial material, eqn (7) cannot be factorized in the same way, and describes a more complicated pair of wave-normal surfaces.

Birefringence is often measured for rays propagating along one of the optical axes (or measured in a two-dimensional material). In this case, **n** has two eigenvalues which can be labeled n_1 and n_2. **n** can be diagonalized by:

$$\mathbf{n}=\mathbf{R}(\chi)\cdot\begin{bmatrix}n_1 & 0\\ 0 & n_2\end{bmatrix}\cdot\mathbf{R}(\chi)^{\mathrm{T}} \quad (9)$$

where **R**(χ) is the rotation matrix through an angle χ. Rather than specifying the complete tensor **n**, we may now simply specify the *magnitude* of the birefringence Δ*n*, and *extinction angle* χ, where $\Delta n = n_1 - n_2$.

Extinction angle



A sand grain of volcanic glass under the petrographic microscope. Its amorphous nature makes it go extinct in cross-polarized light (bottom frame), and thus does not have an extinction angle. Scale box in millimeters.

Undulose extinction in quartz.

Extinction is a term used in optical mineralogy and petrology, which describes when cross-polarized light dims, as viewed through a thin section of a mineral in a petrographic microscope. An isotropic minerals, opaque (metallic) minerals, or amophous materials (glass) show no light (i.e. constant extinction). Anisotropic minerals will show one extinction for each 90 degrees of stage rotation.

The **Extinction angle** is the measure between the cleavage direction or habit of a mineral and the extinction. To find this, simply line up the cleavage lines/long direction with one of the cross hairs in the microscope, and turn the mineral until the extinction occurs. The number of degrees the stage was rotated is the extinction angle, between 0-89 degrees. 90 degrees would be considered zero degrees, and is known as parallel extinction. Inclined extinction is a measured angle between 1-89 degrees. Minerals with two cleavages can have two extinction angles, and minerals in which the multiple angles are the same are called symmetrical extinction. Minerals that have no cleavage or elongation can not have an extinction angle.

Minerals with undulose extinction, solid solution/zonation, or other factors (e.g. Bird's eye extinction in mica) that may inhibit this measure and may be more difficult to use.

Conoscopic interference pattern

A **Conoscopic interference pattern** or **interference figure** is the best way to determine if a mineral is uniaxial or biaxial and also for determining optic sign in optical mineralogy. The observed interference figure essentially shows all possible birefringence colors at once, including the extinctions (in dark bands called isogyres).

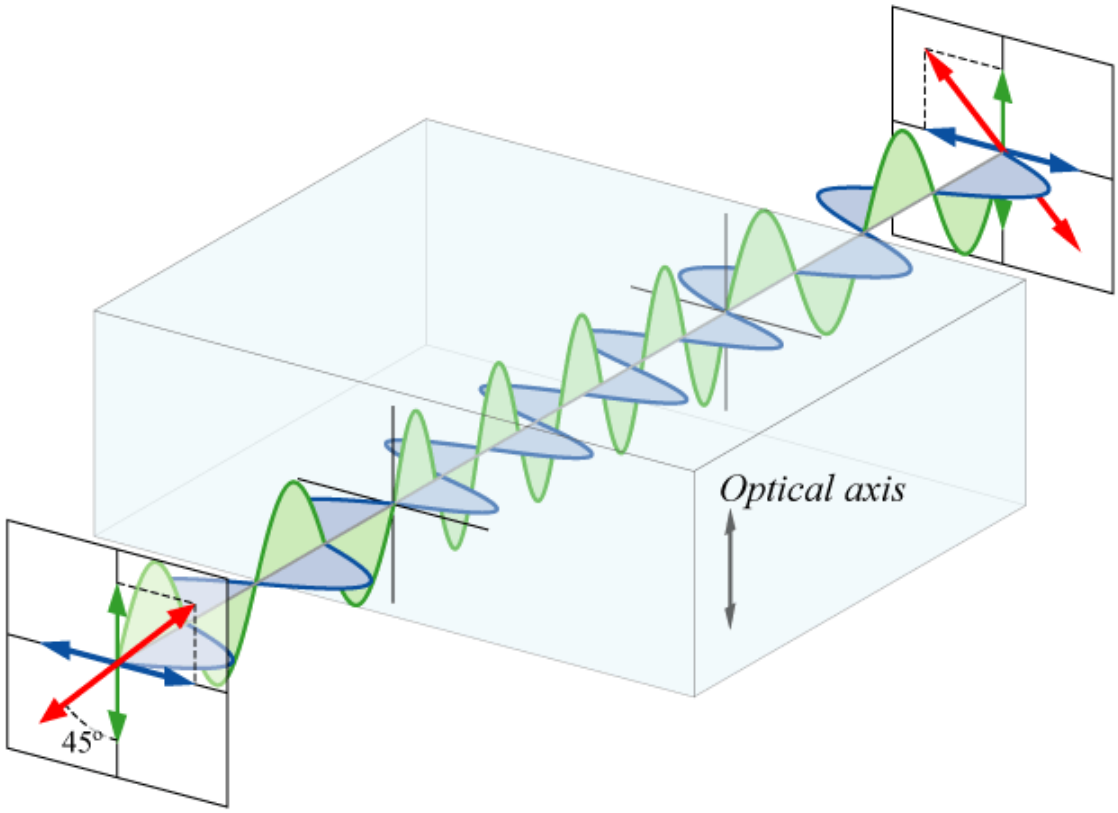
In optical mineralogy a petrographic microscope and cross-polarized light are often used to view the interference pattern. This is done by placing a Bertrand lens (Emile Bertrand, 1878) between a high-power microscope objective and the eyepiece. The microscope's condenser is brought up close underneath the specimen to produce a wide divergence of polarized rays through a small point. There are many other techniques used to observe the interference pattern.

A uniaxial mineral will show a typical 'Maltese' cross shape and its isogyres, which will revolve/orbit around a projection of the optical axis as the stage is rotated.

A biaxial mineral will typically show a saddle-shaped figure (with one isogyre thicker than the other, typically) that will often morph into to curved isogyres with rotation of the stage. The difference in these curved isogyres is known as the "2V" angle. In minerals that have far-off-center optic axes, only one part of the above sequence may be seen.

A Michel-Levy Chart is often used in conjunction with the interference pattern to determine useful information that aids in the identification of minerals.

Wave plate



A half-wave plate. Linearly polarized light entering a wave plate can be resolved into two waves, parallel (shown as green) and perpendicular (blue) to the optical axis of the wave plate. In the plate, the parallel wave propagates slightly slower than the perpendicular one. At the far side of the plate, the parallel wave is exactly half of a wavelength delayed relative to the perpendicular wave, and the resulting combination (red) is orthogonally polarized compared to its entrance state.

A **wave plate** or **retarder** is an optical device that alters the polarization state of a light wave travelling through it. A wave plate works by shifting the phase between two perpendicular polarization components of the light wave. A typical wave plate is simply a birefringent crystal with a carefully chosen orientation and thickness. The crystal is cut so that the extraordinary axis or "optic axis" is parallel to the surfaces of the plate. Light polarized along this axis travels through the crystal at a different speed than light with the perpendicular polarization, creating a phase difference. When the extraordinary index is smaller than the ordinary index, as in calcite, the extraordinary axis is called the "fast axis" and the perpendicular direction in the plane of the surfaces is called the "slow axis".

Depending on the thickness of the crystal, light with polarization components along both axes will emerge in a different polarization state. The wave plate is characterized by the

amount of relative phase, Γ, that it imparts on the two components, which is related to the birefringence Δn and the thickness L of the crystal by the formula

$$\Gamma = \frac{2\pi \, \Delta n \, L}{\lambda_0}$$

where λ_0 is the vacuum wavelength of the light. For instance a **quarter-wave plate** creates a quarter-wavelength phase shift and can change linearly polarized light to circular and vice versa. This is done by adjusting the plane of the incident light so that it makes 45° angle with the fast axis. This gives ordinary and extraordinary waves with equal amplitude.

The other common type of wave plate is a **half-wave plate**, which retards one polarization by half a wavelength, or 180 degrees. This type of wave plate changes the polarization direction of linear polarized light. Wave plates in general as well as polarizers can be described using the Jones matrix formalism, which uses a vector to represent the polarization state of light and a matrix to represent the linear transformation of a wave plate or polarizer.

Because of dispersion, a simple wave plate will impart a phase difference that depends on the wavelength of the light. Waveplates are thus manufactured to work for a particular range of wavelengths. The dispersion can be minimized by stacking two waveplates that differ by a tiny amount in thickness back-to-back, with the slow axis of one along the fast axis of the other. With this configuration, the relative phase imparted can be, for the case of a half-wave plate, half a wavelength rather than half plus an integer. This is called a **zero-order wave plate**. Like lenses, wave plates can also be made achromatic by combining materials with different dispersion.

For a single wave plate changing the wavelength of the light introduces a linear error in the phase. Tilt of the wave plate enters via 1/cos into the path length and thus only quadratically into the phase. For the extraordinary polarization the tilt also changes the refractive index to the ordinary via cos, so combined with the path length, the phase shift for the extraordinary light due to tilt is zero.

A polarization independent phase shift of zero order needs a plate with thickness of one wavelength. For Calcite the refractive index changes in the first decimal place, so that a true zero order plate is ten times as thick as one wavelength. For quartz and magnesium fluoride the refractive index changes in the second decimal place and true zero order plates are common for wave-lengths above 1 μm.

Chapter-5

Antimony Minerals

Berthierite

Berthierite

Berthierite

General	
Category	Mineral
Chemical formula	$FeSb_2S_4$
Strunz classification	02.HA.20

Identification	
Color	steel grey
Crystal system	Orthorhombic
Cleavage	poor/indistinct
Mohs scale hardness	2-3
Luster	metallic

Diaphaneity	opaque
Specific gravity	4.64

Berthierite is a mineral, a sulfide of iron and antimony with formula $FeSb_2S_4$. It is steel grey in colour with a metallic lustre which can be covered by an iridescent tarnish. Because of its appearance it is often mistaken for stibnite.

It was discovered in France in 1827 and named for the French chemist, Pierre Berthier.

Boulangerite

Boulangerite

Boulangerite, found in Romania

General

Category	Sulfosalt minerals
Chemical formula	$Pb_5Sb_4S_{11}$
Strunz classification	02.HC.15

Boulangerite is a sulfosalt mineral, lead antimony sulfide, formula $Pb_5Sb_4S_{11}$. It was named in 1837 in honor of French mining engineer Charles Boulanger. It forms metallic grey monoclinic crystals. Sometimes the crystals form a fine feathery mass which has been called plumosite.

Bournonite

Bournonite

Bournonite and baryte

General	
Category	Sulfosalt mineral
Chemical formula	$PbCuSbS_3$
Strunz classification	02.GA.50
Dana classification	3.4.3.2

Identification	
Color	Steel-gray to iron-black
Crystal habit	Crystals short prismatic to tabular, typically striated; commonly as subparallel aggregates. Also massive, granular to compact
Crystal system	Orthorhombic
Twinning	On {110}, commonly forming cross or cogwheel aggregates
Cleavage	[010] Imperfect

Fracture	Subconchoidal to uneven
Mohs scale hardness	2.5 - 3.0
Luster	Brilliant to dull
Streak	Steel-gray to iron-black
Diaphaneity	Opaque
Specific gravity	5.7 - 5.9
Pleochroism	Very weak

Bournonite is a sulfosalt mineral species, a sulfantimonite of lead and copper with the formula $PbCuSbS_3$.

It was first mentioned by Philip Rashleigh in 1797 as an ore of antimony and was more completely described in 1804 by French crystallographer and mineralogist Jacques Louis de Bournon (1751–1825), after whom it was named. The name given by Bournon himself (in 1813) was **endellione**, since used in the form **endellionite**, after the locality in Cornwall where the mineral was first found.

The crystals are orthorhombic, and are generally tabular in habit owing to the predominance of the basal pinacoid; numerous smooth bright faces are often developed on the edges and corners of the crystals. Usually, however, the crystals are twinned, the twin-plane being a face of the prism (m); the angle between the faces of this prism being nearly a right angIe (86 20), the twinning gives rise to cruciform groups and when it is often repeated the group has the appearance of a cog-wheel, hence the name *Rdelerz* (wheel-ore) of the Kapnik miners. The repeated twinning gives rise to twin-lamellae, which may be detected on the fractured surfaces, even of the massive material.

It is a mineral in medium temperature hydrothermal vein deposits. It commonly occurs with galena, tetrahedrite, sphalerite, chalcopyrite, pyrite, stibnite, zinkenite, siderite, quartz, rhodochrosite, dolomite and barite.

It was first described for an occurrence in Wheal Boys in the parish of St Endellion in Cornwall, it was found associated with jamesonite, sphalerite and siderite. Later, still better crystals were found in another Cornish mine, namely, Herodsfoot mine near Liskeard, which was worked for argentiferous galena. Fine crystals of large size have been found with quartz and siderite in the mines at Neudorf in the Harz, and with sphalerite and tetrahedrite at Cavnic near Baia Mare in Romania. It has been reported from a large number of other localities.

Cylindrite

Cylindrite

Trinacria Mine, Callipampa, Poopó Province, Oruro Department, Bolivia

General

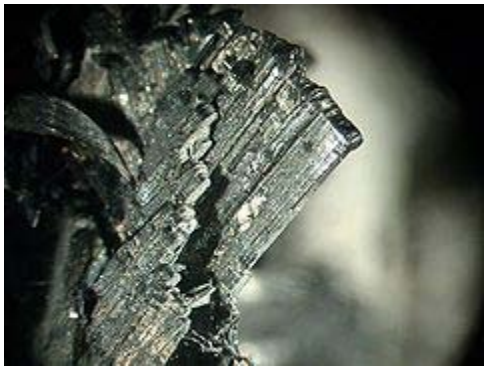
Category	Sulfosalt minerals
Chemical formula	$Pb_3Sn_4FeSb_2S_{14}$
Strunz classification	02.HF.25a

Cylindrite is a sulfosalt mineral containing tin, lead, antimony and iron with formula: $Pb_3Sn_4FeSb_2S_{14}$. It forms triclinic pinacoidal crystals which often occur as tubes or cylinders which are in fact rolled sheets. It has a black to lead grey metallic colour with a Mohs hardness of 2 to 3 and a specific gravity of 5.4.

It was first discovered in the Santa Cruz mine, Oruro Department, Bolivia in 1893. The name arises from its curious cylindrical crystal form it almost unique among mineral kingdom.

Franckeite

Franckeite



Franckeite var. Potosíite, San José Mine, Cercado Province Bolivia. Field of view about 10mm.

General	
Category	Sulfosalt mineral
Chemical formula	$(Pb,Sn^{2+})_6Fe^{2+}Sn_2Sb_2S_{14}$
Strunz classification	02.HF.25b
Dana classification	03.01.04.02

Identification	
Color	Grayish black
Crystal habit	Typically in spherical, rosette aggregates of thin plates; commonly massive, radiated, or foliated
Crystal system	Triclinic - Pinacoidal H-M Symbol (1) Space Group: P1
Twinning	Complex
Cleavage	{010}, perfect
Tenacity	Flexible, inelastic; slightly malleable

Mohs scale hardness	2.5 - 3
Luster	Metallic
Streak	Grayish black
Diaphaneity	Opaque
Specific gravity	5.88 – 5.92
Pleochroism	Weak

Franckeite, chemical formula $Pb_5Sn_3Sb_2S_{14}$, belongs to a family of complex sulfide minerals. Franckeite is a sulfosalt. It is closely related to cylindrite.

It was first described in 1893 for an occurrence in Chocaya, Potosí Department, Bolivia. It is named after the mining engineers, Carl and Ernest Francke. It can be found in Bolivia at Poopó in Oruro and at Las Aminas, southeast of Chocaya, in Potosi. Franckeite has an average density of 5.7 and can be both grayish black, blackish gray in color.

It occurs in hydrothermal silver-tin deposits in Bolivia and in contact metamorphosed limestone deposit in the Kalkar quarry in California. It occurs with cylindrite, teallite, plagionite, zinkenite, cassiterite, wurtzite, pyrrhotite, marcasite, arsenopyrite, galena, pyrite, sphalerite, siderite and stannite.

Kermesite

Kermesite

General	
Category	Oxysulfide
Chemical formula	(Sb_2S_2O)
Strunz classification	02.FD.05
Dana classification	02.13.01.01

Identification	
Color	Red to cherry red
Crystal habit	Acicular, fibrous, radial
Crystal system	Triclinic Pinacoidal 1
Cleavage	Perfect {100}, parting on {010}
Fracture	Brittle
Tenacity	Sectile
Mohs scale hardness	1 - 2
Luster	Adamantine to semimetallic
Streak	Brownish red
Diaphaneity	Translucent, Opaque
Specific gravity	4.5 - 4.8+
Optical properties	Biaxial (+)

Refractive index nα = 2.720 nβ = 2.740 nγ = 2.740

Pleochroism None

Kermesite or antimony oxysulfide is also known as **red antimony** (Sb_2S_2O) . The name kermesite is a name derived from the Persian *qurmizq* (زمرق), which later became "crimson" and was given to the mineral's color which ranges from cherry red to a deep red bordering on black. Kermesite is the result of partial oxidation between stibnite (Sb_2S_3) and other antimony oxides such as valentinite (Sb_2O_3) or stibiconite ($Sb_3O_6(OH)$). Under certain conditions with oxygenated fluids the transformation of all sulfur to oxygen would occur but kermesite occurs when that transformation is halted.

Lustrous, acicular, deep wine-red kermesite crystals, up to 4 cm.long, on massive sulfide matrix, from Pezinok, Malé Karpaty Mts, Bratislava Region, Slovakia.

Mining and specimens

Deposits of this mineral have been found all over the world, however notable deposits have been found in Braunsdorf, near Freiberg, Saxony, Germany; Pernek, Pezinok, and Pribram, Czechoslovakia; the Lac Nicolet mine, South Ham Township, Wolfe County, Quebec, Canada; Sombrerete, Zacatecas, Mexico; Santa Cruz and San Francisco mines, Poopo, Oruro, Bolivia; Que Que, Zimbabwe; Djebel Haminate, Algeria; Broken Hill, New South Wales, Australia; Mohave, Kern County, California and Burke, Shoshone County, Idaho.

History and uses

Kermesite or red antimony has been used as early as the Old Kingdom's 6th Dynasty in ancient Egypt (c.2345-2181 BCE) in lip cosmetics and in the 18th Dynasty Queen Hatshepsut (Maatkare) (1498-1483 BCE) negotiated with the Land of Punt for it s colored antimony deposits. Besides stibnite which was used for eye liner red antimony is one of the oldest minerals used in cosmetics. Further archaeological evidence indicates that antimony levels were higher in ancient Egyptian female remains which had exposure to both antimony compounds (Bencze, 1994). Because of its color, the precipitate of kermesite was used as a coloring agent and in alchemy. Because of alchemy's focus on material transformation as evidenced by color, red antimony was used to produce the red state. Kermesite is the mineral state for Kermes mineral which was used extensively in the medical field for centuries

Presently, kermesite is collected for the beauty of its crystal metallic structure and not used in either cosmetics or the medical field any longer due to the toxic affects that it shares with antimony; less harmful substitutes have been found using both organic and pharamceutical production.

Miargyrite

Miargyrite

Miargyrite, Flint district, Idaho

General	
Category	Mineral
Chemical formula	$AgSbS_2$
Strunz classification	02.HA.10

Identification	
Crystal system	Monoclinic
Mohs scale hardness	2-2.5
Streak	red
Specific gravity	5.2

Miargyrite is a mineral, a sulfide of silver and antimony with the formula $AgSbS_2$. It is a dimorph of Cuboargyrite. Originally discovered in the Freiberg district of Germany in 1824, it has subsequently been found in many places where silver is mined. It usually

occurs in low temperature hydrothermal deposits. and forms black metallic crystals which may show a dark red internal reflection. The streak is also red.

Miargyrite is named from the Greek *meyon*, "smaller" and *argyros*, "silver," as its silver content is lower than most silver sulfides.

Miargyrite, San Genaro Mine, Castrovirreyna District, Peru. Size 6.1 x 4.2 x 2.7 cm.

Polybasite

Polybasite

Locality: Arizpe, Sonora, Mexico. Scale bar is one inch (2.5 cm.)

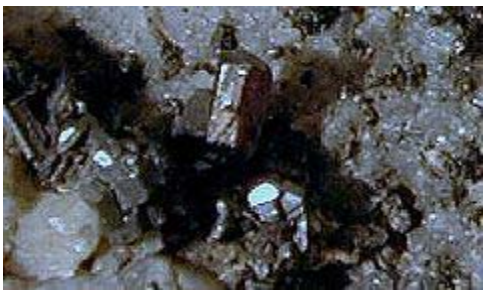
General	
Category	Sulfosalt minerals
Chemical formula	$[(Ag,Cu)_6(Sb,As)_2S_7][Ag_9CuS_4]$
Strunz classification	02.GB.15

Polybasite is a sulfosalt mineral of silver, copper, antimony and arsenic. Its chemical formula is $[(Ag,Cu)_6(Sb,As)_2S_7][Ag_9CuS_4]$.

It forms black monoclinic crystals (thin, tabular, with six corners) which can show dark red internal reflections. It has a Mohs hardness of 2.5 to 3. It is found worldwide and is an ore of silver. The name comes from the number of base metals in the mineral.

Unusual polybasite specimen from Mayo Mining District, Yukon Territory, Canada. Size 3.0 x 2.2 x 1.3 cm.

Pyrargyrite

Pyrargyrite

General

Category Mineral

Chemical formula	silver antimony sulfide:Ag_3SbS_3
Strunz classification	02.GA.05
Identification	
Color	dark red to red-black
Crystal habit	Include prismatic crystals with rhombohedral and scalenohedral faces forming terminations. There is no perpendicular mirror plane and therefore a hemimorphic crystal can be seen, in some rare examples, with differing terminations at the top and bottom of the crystal. Typical crystals are poorly formed and modified heavily by secondary faces. Also found massive.
Crystal system	trigonal; 3m
Cleavage	Sometimes distinct in three directions forming rhombohedrons
Fracture	conchoidal
Mohs scale hardness	2.5
Luster	adamantine
Streak	dark cherry red
Specific gravity	approximately 5.8
Refractive index	translucent to nearly opaque
Other characteristics	darkens upon exposure to light; crystals are frequently striated

Pyrargyrite is a sulfosalt mineral consisting of silver sulfantimonide, Ag_3SbS_3. Known also as dark red silver ore or ruby silver, it is an important source of the metal.

It is closely allied to, and isomorphous with, the corresponding sulfarsenide known as proustite or light red silver ore. Ruby silver or red silver ore (German *Rotgiiltigerz*) was mentioned by Georg Agricola in 1546, but the two species so closely resemble one another that they were not completely distinguished until chemical analyses of both were made.

Both crystallize in the ditrigonal pyramidal (hemimorphic-hemihedral) class of the rhombohedral system, possessing the same degree of symmetry as tourmaline. Crystals are perfectly developed and are usually prismatic in habit; they are frequently attached at one end, the hemimorphic character being then evident by the fact that the oblique striations on the prism faces are directed towards one end only of the crystal. Twinning according to several laws is not uncommon. The hexagonal prisms of pyrargyrite are usually terminated by a low hexagonal pyramid or by a drusy basal plane.

The color of pyrargyrite is usually greyish-black and the lustre metallic-adamantine; large crystals are opaque, but small ones and thin splinters are deep ruby-red by transmitted light, hence the name, from the Greek *pyr* and *argyros*, "fire-silver" in allusion to color and silver content, given by E. F. Glocker in 1831. The streak is purplish-red, thus differing markedly from the scarlet streak of proustite and affording a ready means of distinguishing the two minerals. The Mohs hardness is 2.75, and the specific gravity 5.85. The refractive indices ($n\omega=3.084$ $n\varepsilon=2.881$) and birefringence ($\delta=0.203$) are very high. There is no very distinct cleavage and the fracture is conchoidal. The mineral occurs in metalliferous veins with calcite, argentiferous galena, native silver, native arsenic, &c. The best crystallized specimens are from Sankt Andreasberg in the Harz, Freiberg in Saxony, and Guanajuato in Mexico. It is not uncommon in many silver mines in the United States, but rarely as distinct crystals; and it has been found in some Cornish mines.

Pyrargyrite silver ore from the Comstock Lode, Storey Co., Nevada, USA

Although the red silver ores afford a good example of isomorphism, they rarely form mixtures; pyrargyrite rarely contains as much as 3% of arsenic replacing antimony, and the same is true of antimony in proustite. Dimorphous with pyrargyrite and proustite respectively are the rare monoclinic species pyrostilpnite or fireblende (Ag_3SbS_3) and xanthoconite (Ag_3AsS_3): these four minerals thus form an isodimorphous group.

Stibnite

Stibnite

Stibnite in the Carnegie Museum of Natural History

General	
Category	Sulfide mineral
Chemical formula	Sb_2S_3
Strunz classification	02.DB.05a
Crystal symmetry	Orthorhombic 2/m 2/m 2/m
Unit cell	a = 11.229 Å, b = 11.31 Å, c = 3.8389 Å; Z = 4

Identification	
Color	Lead-gray, tarnishing blackish or iridescent; in polished section, white
Crystal habit	Massive, radiating and elongated crystals. Massive and granular
Crystal system	Orthorhombic, Dipyramidal
Cleavage	Perfect and easy on {010}; imperfect on {100} and {110}
Fracture	Subconchoidal
Tenacity	Highly flexible but not elastic; slightly

	sectile
Mohs scale hardness	2
Luster	Splendent on fresh crystals surfaces, otherwise metallic
Streak	Similar to color
Diaphaneity	Opaque
Specific gravity	4.63
Solubility	decomposed with hydrochloric acid
Other characteristics	Anisotropism: Strong
Major varieties	
Metastibnite	Earthy, reddish deposits

Stibnite, sometimes called **antimonite**, is a sulfide mineral with the formula Sb_2S_3. This soft grey material crystallizes in an orthorhombic space group. It is the most important source for the metalloid antimony. The abbreviation for antimony, Sb, is taken from stibnite.

Structure

Crystals from Henan Province, China (size: 16.8 x 5.4 x 5.4 cm)

Stibnite has a structure similar to that of arsenic trisulfide, As_2S_3. The Sb(III) centers, which are pyramidal and three-coordinate, are linked via bent two-coordinate sulfide ions. It is grey when fresh, but can turn superficially black due to oxidation in air.

Uses

Pastes of Sb_2S_3 powder in fat or in other materials have been used since 3000 BC as eye cosmetics in the Middle East and farther afield; in this use, Sb_2S_3 is called kohl. It was used to darken the brows and lashes, or to draw a line around the perimeter of the eye.

Antimony trisulfide finds use in pyrotechnic compositions, namely in the glitter and fountain mixtures. Needle-like crystals, "Chinese Needle", are used in glitter compositions and white pyrotechnic stars. The "Dark Pyro" version is used in flash powders to increase their sensitivity and sharpen their report. It is also a component of modern safety matches. It was formerly used in flash compositions, but its use was abandoned due to toxicity and sensitivity to static electricity.

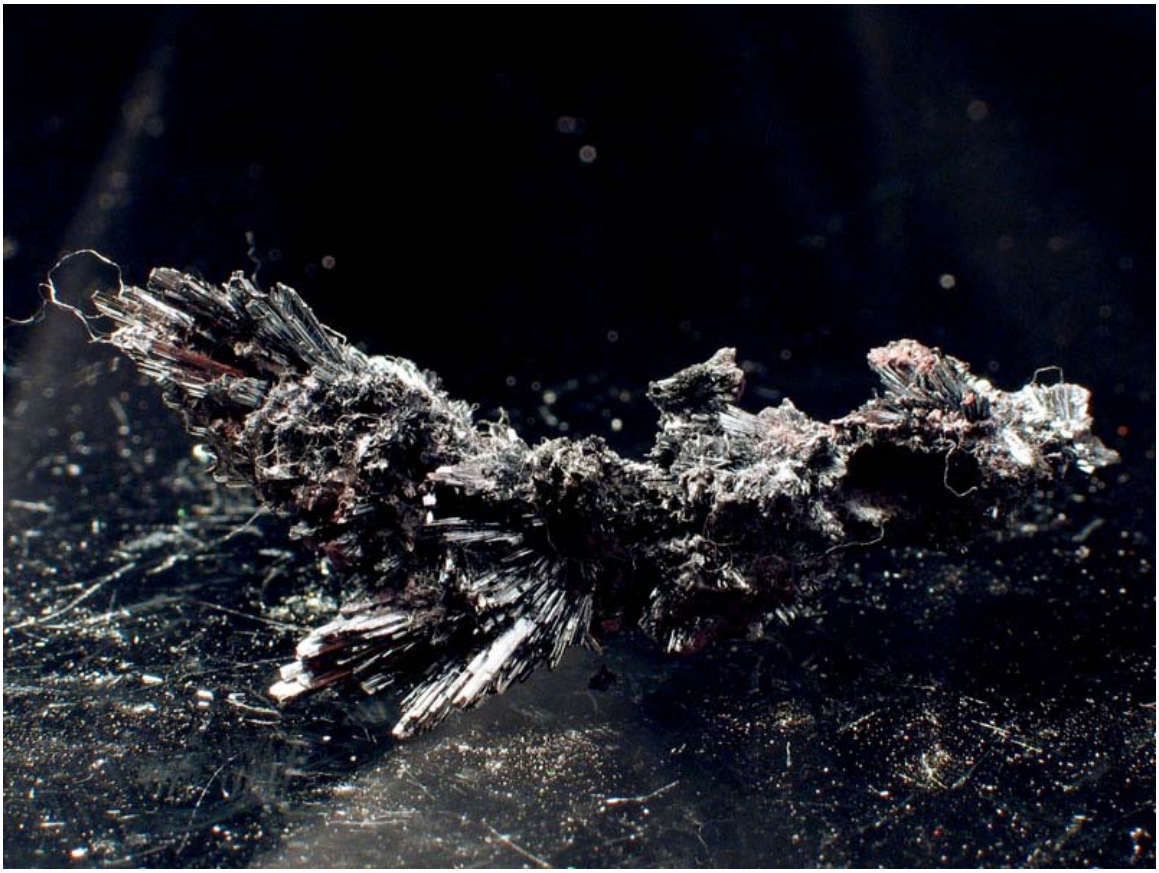
The natural sulfide of antimony, stibnite, was known and used in Biblical times, as a medication and in Islamic/pre-Islamic times as a cosmetic. The Sunan Abi Dawood reports, “prophet Muhammad said: 'Among the best types of collyrium is antimony (ithmid) for it clears the vision and makes the hair sprout.'”

Occurrence

Needles of stibnite within a transparent crystal of calcite (size: 4.5 x 3.5 x 1.8 cm)

Small deposits of stibnite are common, but large deposits are rare. It occurs in Canada, Mexico, Peru, Japan, China, Germany, Romania, Italy, France, England, Algeria, and Kalimantan, Borneo. In the United States it is found in Arkansas, Idaho, Nevada, California, and Alaska.

As of May 2007, the largest specimen on public display (1000 pounds) is at the American Museum of Natural History. The largest documented single crystals of stibnite measured ~60x5x5 cm^3 and originated from different locations including Japan, France and Germany.



Chapter-6

Barium Minerals

Barytocalcite

Barytocalcite

Barytocalcite from England

General	
Category	Carbonate minerals
Chemical formula	$BaCa(CO_3)_2$
Strunz classification	05.AB.45

Barytocalcite is a barium calcium carbonate mineral with chemical formula: $BaCa(CO_3)_2$. It crystallizes in the monoclinic crystal system typically as massive to druzey accumulations of transparent white to yellow to grey aggregates of slender prismatic crystals. It has a Mohs hardness of 4 and a specific gravity of 3.64 to 3.66.

It was first described in 1824 for an occurrence in Blagill Mine in North Pennines, Cumbria (Cumberland), England.

Celsian

Celsian

celsian (transparent/gray in photo) in sanbornite (white) matrix—Incline, Maricopa County, California

General	
Category	Feldspar
Chemical formula	$BaAl_2Si_2O_8$

Identification	
Color	usually colorless and transparent
Crystal habit	adularia, larger, snout crystals, and long, slender to acicular.
Crystal system	monoclinic
Twinning	manebach twins on (001), baveno twins (021), rare lamellar twinning
Cleavage	c(001) perfect cleavage and a b(010) good cleavage
Mohs scale hardness	6

Luster	pearly to non-fluorescent
Diaphaneity	usually colorless and transparent
Density	3.31 to 3.33 g/cm³
Optical properties	2V angle which is approximately 880
Refractive index	moderate relief
Birefringence	0.014, biaxial -

Celsian is an uncommon feldspar mineral, **barium aluminosilicate**, $BaAl_2Si_2O_8$. The mineral occurs in contact metamorphic rocks with significant barium content. Its crystal system is monoclinic, and it is white, yellow, or transparent in appearance. In pure form, it is transparent. Synthetic barium aluminosilicate is used as a ceramic in dental fillings and other applications.

The mineral is named after Anders Celsius.

Composition

Celsian is a barium feldspar with a chemical composition $BaAl_2Si_2O_8$. It forms part of the feldspar group and belongs to the celsian-hyalophane series and the celsian-orthoclase series. It has some resemblance to anorthite, and it has four distinct polymorphs. The essential elements are Si,Al,O and Ba. Some common impurities in the mineral are Fe, Ti, Mg,K and Ca. Celsian is stable from room temperature up to 1590 °C (Lin and Foster,1968) .The most common trace elements are potassium and calcium, in an analysis of the approximate chemical composition of celsian the following wt% were found: • SiO_2—35.1 • Al_2O_3---26.8 • BaO----35.8 • K_2O-----2.3 Total:100.0 (Newham and Megaw,1960).

Geologic occurrence

Celsian is of limited occurrence. Most of the barium feldspars are associated with exhalative hydrothermal processes and low-and medium-grade metamorphism (Moro and Cembranos and Fernandez, 2001). It is also associated with sedimentary and meta sedimentary rocks, manganese, ferromanganese and barite deposits. Barium is rarely found in its pure form since it quickly oxidizes with air, it is more commonly found and extracted from barite, in other cases the barium may be present due to metamorphic events.

Celsian can be found in places like Wales, Zamora (Spain), Alaska, California, Sweden and Japan, also with hendricksite on the Franklin mines in New Jersey (N.J), others locations of Celsian are showned in figure 1.

Structure

The symmetry in celsian is somewhat different from the symmetry normally found in feldspars. It is monoclinic with a body centered lattice similar to those of anorthite. Not sufficient evidence has been found to suggest that celsian lacks a center of symmetry, so its space group is I 2/c (Newnham and Megaw, 1960). The space group differs from others of its group like orthoclase, albite and body center anorthite are C2/m, C1bar and I1bar.

X-ray analysis shows that the values for the lattice parameters *a*, *b*, *c* axes and angles are approximately *a*=863 pm, *b*=131.0 pm, *c*=1400 pm and β=116°, θ=90°(Gay, 1956).

There are 8 formula units per cell, and the general position is eightfold, so all atoms can lie in general positions (Newnham and Megaw,1960). This structure is very similar to that of orthoclase and sanidine but differs in a couple of ways: 1. The distribution of Si and Al. 2. The coordinates of all the atoms. The distribution of silicon and aluminum along the tetrahedral sites mixed with the nature of the barium atom makes an impact on the surrounding silicate framework (Newham and Megaw,1960). The Si-Al bonds are partially ordered, and in some cases the aluminum substitute's silicon.

The order in celsian is very simple, each aluminum tetrahedron is surrounded by four silicon tetrahedral, and vice versa (Newham and Megaw,1960). Also there is another type of transformation besides aluminum-silicon, where silicon-poor goes into a silicon-rich network that involves having to simultaneously be a replacement of Al, and Si at other sites.

The barium ion has an irregular configuration close to the one in potassium in the feldspars. Each barium has an oxygen close, and thanks to this configuration it has a strong effect on the silicon-oxygen-silicon bond angles.

Polymorphism of Celsian

There are four distinctive polymorphs of Celsian, two of them are the natural minerals and the other two are synthetic products. The first are paracelsian and celsian, the second ones are hexacelsian and the other one is related to the mineral cymrite (Lin and foster, 1967). The order of increasing stability is paracelsian→hexacelsian→celsian in a temperature range between 500C to the 1000C.

As temperature rises from the 1,600 °C to 1,760 °C it goes from celsian to a reversible form of hexacelsian. Paracelsian is less stable than the other two and Celsian is the most stable.

TwiningBarium feldspars occur in optically uniform crystals where the twining is poorly developed, except on coarse crystals. Eighteen crystals forms have been identified; eleven of them coincide with those known for the orthoclase. On this structures it was found manebach twins on (001), baveno twins (021). Some samples of celsian were

found to have a rare lamellar twinning (Spencer, 1941). Figure 5 : Celsian crystals from Benalt mine, Carnavoshire. (Spencer, 1941)

Physical properties

Celsian shows a c(001) perfect cleavage and a b(010) good cleavage, which marks the difference with its polymorph paracelsian which has a [110] indistinct cleavage.There are different crystals habits like adularia, larger, snout crystals (spencer, 1941), and long, slender to acicular. It is usually colorless and transparent with a pearly to non-fluorescent luster.

The density is about 3.31 to 3.33 g/cm³. This might be the case due to some impurities in the structure of the mineral. It has a hardness of 6 on the Moh's scale, this hardness is due to the short length of the bond in the structure, since is relative short tends to be harder. Some optical properties

Some other optical properties are the 2V angle which is approximately 880 with a maximum birefringence of 0.014, biaxial with a negative sign (Newnham and Megaw, 1960). It has a moderate relief.

Uses

Celsian has very attractive features such as chemical stability and high mechanical resistance, which can be favourably exploited in order to obtain enhanced-performance composites with respect to bulk glass. (Cannillo, Carlier, Manfredini, Montorsi, and Siligardi 2006). Many studies shows that by increasing the amount of celsian phases in the glasses results in increased bulk of crytaslization.(Khater and Idris, 2004)

The uses of celsian are mostly related to glass and ceramics. This uses are usually achieved by the preparation of pure monoclinic celsian.

Harmotome

Harmotome

Harmotome

General

Category zeolites

Chemical formula $(Ba_{0.5},Ca_{0.5},Na,K)_5Al_5,Si_{11}O_{32}\cdot 12(H_2O)$

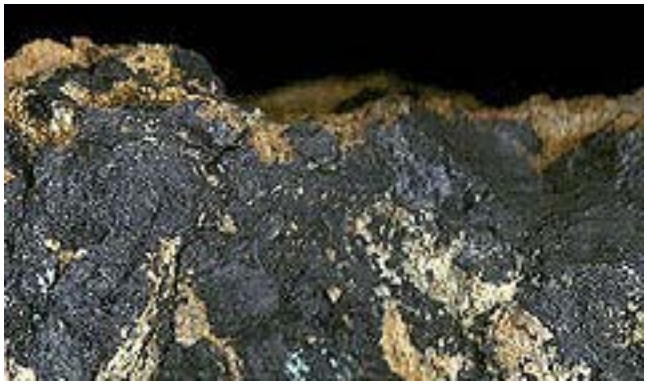
Harmotome is a mineral, one of the rarer zeolites; a hydrated barium silicate with formula: $(Ba_{0.5},Ca_{0.5},Na,K)_5Al_5,Si_{11}O_{32}\cdot 12(H_2O)$. It forms vitreous white well defined monoclinic crystals, often associated with calcite and other zeolites. It has a Mohs hardness of 4 to 5 and a specific gravity of 2.44 to 2.5.

Name and discovery

Named from the greek words *harmos* (I combine) and *temseis* (I cut) because the pyramid divides parallel to the plane that passes through the terminal edges. It was first described in 1801 from an occurrence in the Harz Mountains, Lower Saxony, Germany.

Psilomelane

Psilomelane



A native sample of psilomelane

General	
Category	Mineral
Chemical formula	The general formula $Ba(Mn^{2+})(Mn^{4+})_8O_{16}(OH)_4$ or as $(Ba,H_2O)_2Mn_5O_{10}$

Barium Manganese Oxide Hydroxide

Identification	
Molar mass	590.03 gm
Color	black with gray pyrolusite bands
Crystal habit	Botryoidal, Mammillary, Reniform
Crystal system	monoclinic
Cleavage	none
Fracture	conchoidal and uneven
Mohs scale hardness	5.0 - 6.0
Luster	Sub-Metallic, Dull
Streak	brownish black
Diaphaneity	Opaque
Specific gravity	3.7 - 4.7
Polish luster	vitreous to subadamantine
Solubility	in hydrochloric acid
Other characteristics	hard black manganese oxides such as hollandite and romanechite

Polished specimen of manganese ore from the Batesville, Arkansas district. Slab of manganese ore showing an intimate mixture of hausmannite and psilomelane in a roughly zonal arrangement and a radiating mass of white barite at the center. The light steel-gray mineral and the black mineral immediately adjacent to the barite are **psilomelane**. The rest of the black mineral is **hausmannite.** Natural size.

Psilomelane, also known as **black hematite**, is a group name for hard black manganese oxides such as hollandite and romanechite. Psilomelane consists of hydrous manganese oxide with variable amounts of barium and potassium.

Formula

Generalized formula may be represented as $Ba(Mn^{2+})(Mn^{4+})_8O_{16}(OH)_4$ or as $(Ba,H_2O)_2Mn_5O_{10}$. It is sometimes considered to be a hydrous manganese manganate, but

of doubtful composition. The amount of manganese present corresponds to 70-80% of manganous oxide with 10-15% of available oxygen.

Characteristics

Psilomelane is amorphous and occurs as botryoidal and stalactitic masses with a smooth shining surface and submetallic lustre. The mineral is readily distinguished from other hydrous manganese oxides (manganite and wad) by its greater hardness 5 to 6; the specific gravity varies from 3.7 to 4.7. The streak is brownish black and the fracture smooth. Owing to its amorphous nature, the mineral often contains admixed impurities, such as iron hydroxides. It is soluble in hydrochloric acid with evolution of chlorine gas.

History and occurrence

The name has reference to this characteristic appearance, from the Greek for (naked, smooth) and (black); a Latinized form is calvonigrite, and a German name with the same meaning is **Schwarzer Glaskopf**. It is a common and important ore of manganese, occurring under the same conditions and having the same commercial applications as pyrolusite. It is found at many localities; amongst those which have yielded typical botryoidal specimens may be mentioned the Restormel iron mine at Lostwithiel in Cornwall, Brendon Hills in Somerset, Hoy in Orkney, Sayn near Coblenz, and Crimora in Augusta county, Virginia. With pyrolusite it is extensively mined in Vermont, Virginia, Arkansas, and Nova Scotia.

Psilomelane is also cut, shaped, and polished for a variety of jewelry applications.

Romanèchite

Romanèchite

Romanèchite, La Negrita Mine, Rio Negro, Argentina

General	
Category	Oxide minerals
Chemical formula	$(Ba,H_2O)_2(Mn^{+4},Mn^{+3})_5O_{10}$
Strunz classification	04.DK.10

Romanèchite ($(Ba,H_2O)_2(Mn^{+4},Mn^{+3})_5O_{10}$) is the primary constituent of psilomelane, which is a mixture of minerals. Most psilomelane is not pure romanechite, so it is incorrect to consider them synonyms. Romanèchite is a valuable ore of manganese, which is used in steelmaking. It has a monoclinic crystal structure, a hardness of 6 and a specific gravity of 4.7-5. It is associated with hematite, barite, pyrolusite, quartz and other manganese oxide minerals. It has been found in France, Germany, England, Brazil and various parts of the United States, including Arizona, Virginia and Michigan.

Witherite

Witherite	

Witherite from Cave-in-Rock (size: 4.9 x 3.7 x 3.2 cm)

General	
Category	Carbonate mineral
Chemical formula	$BaCO_3$
Strunz classification	05.AB.15
Crystal symmetry	Orthorhombic dipyramidal (2/m 2/m 2/m)
Unit cell	a = 5.31 Å, b = 8.9 Å, c = 6.43 Å; Z = 4

Identification	
Color	Colorless, white, pale gray, with possible tints of pale yellow, pale brown, or pale green
Crystal habit	Striated short prismatic crystals, also botryoidal to spherical, columnar fibrous, granular, massive.
Crystal system	Orthorhombic
Twinning	On {110}, universal
Cleavage	Distinct on {010} poor on on {110}, {012}

Fracture	Subconchoidal
Mohs scale hardness	3.0 - 3.5
Luster	Vitreous, resinous on fractures
Streak	White
Diaphaneity	Subtransparent to translucent
Specific gravity	4.3
Optical properties	Biaxial (-)
Refractive index	$n_\alpha = 1.529$ $n_\beta = 1.676$ $n_\gamma = 1.677$
Birefringence	$\delta = 0.148$
2V angle	Measured: 16°, calculated: 8°
Dispersion	Weak
Ultraviolet fluorescence	Fluorescent and phosphorescent, short UV=bluish white, long UV=bluish white

Witherite is a barium carbonate mineral, $BaCO_3$, in the aragonite group. Witherite crystallizes in the orthorhombic system and virtually always is twinned. The mineral is colorless, milky white, grey, pale yellow, green, to pale brown. The specific gravity is 4.3, which is high for a translucent mineral. It fluoresces light blue under both long and short-wave UV light, and is phosphorescent under short-wave UV light.

Two sharp pseudohexagonal crystals of witherite on calcite from Hardin County, Illinois (size: 6.4 x 5.4 x 3.4 cm)

Witherite forms in low-temperature hydrothermal environments. It is commonly associated with fluorite, celestine, galena, barite, calcite and aragonite. Witherite occurrences include: Cave-in-Rock, Illinois, USA; Alston Moor, Cumbria, Anglezarke, Lancashire and Burnhope, County Durham, England; Thunder Bay area, Ontario, Canada, Germany and Poland (Tarnowskie Góry and Tajno at Suwałki Region).

Witherite was named for William Withering (1741-1799) an English physician and naturalist.

Risk to Human Health

The 18th century naturalist Dr. Leigh recorded its lethal effects after the death of a farmer's wife and child. James Watt Jnr. experimented with the mineral on animals and he recorded the same lethal properties. Until the 18th century farmers at Anglezarke used the mineral as rat poison.

Industrial Use

Another experiment was conducted by Josiah Wedgwood who used it in his 'Jasper ware', the mineral had previously been considered as worthless.

Chapter-7

Silver Minerals

Acanthite

Acanthite

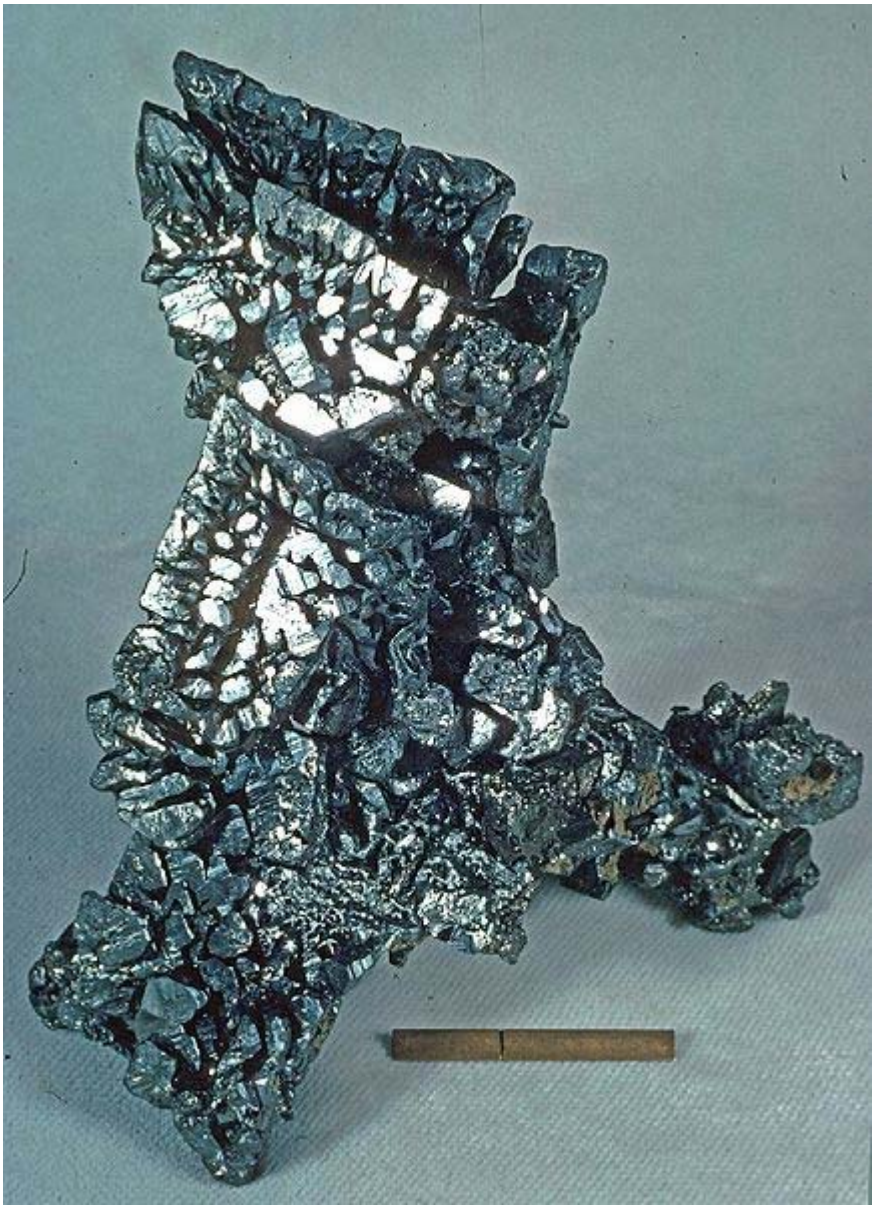
Acanthite on calcite - Locality: Freiberg District, Erzgebirge, Saxony, Germany - Scale is one inch with a rule at one cm

General	
Category	Sulfide mineral
Chemical formula	Ag_2S

Strunz classification	02.BA.30a
Crystal symmetry	Monoclinic 2/m
Unit cell	a = 4.229 Å, b = 6.931 Å, c = 7.862 Å; β = 99.61°; Z = 4
Identification	
Color	Iron-black
Crystal habit	Primary crystals rare, prismatic to long prismatic, elongated along [001], may be tubular; massive. Commonly paramorphic after the cubic high-temperature phase ("argentite"), of original cubic or octahedral habit
Crystal system	Monoclinic prismatic
Twinning	Polysynthetic on {111}, may be very complex due to inversion; contact on {101}
Cleavage	Indistinct
Fracture	Uneven
Tenacity	Sectile
Mohs scale hardness	2.0 - 2.5
Luster	Metallic
Streak	Black
Diaphaneity	Opaque
Specific gravity	7.20 - 7.22

Acanthite, Ag_2S, crystallizes in the monoclinic system and is the stable form of silver sulfide below 173 °C. Argentite is the stable form above that temperature. As argentite cools below that temperature its cubic form is distorted to the monoclinic form of acanthite. Below 173 °C acanthite forms directly. Acanthite is the only stable form in normal air temperature.

Occurrence



Acanthite - Locality: Chispas Mine, Arizpe, Mun. de Arizpe, Sonora, Mexico - Scale is one inch with a rule at one cm

Acanthite is a common silver mineral in moderately low-temperature hydrothermal veins and in zones of supergene enrichment. It occurs in association with native silver, pyrargyrite, proustite, polybasite, stephanite, aguilarite, galena, chalcopyrite, sphalerite, calcite and quartz.

Acanthite was first described in 1855 for an occurrence in the Jáchymov (St Joachimsthal) District, Krušné Hory Mts (Erzgebirge), Karlovy Vary Region, Bohemia,

Czech Republic. The name is from the Greek "akantha" meaning thorn or arrow, in reference to its crystal shape.

Chlorargyrite

Chlorargyrite

Bromian chlorargyrite (embolite), Chañarcillo, Copiapó Province, Chile. Size: 5.0 x 4.7 x 1.0 cm.

General	
Category	Halide
Chemical formula	AgCl
Strunz classification	03.AA.15

Chlorargyrite is the mineral form of silver chloride (AgCl). Chlorargyrite occurs as a secondary mineral phase in the oxidation of silver mineral deposits. It crystallizes in the isometric - hexoctahedral crystal class. Typically massive to columnar in occurrence it also has been found as colorless to variably yellow cubic crystals. The color changes to brown or purple on exposure to light. It is quite soft with a Mohs hardness of 1 to 2 and dense with a specific gravity of 5.55. It is also known as **cerargyrite** and, when weathered by desert air, as **horn silver**. Bromian chlorargyrite (or embolite) is also common. Chlorargyrite is water insoluble.

It was first described in 1877 for occurrences in the Broken Hill district, New South Wales, Australia. The name is from the Greek, chloros for "pale green" and Latin for silver, argentum.

Dyscrasite

Dyscrasite

Twinned dyscrasite crystals from the Czech Republic (size: 4.5 x 4.5 x 3.3 cm)

General	
Category	Antimonide mineral
Chemical formula	Ag_3Sb
Strunz classification	02.AA.35
Crystal symmetry	Orthorhombic pyramidal *mm*2
Unit cell	a = 3.008 Å, b = 4.828 Å, c = 5.214 Å; Z = 1

Identification	
Color	Silver-white (tarnishes to lead-gray, yellowish, or black)
Crystal habit	Pyramidal crystals also cylindrical, prismatic to platy, striated; granular, foliated or massive

Crystal system	Orthorhombic
Twinning	On {110} produces pseudohexagonal forms
Cleavage	Distinct on {001} {001}, imperfect on {110}
Fracture	Irregular or uneven
Tenacity	Sectile
Mohs scale hardness	3½ - 4
Luster	Metallic
Streak	Silver-white
Diaphaneity	Opaque
Specific gravity	9.4 - 10
Birefringence	Very Weak
Pleochroism	Very Weak

The silver antimonide mineral **dyscrasite** has the chemical formula Ag_3Sb. It is an opaque, silver white, metallic mineral which crystallizes in the orthorhombic crystal system. It forms pyramidal crystals up to 5 cm and can also form cylindrical and prismatic crystals.

Crystallography and properties

Dyscrasite demonstrates weak anisotropism. Anisotropism occurs when a mineral has two different indexes of refraction. Dyscrasite's color under plane polarized light is most likely dark grey/black. When spun on a rotatable stage of a microscope (under plane polarized light), dyscrasite's color should slightly change shades. This property is called pleochroism. Dyscrasite exhibits very weak pleochroism.

Dyscrasite belongs to the orthorhombic crystal class, meaning all three of its axes (a, b, and c) are unequal in length and are 90° to each other.

Discovery and occurrence

It was first described for an occurrence in 1797 in the Wenzel Mine, Black Forest, Germany. The name dyscrasite comes from the Greek word δυσκράσις, meaning "a bad alloy."

It occurs as a hydrothermal mineral in silver bearing veins in association with native silver, pyrargyrite, acanthite, stromeyerite, tetrahedrite, allemontite, galena, calcite and baryte.

Hessite

Hessite

Hessite and Quartz specimen from Botés, Alba County, Romania, featuring unusually thick and stout crystals of this rare silver telluride mineral. Size 3.6 x 2.2 x 1.5 cm.

General	
Category	Sulfide minerals
Chemical formula	Ag_2Te
Strunz classification	02.BA.30c

Hessite is a mineral form of disilver telluride (Ag_2Te). It is a soft, dark grey telluride mineral which forms monoclinic crystals.

It is named after Germain Henri Hess (1802–1850).

Hessite is found in the USA in Eagle County, Colorado and in Calaveras County, California and in many other locations.

Stützite (Ag_7Te_4) and empressite (AgTe) are related silver telluride minerals.

Proustite

Proustite

Proustite on matrix, crystal size: 1 cm, Chañarcillo district, Chile

General	
Category	Sulfosalt mineral
Chemical formula	Ag_3AsS_3
Strunz classification	02.GA.05 Neso-sulfarsenites
Dana classification	03.04.01.01 Proustite group
Crystal symmetry	H-M Symbol (32/m)
Unit cell	a = 10.79 Å, c = 8.69 Å Z = 6
Identification	
Color	Scarlet-vermilion
Crystal habit	Crystals prismatic and scalenohedral, massive, compact
Crystal system	Trigonal - Hexagonal Scalenohedral Space Group: R 3c
Twinning	Common
Cleavage	Distinct on {1011}
Fracture	Conchoidal to uneven
Tenacity	Brittle
Mohs scale hardness	2 – 2.5
Luster	Adamantine
Streak	Vermilion
Diaphaneity	Translucent, darkens when exposed to light
Specific gravity	5.57 measured, 5.625 calculated
Optical	Uniaxial (-)

properties

Refractive index $n_\omega = 3.087 - 3.088$ $n_\varepsilon = 2.792$

Birefringence $\delta = 0.295 - 0.296$

Pleochroism Moderate; cochineal-red to blood-red

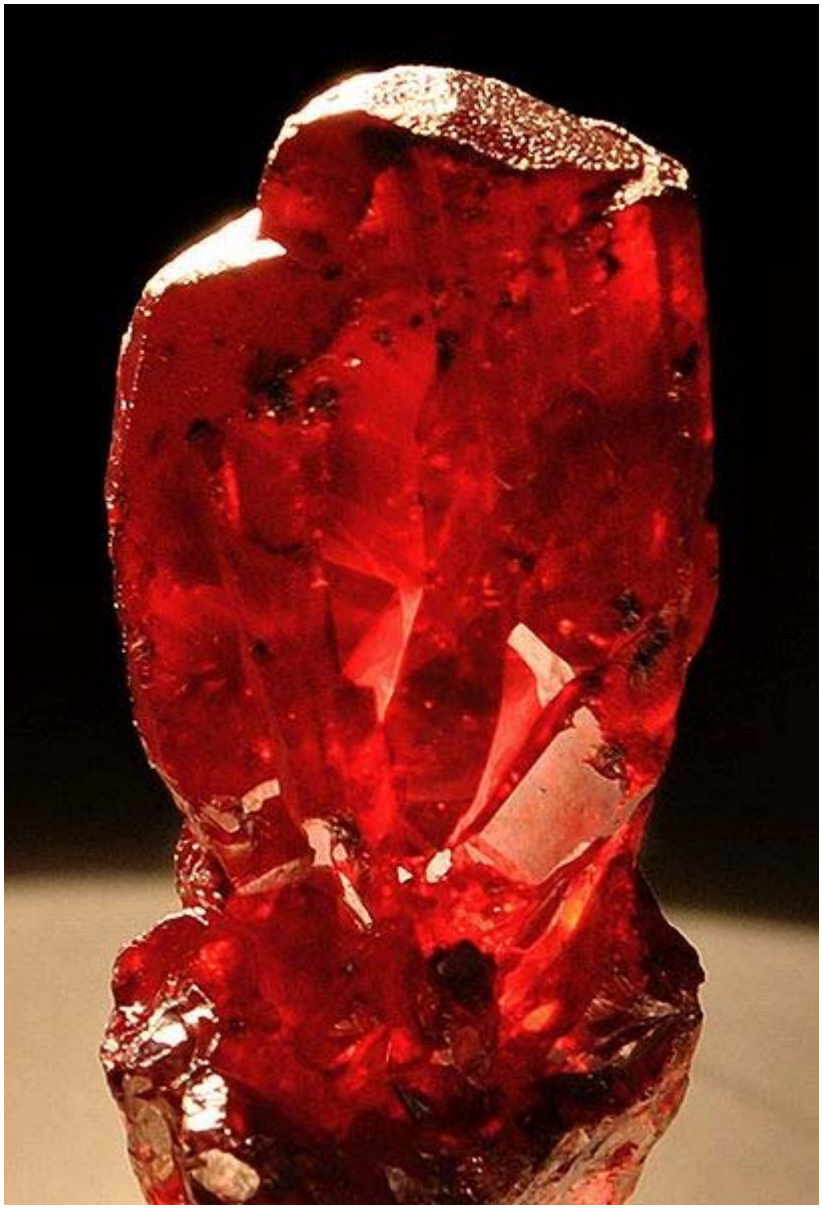
Proustite is a sulfosalt mineral consisting of silver sulfarsenide, Ag_3AsS_3, known also as **light red silver** or **ruby silver ore**, and an important source of the metal. It is closely allied to the corresponding sulfantimonide, pyrargyrite, from which it was distinguished by the chemical analyses of Joseph L. Proust (1754-1826) in 1804, after whom the mineral received its name.

The prismatic crystals are often terminated by the scalenohedron and the obtuse rhombohedron, thus resembling calcite (dog-tooth-spar) in habit. The color is scarlet-vermilion and the lustre adamantine; crystals are transparent and very brilliant, but on exposure to light they soon become dull black and opaque. The streak is scarlet, the hardness 2.5, and the specific gravity 5.57.

Proustite occurs in hydrothermal deposits as a phase in the oxidized and supergene zone. I is associated with other silver minerals and sulfides such as native silver, native arsenic, xanthoconite, stephanite, acanthite, tetrahedrite and chlorargyrite.

Magnificent groups of large crystals have been found at Chañarcillo in Chile; other localities which have yielded fine specimens are Freiberg and Marienberg in Saxony, Joachimsthal in Bohemia and Markirch in Alsace.

Proustite (long prismatic crystal) - Chañarcillo, Copiapo Province, Chile. Specimen height is 4 cm.



Chapter-8

Lead Minerals

Anglesite

Anglesite

Anglesite Touizit Morroco

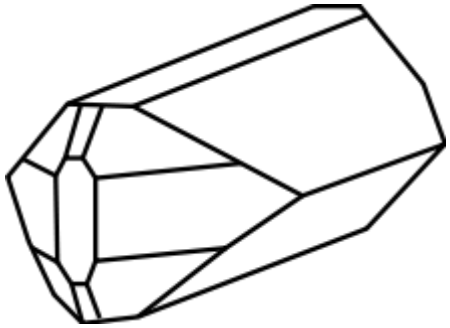
General	
Category	Sulfate minerals
Chemical formula	$PbSO_4$
Strunz classification	07.AD.35

Identification	
Color	Colorless to white, commonly tinted gray; orange, yellow, green, blue, rarely violet
Crystal habit	Granular, banded, nodular to stalactitic
Crystal system	Orthorhombic - Dipyramidal (2/m 2/m

	2/m)
Cleavage	[001] good, [210] distinct
Fracture	Brittle to conchoidal
Mohs scale hardness	2.5 - 3.0
Luster	Adamantine crystals, dull when massive earthy
Streak	White
Diaphaneity	Transparent to translucent
Specific gravity	6.3
Optical properties	Biaxial (+)
Refractive index	$n\alpha = 1.878$ $n\beta = 1.883$ $n\gamma = 1.895$
Fusibility	1.5

Anglesite is a lead sulfate mineral, $PbSO_4$. It occurs as an oxidation product of primary lead sulfide ore, galena. Anglesite occurs as prismatic orthorhombic crystals and earthy masses, and is isomorphous with barite and celestine. It has a high specific gravity of 6.3 due to its lead content, 74% by mass; its hardness is 2.5 - 3. Color is white, gray with pale yellow streaks. It may be dark gray if impure.

Anglesite crystal from Touissit District, Morocco (size: 2.8 x 1.6 x 0.5 cm)



Anglesite diagram illustrating its orthorhombic crystalline form

Beudantite

Beudantite

Large brown crystals of Beudantite.

General	
Category	Arsenate minerals
Chemical formula	$PbFe_3(OH)_6SO_4AsO_4$
Strunz classification	08.BL.10
Dana classification	43.4.1.1
Crystal symmetry	Trigonal 3 2/m
Unit cell	a = 7.32 Å, c = 17.02 Å; Z = 3

Identification	
Color	black, dark green, brown, yellowish, red, greenish yellow, brown

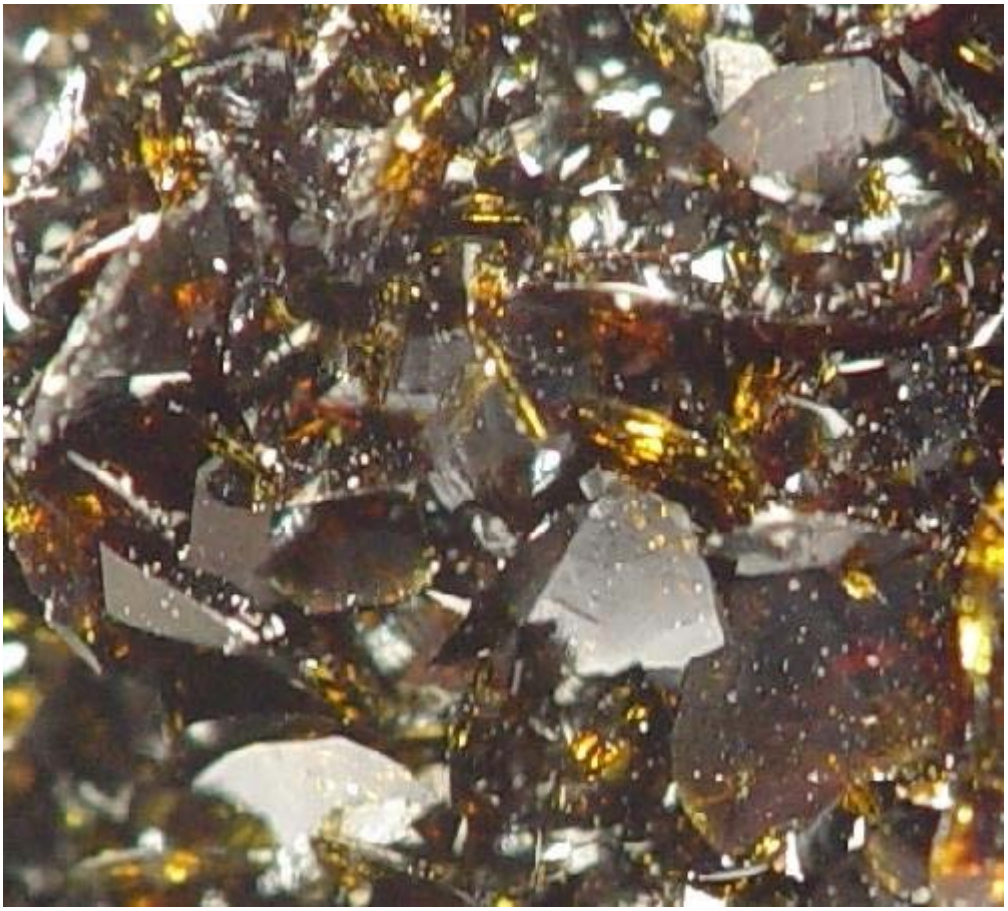
Crystal habit	tabular, acute rhombohedral, pseudo-cubic, pseudo-cuboctahedral
Crystal system	Trigonal Hexagonal Scalenohedral
Cleavage	distinct; good on {0001}
Mohs scale hardness	3.5-4.5
Luster	vitreous, resinous
Streak	grayish yellow to green
Diaphaneity	transparent, translucent
Specific gravity	4.48
Optical properties	Uniaxial (-)
Refractive index	$n_\omega = 1.957$ $n_\varepsilon = 1.943$
Birefringence	$\delta = 0.014$
Pleochroism	visible
Other characteristics	Soluble in HCl

Beudandite is a secondary mineral occurring in the oxidized zones of polymetallic deposits. It is a lead, iron, arsenate, sulfate with endmember formula: $PbFe_3(OH)_6SO_4AsO_4$.

Beudantite is in a subgroup of the alunite group. It is the arsenate analogue of the phosphate corkite. Beudantite also forms a solid-solution with segnitite and plumbojarosite.

It crystallizes in the trigonal crystal system and shows a variety of crystal habits including tabular, acute rhombohedral, pseudo-cubic and pseudo-cuboctahedral.

It occurs in association with carminite, scorodite, mimetite, dussertite, arseniosiderite, pharmacosiderite, olivenite, bayldonite, duftite, anglesite, cerussite and azurite.



Discovery

Beudantite was first described in 1826 for an occurrence in the Louise Mine, Wied Iron Spar District, Westerwald, Rhineland-Palatinate, Germany. It was named after French mineralogist François Sulpice Beudant (1787-1850).

Crocoite

Crocoite

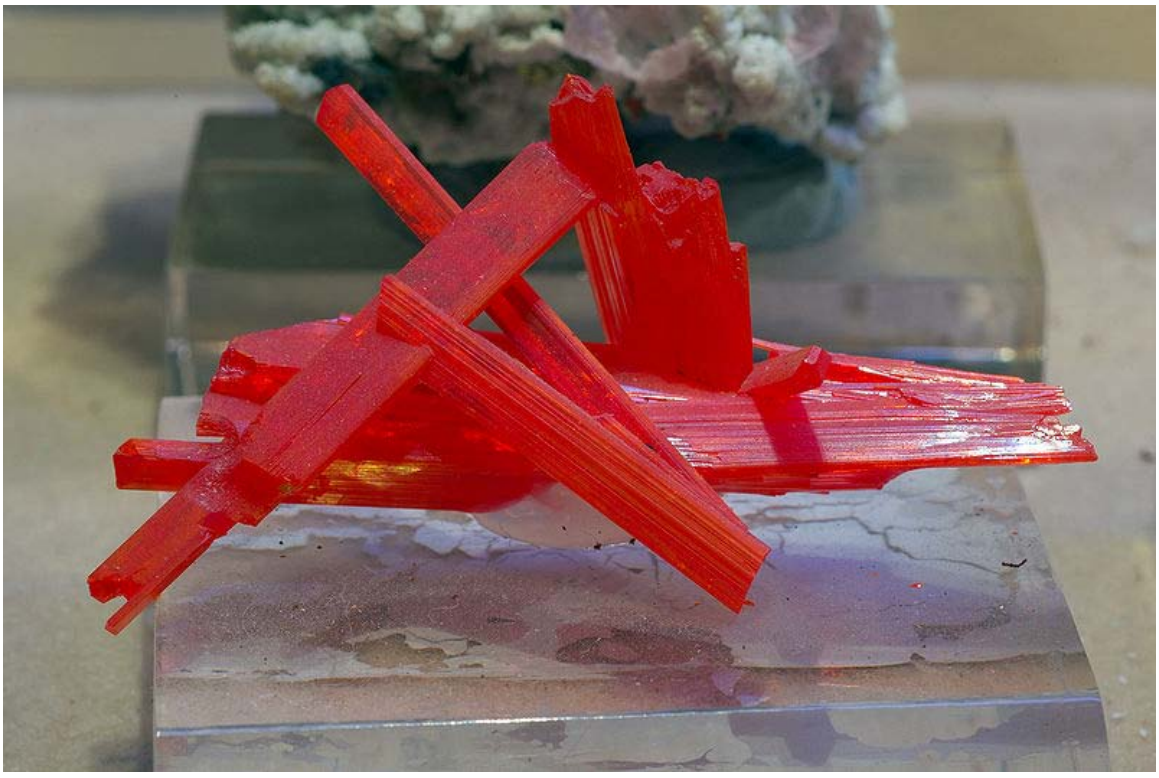
Crocoite from Dundas, Tasmania.

General	
Category	Chromate mineral
Chemical formula	Lead Chromate $PbCrO_4$
Strunz classification	07.FA.20

Identification	
Color	Orange, red, yellow
Crystal habit	Coarsely crystalline to acicular
Crystal system	Monoclinic prismatic (2/m)
Cleavage	Distinct on {110} indistinct on {001} and {100}
Fracture	Conchoidal to uneven
Tenacity	Sectile
Mohs scale hardness	2.5–3
Luster	Adamantine
Streak	Yellowish orange
Diaphaneity	Transparent to translucent

Specific gravity	5.9–6.1
Optical properties	Biaxial (+)
Refractive index	nα = 2.290(2) nβ = 2.360(2) nγ = 2.660(2)
Birefringence	δ = 0.370
Pleochroism	Weak

Crocoite is a mineral consisting of lead chromate, $PbCrO_4$, and crystallizing in the monoclinic crystal system. It is sometimes used as a paint, being identical in composition with the artificial product chrome yellow. It was discovered at Berezovsky deposit near Ekaterinburg in the Urals in 1766; and named crocoise by F. S. Beudant in 1832, from the Greek κροκος, saffron, in allusion to its color, a name first altered to crocoisite and afterwards to crocoite. It is found as well-developed crystals, although these are usually poorly terminated. Crystals are of a bright hyacinth-red color, translucent, and have an adamantine to vitreous lustre. On exposure to light much of the translucency and brilliancy is lost. The streak is orange-yellow; Mohs hardness is 2.5–3; and the specific gravity is 6.0. In the Urals the crystals are found in quartz-veins traversing granite or gneiss. Other localities which have yielded good crystallized specimens are Congonhas do Campo near Ouro Preto in Brazil, Luzon in the Philippines, and Mutare in Mashonaland.



Crocoite specimen from the Red Lead Mine, Tasmania, Australia

Gold is often found associated with this mineral. Exceptional examples of crocoite crystals have been found in the Adelaide Mine at Dundas, Tasmania; they are long slender prisms, 3 or 4 inches in length, with a brilliant lustre and color. Crocoite is also the official Tasmanian mineral emblem.

Associated with crocoite at Berezovsk are the similar minerals phoenicochroite and vauquelinite. The former is a basic lead chromate, Pb_2CrO_5, and the latter a lead and copper phosphate-chromate, $Pb_2CuCrO_4PO_4OH$. Vauquelinite forms brown or green monoclinic crystals, and was named after L. N. Vauquelin, who in 1797 discovered (simultaneously with and independently of M. H. Klaproth) the element chromium in crocoite.

Crystal intergrowth of the secondary lead mineral crocoite

Relative rarity of crocoite is connected with specific conditions required for its formation: an oxidation zone of lead ore bed and presence of ultramafic rocks serving as the source

of Cr (in chromite). Oxidation of Cr^{3+} into CrO_4^{2-} (from chromite) and decomposition of galena (or other primary Pb minerals) are required for crocoite formation.

Crocoite on pyromorphite - Berezovsk - Deposit Topotype

Descloizite

Descloizite

Descloizite specimen from Berg Aukas (Berg Aukus), Namibia, 9.5 x 8.9 x 4.9 cm]]

General	
Category	Vanadate mineral
Chemical formula	$(Pb,Zn)_2VO_4OH$
Strunz classification	08.BH.40
Crystal symmetry	Orthorhombic (2/m 2/m 2/m) - dipyramidal
Unit cell	a = 7.593 Å, b = 6.057 Å, c = 9.416 Å; Z = 4

Identification	
Color	Brownish red, red-orange, reddish to blackish brown, nearly black
Crystal habit	Zoned tabular crystals common, encrustations and plumose aggregates
Crystal system	Orthorhombic
Cleavage	None

Fracture	Irregular, sub-conchoidal
Tenacity	Brittle
Mohs scale hardness	3 - 3.5
Luster	Greasy
Streak	Orange to brownish red
Diaphaneity	Transparent to opaque
Specific gravity	6.1 - 6.2
Optical properties	Biaxial (-)
Refractive index	$n_\alpha = 2.185$ $n_\beta = 2.265$ $n_\gamma = 2.350$
Birefringence	$\delta = 0.165$
Pleochroism	Visible
2V angle	85° to 90°
Dispersion	Strong r > v rarely r < v

Descloizite is a rare mineral species consisting of basic lead and zinc vanadate, $(Pb,Zn)_2(OH)VO_4$, crystallizing in the orthorhombic system and isomorphous with olivenite.

The color is deep cherry-red to brown or black, and the crystals are transparent or translucent with a greasy lustre; the streak is orange-yellow to brown; specific gravity 5.9 to 6.2; hardness 31/2. A variety known as cuprodescloizite is dull green in color; it contains a considerable amount of copper replacing zinc and some arsenic replacing vanadium. Appreciable gallium and germanium may also be incorporated into the crystal structure.

Discovery and occurrence

Superb spear-point bladed crystals of Descloizite, Berg Aukas, Namibia. Size 3.6 x 3.1 x .9 cm.

It was discovered in the Sierra de Córdoba deposit in Córdoba, Argentina in 1854 and named in honor of the French mineralogist Alfred Des Cloizeaux. It occurs as small prismatic or pyramidal crystals, usually forming drusy crusts and stalactitic aggregates; also as fibrous encrusting masses with a mammillary surface.

Descloizite occurs in oxidised portions of veins of lead ores in association with pyromorphite, vanadinite, wulfenite, mottramite, mimetite and cerussite.

The Otavi Mountainland of northern Namibia was once considered home to the greatest vanadium deposits in the world, including those at Berg Aukas, Abenab, Baltika and Uitsab. Descloizite and mottramite were the main ore minerals in each of these deposits, which are now exhausted. Other localities are the Sierra de Cordoba in Argentina; Lake Valley in Sierra County, New Mexico; Arizona; Phoenixville in Pennsylvania and Kappel (Eisen-Kappel) near Klagenfurt in Carinthia.

Duftite

Duftite

Duftite from Benahadux, Almeria, Andalusia, Spain.

Specimen size 2.4 cm

General	
Category	Arsenate minerals
Chemical formula	$PbCuAsO_4(OH)$
Strunz classification	08.BH.35
Dana classification	41.5.1.4
Crystal symmetry	Orthorhombic 222
Unit cell	a = 7.768(1) Å, b = 9.211(1) Å, c = 5.999(1) Å; Z=4

Identification	
Molar mass	426.67 g
Color	Green, olive green or grey green.

	Generally zoned due to compositional variations
Crystal habit	Tiny crystals elongated along [001] with curved and rough faces, aggregated into crusts. Crystals may be pseudo-octahedral.
Crystal system	Orthorhombic 222 disphenoidal
Cleavage	Indistinct
Fracture	Uneven to conchoidal
Mohs scale hardness	4.5
Luster	Vitreous on fracture surfaces and dull on crystal faces
Streak	Pale green or white
Diaphaneity	Crystals are transparent to translucent
Specific gravity	6.4 (measured), 6.60 (calculated)
Optical properties	Biaxial (-)
Refractive index	n_α = 2.03 to 2.04, n_β = 2.06 to 2.08, n_γ = 2.08 to 2.10
Birefringence	δ = 0.0600
2V angle	Large
Dispersion	r > v, perceptible
Other characteristics	Decrepitates on heating. Not radioactive.

Duftite is a relatively common arsenate mineral with the formula $CuPb(AsO_4)(OH)$, related to conichalcite. It is green and often forms botryoidal aggregates. It is a member of the Adelite-Descloizite Group, Conichalcite-Duftite Series. Duftite and conichalcite specimens from Tsumeb are commonly zoned in colour and composition. Microprobe analyses and X-ray powder-diffraction studies indicate extensive substitution of Zn for Cu, and Ca for Pb in the duftite structure. This indicates a solid solution among conichalcite, $CaCu(AsO_4)(OH)$, austinite, $CaZn(AsO_4)(OH)$ and duftite

$PbCu(AsO_4)(OH)$, all of them belonging to the adelite group of arsenates. It was named after Mining Councilor G Duft, Director of the Otavi Mine and Railroad Company, Tsumeb, Namibia. The type locality is the Tsumeb Mine, Tsumeb, Otjikoto Region, Namibia.

Structure

The structure is composed of chains of edge-sharing CuO_6 distorted octahedra parallel to the c axis. The chains are linked by AsO_4 tetrahedra and Pb atoms.

Environment

Duftite is an uncommon product of weathered sulfide ore deposits. It is associated with azurite at the type locality, and with bayldonite, segnitite, agardite and gartrellite at the Central Cobar Mines, New South Wales, Australia, where some pseudomorphs of duftite after mimetite have also found. It occurs in association with olivenite, mottramite, azurite, malachite, wulfenite and calcite in the Tsumeb, Namibia deposite. It occurs with bayldonite, beudantite, mimetite and cerussite in the Cap Garonne mine, France.

Duftite on cerussite, Tsumeb mine, Namibia. Size: 6 x 5 x 3 cm.

Distribution

Reported from Argentina, Australia, Austria, Chile, the Czech Republic, France, Germany, Greece, Italy, Japan, Mexico, Namibia, Poland, Portugal, Russia, South Africa, Spain, Switzerland, the UK, the USA and Zimbabwe.

Mimetite

Mimetite

General	
Category	Arsenate minerals
Chemical formula	$Pb_5(AsO_4)_3Cl$ lead chloro-arsenate
Strunz classification	08.BN.05

Identification	
Color	Yellow, Brown, Orange, Red, White
Crystal habit	Reniform, botryoidal, globular, prismatic
Crystal system	Hexagonal
Cleavage	[1011] Imperfect
Fracture	Brittle, conchoidal
Mohs scale hardness	3.5 - 4
Luster	Resinous, adamantine
Streak	White

Diaphaneity	Subtransparent to translucent
Specific gravity	7.1 - 7.24
Refractive index	2.129 - 2.144

Mimetite, whose name derives from the Greek Μιμητής *mimethes*, meaning "imitator", is an arsenate mineral which forms as a secondary mineral in lead deposits, usually by the oxidation of galena and arsenopyrite. The name is a reference to mimetite's resemblance to the mineral pyromorphite. This resemblance is not coincidental, as mimetite forms a mineral series with pyromorphite ($Pb_5(PO_4)_3Cl$) and with vanadinite ($Pb_5(VO_4)_3Cl$). The most notable occurrences are Mapimi, Durango, Mexico and Tsumeb, Namibia.

Uses of mimetite

Mimetite from Namibia

Industrially, mimetite is a minor ore of lead, especially when found in relatively large quantities. The chief use of mimetite is as a collector's specimen, often creating very attractive botryoidal crusts on the surface of the specimen. Though mimetite is also found in prismatic crystal forms, it is not used as a gemstone due to its softness. The best of these prismatic forms have been found in Johanngeorgenstadt in Saxony and Wheal Unity in Cornwall, England.

Associated minerals

Mimetite is found in association with lead and arsenic minerals, including those minerals with which it forms a series. Some associated minerals include:

- Bellite
- Calcite, $CaCO_3$
- Galena, PbS
- Pyromorphite, $Pb_5(PO_4)_3Cl$
- Smithsonite, $ZnCO_3$
- Vanadinite, $Pb_5(VO_4)_3Cl$
- Wulfenite, $PbMoO_4$

Alternative names

Alternative names of mimetite include arsenopyromorphite, mimetesite, and prixite. Campylite is the name for a variety with barrel shaped crystals of a brownish-red or orange-yellow color and containing a considerable proportion of phosphoric acid.

Notes for identification

Useful information pertaining to the field identification of mimetite include its habit, color, and high density. However, this mineral's similarity to pyromorphite can be problematic, especially since these minerals are known to share colors. Pyromorphite is typically green, and mimetite is typically yellow, but specimens of each are known in the other's colors. As a result, some identification may require lab analysis.

Mimetite, Pingtouling Mine, Guangdong Province, China. Size: 2.2 x 2.1 x 1.8 cm.

Mimetite, Santa Eulalia, Chihuahua, Mexico. Size: 5.4 x 3.9 x 1.5 cm.

Mimetite, Bilbao mine, Zacatecas, Mexico. Size: 7.9 x 5.8 x 3.4 cm.

A thumbnail sample of mimetite.