



Malachite, Tsumeb – 21 × 25 mm



Cacosxene, Rotläufchen – 10 × 12 mm



Cerussite, Tsumeb – 24 × 28 mm



Realgar, Romania – 80 × 95 mm





The Magic of Minerals

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Frontispiece:

Cacoxenite – $\text{Fe}_4^{3+}[\text{OH}|\text{PO}_4]_3 \cdot 12\text{H}_2\text{O}$
(hexagonal, yellow) with

Beraunite – $\text{Fe}^{2+}\text{Fe}_5^{3+}[(\text{OH})_5(\text{PO}_4)_4] \cdot 6\text{H}_2\text{O}$
(monoclinic, brown)

Rotläufchen Mine near Wetzlar/FRG
Original size 5 × 6 mm

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The Crystalline Nature of Matter

Crystals, Minerals, Rocks

Mineralogy, as a branch of geoscience, has as its subject the composition of the solid crust of the earth. We recognize that our earth once circled the sun as a red-hot glowing sphere, many billions of years ago – a length of time virtually unimaginable to the human mind. In its interminable orbits through space much of its heat was dissipated and it slowly cooled and congealed. The earth, once a fiery globe, gradually became a mass of gas and liquid molten matter. Even in the early stages, a separation of this molten material occurred, forming metallic, sulfide, and silicate layers. The separation of these layers came about because of the different densities of the metals and compounds which were forming. The heavy metals collected mostly in the inner core and the lighter silicates “floated” to the upper levels. As the temperature of the surface further cooled to about 1500° to 1000°C the first solid crystals of minerals were formed and eventually a coherent, thin outer shell was produced. This primary solid crust on our planet represented the beginning of geologic time and took place, to the best of our knowledge, about 4.5 billion years ago. Since that time there has been a continual development of minerals deep with-

in the earth so that finally, after uncountable meltings and recrystallizations, the crust evolved as we know it today. The crust of the earth is separated from the underlying upper mantle by a discontinuous interface, as shown through seismic measurements of the speed of shock waves as they travel through these layers. This interface is known as the Mohorovičić discontinuity, named after a prominent Yugoslavian geophysicist. It is characterized by a notable variance in depth. Under the continents it lies about 35 km deep, under the higher mountains it is as much as 50 km deep, and under the ocean floor it is only 5 to 10 km deep. Compared with the total diameter of our planet – the earth’s radius at the equator is 6378 km – this outer crust is extremely thin. If one were to compare the earth with an apple, the crust would be about as thick as the apple’s skin. This means that the crust comprises less than 1% of the total volume of the earth. Our knowledge of the minerals of the earth’s crust is limited to the zone just beneath or at the earth’s surface. Quarries, gravel pits, roadcuts and tunnels let us see the mineralogic components of the hard rock commonly covered by soil or humus. We get a deeper view of the crust in mines. The deepest mine shafts are those of the gold mines in the Witwatersrand region, near Johannesburg in

South Africa, which descend to a depth of almost 3500 m. That we know something of the earth’s crust to a depth of about 16 km lies in the fact that the processes of mountain building and faulting have brought deeper materials up to the surface where they can be examined.

As recently as the beginning of this century, mineralogy was merely a descriptive science. Its essential activity was, from the earliest days, limited to the *Kingdom of Minerals*. The term mineral derives from the Latin *minare*, meaning mining, and *mina*, the shaft. Therefore mineral became the term for the material recovered from mines or shafts. Today, the field of mineralogy is much more complex. As an experimental science it deals not only with the clarification of genetic problems of mineral formation, but also with crystallochemical questions of great value to industry and technology. Therefore mineralogy, as a basic science, is closely allied with the other natural sciences of geology, chemistry and physics. A modern mineralogist cannot function without the research methods of these other sciences.

Mineralogy today, reflecting its historical development, is organized into crystallography, mineralogy and petrology.

Crystallography deals with the crystalline condition of materials. In contrast to gases and liquids, crystals are solids in which the chemical building blocks – atoms, ions (positive and negative charged atoms), or molecules – are arranged in regular, repeating arrays to form three-dimensional crystal lattices. It does not matter if the crystal is a natural product or produced by synthesis in a laboratory. *Krystallos* to the ancient Greeks was ice or colorless and transparent quartz (rock crystal). This is the name that has been adopted for the science. The obvious symmetric forms of smooth planes bounded by straight edges are exterior manifestations of the internal order of the atoms within. Even so, a piece of quartz that has been rounded by abrasion in a river bed so that it is devoid of any edges or lustrous faces is still termed a crystal. Its internal structure remains unchanged by this external mechanical alteration of its surface. Even the smallest grain of sand, once a component of solid rock, freed by decomposition and reduced in size in the course of thousands of years of transport in rivers and seas, has the same crystalline structure as an immense quartz crystal weighing as much as a ton and completely bounded by lustrous planar surfaces. In contrast, a piece of glass that is cut and polished to resem-

ble a quartz crystal on the outside remains a piece of glass no matter what external form is artificially given to it. Its atoms are not geometrically arranged. That is to say that glass, despite its relative hardness and solidity, is not a crystalline body, but a highly viscous amorphous liquid. For this reason the often artistically cut “crystal glass” or “lead glass” can in no way be considered identical with naturally occurring or even synthetically produced crystals.

The phases of the materials surrounding us are either gaseous, fluid, or solid. Sometimes the same substance can be found in all three forms. Water, under normal pressure-temperature conditions is a liquid, that is its molecular groups not ordered and without stable coherence in the liquid state. Below the freezing point of 0°C the H₂O molecules arrange themselves into a rather precise space lattice, and form the solid crystalline phase ice. When one heats water to above its boiling point of 100°C, the H₂O molecules have the power to escape the liquid surface in large quantities and become the gaseous phase steam. The crystalline state is the normal state of solid materials and is encountered everywhere, also in many areas of daily life. All the metals and alloys that we use, be it the steel of a knife or

gold in jewelry, consist of thousands of minute crystallites. Salt and sugar, the latter readily observed in beautifully formed crystals in rock candy, are other examples of hundreds of thousands of solid inorganic and particular organic compounds. To date, about 500,000 crystalline compounds are known. Through the research efforts of the pharmaceutical industry alone the number is increasing constantly.

Also to be counted as crystals are, with few exceptions, all minerals, whether they be in the form of valuable ores for the production of metals or in the form of mineral components of rocks. But only rarely do these minerals exhibit the beautiful complete crystals for which they are so desired. Such an idiomorphic (Greek *idios* = own, *morpho* = form) condition in crystals is only possible where the growth process is not impeded by the surrounding medium. In most cases there are mutual hindrances during the growth process and the resulting crystals are bounded by irregular surfaces which are described as xenomorphic (Greek *xenos* = strange).

The French mineralogist and crystallographer René Just Haüy (1743–1822) once aptly described crystals as “flowers of the mineral kingdom” because of the beauty and color of

many of their clusters. One cannot fail to be fascinated by the unending variety of their esthetically beautiful and enchanting forms, and many a man has questioned whether all these manifold symmetries can be a miraculous product of nature, without human intervention. Pliny, for example, (23–79 AD), in his 37-volume work of natural history *Historia Naturalis*, claimed that the six-sided prismatic form of *beryllos*, the precious stone and silicate mineral beryl, came from having been artificially shaped by Indian stone cutters. The sizes of naturally occurring crystals range from the most microscopic to giant, with edges up to 10 m such as, for example, the feldspar crystals found in Kristiansand, in Norway. Huge quartz crystals come from deposits in Brazil, one of the largest from this country having a height of about 2 m and a weight of more than 3 t. But the larger a crystal grows, the less idiomorphic it tends to be. The maxim *In minimis Deus maximus est* “God is greatest in the smallest manifestations,” also applies here. It is usually the smallest crystal groups that are the most readily distinguished through their near-perfect morphological development. This condition has led to a large number of mineral hobbyists collecting only the very tiny crystals of exceptional quality, specializing in what

they call micromounts, as they are usually “mounted” on miniature pedestals for viewing under a binocular microscope.

Minerals are inorganic crystals formed in nature without the participation of man. **Mineralogy** deals with these materials. There are exceptions, such as the important earth treasures of organically formed oil and coal. Minerals can occur as simple elements like copper, silver, gold, graphite, diamond or sulfur; but the majority are multi-element compounds like the numerous rock-forming minerals, particularly quartz, feldspar, mica, pyroxene, amphibole or the technologically important ores. From antiquity, minerals mined especially for the extraction of the important metals contained within them have been termed ores. They often have a metallic appearance and a high density. From a mining point of view, however, many other minerals are considered as ores, for example amblygonite for the element lithium, beryl for beryllium or bauxite for aluminum. Traditionally, mercury, which is liquid at normal temperatures, and opal, which is amorphous, do not fit the definition of minerals, but are counted as such. Also included as minerals are substances of cosmic origin, such as those in meteorites and in the rocks from the moon recovered through the Apollo and Luna space programs.

Our planet, whose surface was once composed only of inorganic materials, crystals and minerals, is now the environment for a complex organic life. Weathering processes in the uppermost zones of the earth’s crust worked to break down the solid rocks to produce a soil suitable for plant life. The development of a vegetation further encouraged the development of animals and, finally, of man. Minerals were, and are today, the most important condition for life on earth. Minerals form the foundation of the technical advances of mankind, right up to our present highly developed civilization. Even in prehistoric times our Stone Age ancestors (to ca. 1800 BC) used primitively shaped minerals, such as flint and nephrite (jade), as tools and weapons. They could use pyrite to spark fires and clays to form simple bowls. The working of copper and tin during the Bronze Age (1800–800 BC) to form the metal alloy bronze revealed a great advance in refining techniques. Upon learning to extract iron from iron ore, a skill previously unknown, man entered the Iron Age (ca. 1000 BC), which led to the development of smelting processes, bringing modern technologies in that era. Minerals are the most important raw materials of all industrial countries. Life without minerals as raw materials would be unthinkable.

Without ores the ovens and smelters would be useless, we would have no steel, copper, or aluminum, and the most important technological fundamentals would be missing. Without the important fertilizers it would most certainly be impossible to feed the world's population. The wise use of existing, as well as future, raw material sources is one of the objectives of mineralogy, particularly in its specialized fields of ore deposit science (economic geology), geochemistry, and applied mineralogy (technical mineralogy). Applied mineralogy is the connecting link to industry and technology, binding the extensive sphere of mineralogy with the branches of modern industrial tech-

nology: mining, refining, ceramics and glass, chemistry, fertilizers, abrasives, the manufacture of optical and physical equipment, and especially atomic reactor technology.

Petrology (Greek *petra* = rock, *logos* = science) is the science of the description and composition of rocks, as well as their paragenesis, the origin and the physicochemical conditions which influenced their growth. Rocks are mineral aggregates with similar mineral compositions varying over specified ranges. Most rocks are composed of many of the rock-forming minerals, such as granite, which contains quartz, feldspar and mica. Or they may be composed of only one mineral, such as mar-

ble, which is made up of calcite, or quartzite, which is only quartz. The minerals forming the major part of any rock are called the essential ingredients and may number up to 20, but commonly no more than four. Accompanying minerals, usually comprising less than 1% of the total, are known as accessories. The individual crystals in most rocks grew at the same time and are without crystal forms. Those which crystallized early, such as quartz in the volcanic rock rhyolite, are occasionally found as idiomorphic crystals. Some rocks are organic in origin such as, for example, many limestones and the important energy source, coal.

Silver - Ag

Isometric. The derivation of the name silver can be traced back to the old High German *silabar* and further to the Gothic *silubr*. The Greek name for silver is *argyros* (*argos* = brilliant white). The name refers to the light color of the metal. Berzelius derived the chemical symbol for silver, Ag, from the Latin form *argentum*. Many ancient cultures valued silver more highly than gold. Babylonians, Sumarians, and Wiltites used the metal as the base for their monetary systems. One reason for this is that native silver is rarer in nature than gold. Just as gold was associated with the sun because of its golden yellow, silver, with its soft white shimmer, was associated with the moon. Until the middle of the 18th century the erudite terms for gold and silver were the same as their astronomical names "sol" and "luna", respectively. The nature and origin of the silvery-white metal was not understood and in 1679 was described by Adamus Lonicerus, in his book *Nature and Properties of Metals and Ores* as "derived from a mixture of a clear white quicksilver and a clean white sulfur, which makes it beautifully white." Furthermore, he wrote: "pulverized silver takes away evil scabbiness, when rubbed in foul wounds consumes the bad flesh, strengthens the heart, and makes good blood."

Silver crystallizes mainly in cubes, octahedrons, and dodecahedrons. Commonly it is found in branching tree- or mosslike growths, sheets, or grotesquely

1 Native Silver

Freiberg, Sachsen/GDR

Original size 55 x 41 mm



bent wires (Fig. 1). Unusually beautiful crystals and wires in excess of 20 cm were found at Kongsberg, Norway. The color of the fresh metal is "silver-white," but it oxidizes to a brownish-yellow to black silver sulfide, the color dependent upon the thickness of the coating.

Hardness $2\frac{1}{2}$ –3, specific gravity 10.5 (if pure), otherwise varying between 10 and 12, depending on impurities. In extremely thin sheets silver is blue translucent. It is exceedingly malleable and ductile and can be drawn into fine wires. Gold and silver are miscible in any proportions. Since pure silver is too soft for silverware and jewelry it is usually alloyed with copper. The silver alloys in use today are marked with their silver content in parts per thousand, e. g., 800, 900, and 925. Sterling silver (925) has a content of 925 parts of pure silver and 75 parts of copper.

Ascending hydrothermal deposits in Kongsberg, Norway, produced great masses of native silver (up to 800 kg). Other well-known localities include St. Andreasberg, in the Harz/F.R.G.; Freiberg, Schneeberg, and Annaberg in Saxony; Příbram and Jáchymov (Joachimsthal) in Czechoslovakia. Other important deposits are found in the Cobalt district of Ontario, Canada, as well as in Mexico and Bolivia. Silver was once found extensively in association with argentite and other silver ores in the cementation zones of ore deposits; precipitated from descending solutions at Chñarcillo, Chile, and Broken Hill, Australia; and it was found in association with chalcopyrite in the sedimentary copper deposits at Mansfeld, Germany.

Other than in jewelry and silverware, its main uses are in the electronic industry, plating, and as a catalyst in chemical processing. Large quantities of silver, in the form of chlorides and bromides, are consumed in the photographic industry for the manufacture of light sensitive emulsions. The annual production of silver worldwide is, at the present time, about 9500 tons, mostly recovered from sulfide ores such as galena.

2 **Native Silver** on Calcite
Mexico
Original size 32 × 50 mm





Gold - Au

Isometric. Gold, whose name was originally derived from the Gothic *gulth*, is one of the oldest known metals, and because of its pliability was easily workable in very early times. When and where it was first found and recognized is not known. The first mention of the metal was made in the Weda, the old Indian holy books, which date back to 4000 B.C. To the best of our knowledge, the oldest mined gold was produced in the Middle East, most probably in Mesopotamia where, in 4000 B.C., the Sumarian culture flourished. Archeological excavations of royal tombs near the biblical town of Ur, on the Euphratis River, have brought to light magnificently worked gold and silver jewelry and other treasures such as chalices, tableware, and symbolic figurines. These finds show us that goldsmithing was well established between 2685 and 2654 B.C. Finds at Abydos and Nagada in Egypt tell us that gold was used in this area about 3000 B.C., predating silver usage. Gold was the metal of the sun which was embodied by the god Aton. Its use in jewelry was forbidden to all but the Pharaohs, their families, priests, and other high officials. The first information on locality dates back to 2200 B.C. Gold was first reported in the blue Nile and later in specific gold mines.

The high standards of the goldsmithing art in Egypt are evidenced by the superb treasures found in the tomb of the Pharaoh Tutankhamun, buried in 1350 B.C. His sarcophagus (110 kg of pure gold) was ornately hand-carved to represent a mask of his countenance.

Gold was still closely associated with sun worship hundreds of years later in the Inca civilization, whose people prayed to the sun god Viracocha. In his honor, the sun temple Coricancha was built in Cuzco, the capital of the Incas in the 14th century. Its thatched

roof was threaded with gold, and its interior was filled with golden thrones and ornaments.

Gold which more than any other metal, symbolizes power, has always been coveted; for its sake wars have been waged and civilizations destroyed. Spanish conquistadores, in their search for El Dorado, the Land of Gold, destroyed the kingdom of the Incas. Just as Cortés plundered the gold from the Aztecs in Mexico (1519–1521), so too did Pizarro (1524–1533) rob the Incas, and Quesada (1536–1539) the Chibcha Indians of present-day Colombia. Large quantities of pre-Columbian gold artifacts were thrown into the holy lakes as sacrificial offerings. In spite of the plunder and destruction, a remarkable quantity of objects were preserved. A unique collection of about 15,000 pre-Columbian gold artifacts can be found in the Museo d'Oro in Bogota, Colombia.

Man's eternal longing for gold influenced the thinking of Medieval alchemists. Many were preoccupied with the dream of converting base metals, such as lead, to gold. Although their efforts were never successful, many important discoveries and inventions such as porcelain and "ruby glass" resulted.

Paracelsus used the metal in the treatment of heart disease. Gold, pulverized and eaten, was also thought to cure leprosy, fainting, melancholy, and epilepsy. Adamus Lonicerus (1679) believed gold to be a mixture of clear red sulfur and clear white quicksilver. Sharply developed crystals of gold are relatively rare. The crystal forms found include octahedrons, cubes, dodecahedrons, and combinations of these forms. Twinning along octahedral faces, forming dendritic growth, is rather common, however native gold

3 Native Gold on Quartz
Grace Mine, Ontario/Canada
Original size 19 x 30 mm





is also found as masses, sheets, and wires disseminated in rock, and in nugget form.

Because of its color and luster, gold is a very conspicuous metal. A mixture of gold and silver will lighten in color as the proportion of silver is increased, and will vary from yellow-red to brass-yellow to almost silver-white shades. Gold resulting from the decomposition of telluride ores is powdery dark-brown. The hardness is $2\frac{1}{2}$ –3, the specific gravity is 19.28 for pure gold, and from 16 to 19 according to the degree of purity.

Pure gold is extraordinarily malleable and can be beaten into extremely thin sheets (gold leaf) of 0.0001 mm in thickness, through which light has a green shimmer. Native gold is rarely pure and is usually found in combination with 2 to 20% silver and perhaps copper and platinum group metals. Gold with a content of 30% silver is known as electrum. Pure gold does not oxidize in air, so that it always retains its metallic luster. Gold is not soluble in any normal acid and is only attacked by a mixture of nitric and hydrochloric acids (aqua regia). Gold is also soluble in cyanide solutions and mercury. This property is used to separate gold from the barren rock in which it is found. Pure gold is too soft to be used in decorative and functional articles and is, therefore, alloyed with other metals. The proportions most commonly in use are 333 (8 K), 585 (14 K), 750 (18 K), 900 (22 K) parts per 1000 of pure gold. Twenty-four karat gold is pure. The metals with which gold is alloyed are silver, copper, platinum, and nickel. Alloying with silver will cause a yellow color, and with copper a reddish color. White gold consists of a palladium or nickel mixture with gold.

Native gold is the major ore, other gold minerals are rare and of only minor importance.

Primary deposits of gold are called lodes. These are hydrothermal in origin and connected to the “old” gold-quartz veins associated with plutonic rocks and the “new” gold-quartz veins associated with eruptive rocks. In the former case gold is most often found with pyrite and arsenopyrite.

Deposits of this type were found at Brandholz, Fichtelgebirge, the Hohen Tauern at Salzburg, Austria, the 150-km-long gold vein known as the Mother Lode in California, and also deposits in Canada, Zimbabwe and Australia. “New” gold-quartz veins are marked by the presence of both gold and silver tellurides, e.g., the deposits at Brad, Săcărîmb (Nagyág), Rosia-Montană (Verespatak), Baia de Aries (Offenbánya), in Transylvania, Romania; and Cripple Creek, Colorado, and the Comstock lode in Nevada, U.S.A. During the weathering of primary deposits gold was able to withstand the destructive processes and was transported by river action to form secondary deposits, known as gold placers. These placers produce a much purer gold, because much of the silver present in the primary gold was dissolved by the erosional waters. Originally the placer deposits were the only source for this metal, which was mostly accompanied by numerous heavy minerals such as magnetite, monazite, zircon, cassiterite, and others.

Famous old European placer deposits were the “Rhine gold” and the “Tauern gold,” which were worked by the Celts and Romans. Gold was still being found in the Rhine as recently as 1874, when the course of the river was changed. The gold content was very low, about 1 gram per ton. The origin of the “Rhine gold” is unknown.

The discovery of the placer deposits in the Sacramento Valley in California led to the famous gold rush in 1849, as did the discoveries in the Klondike region,

Yukon River, Alaska. Only 2 years later, in 1851, gold was discovered in Australia, first in New South Wales and shortly thereafter in Victoria. One nugget found there in 1869 weighed 70 kg and was named the Welcome Stranger.

The largest and most important deposit is Witwatersrand, Johannesburg, South Africa, which is a fossilized placer of quartz conglomerates of pre-Cambrian age (600 to 900 million years old). It was discovered in 1886 and since production began has always been an important factor in the total world output of gold. Gold serves primarily as a monetary standard throughout the world. Further uses include gold alloys, jewelry, tooth replacements, and the production of technical apparatus.

The annual world production is about 1100 tons, including gold won from the smelting of other metals.

4 Native Gold on Quartz
Zalatna/Romania
Original size 9 × 11 mm



Copper - Cu

Isometric. With gold and silver, copper is one of the earliest known and worked metals. Through discoveries in Iran, Iraq, and Egypt we know that gold, silver, and copper were smelted, cast, and worked around 4000 B.C. In a recent find in Gatal Hüyük, Turkey, copper clothing ornaments were unearthed dating back to 5000 B.C. The Latin word *aes*, a general term for ore, copper or bronze, was derived from the Indo-German designation for copper. Pliny called the metal *aes Cyprium* (Cyprian ore) because the oldest and most important deposits were found on the island of Cyprus. In later usage the form *cyprium* became the Latin word *cuprum* and was the basis of the chemical symbol for the element, Cu, introduced by the Swedish chemist Johann Jacob Berzelius in 1813. The Old High German *kupfar* evolved into today's German word *Kupfer* (copper).

Exceptional crystals of native copper are found at Lake Superior, Michigan. The most common crystal forms are the octahedron, cube, dodecahedron, and combinations of these (see p.44, Figs. 1–3). Twinning causes platy, tree- or feather-like groups of crystals (Fig. 5). Fresh surfaces are copper-red in color with a strong metallic luster, but usually copper is tarnished or coated with blackish or greenish crusts (malachite). Hardness $2\frac{1}{2}$ –3, specific gravity 8.93. In the thinnest films copper transmits green light. The major occurrences of native copper are copper-rich ores, especially those of bornite, which formed in the region between the oxidation and reduction zones, e.g., Siegerland, at Rheinbreitbach at the Rhine, at Bisbee,



5 Native Copper

Aio, Arizona/USA

Original size 28 x 53 mm



Arizona, and in Namibia. The native copper of the Keweenaw Peninsula, Lake Superior, Michigan, which was of great importance in the past, was formed by the reduction of copper in hydrothermal solutions. Masses of copper up to 400 tons in weight were found in brecciated rhyolite and under covers of porphyry.

Copper is the most important non-ferrous metal. It is widely used in the electronics industry as a conductor, and in roofing, water pipes, etc. It is also extensively used as an alloying metal in brass (copper and zinc), bronze (copper and tin), and with various precious metals. Copper sulfate is used as an insecticide, and other copper compounds are important coloring agents. The annual world production, mostly derived from oxides and carbonates of copper, is about 7½ million tons. The most important suppliers of copper ore are Papua-New Guinea, Chile and Canada; for metallic copper Chile and Zambia, among others.

Sulfur - S

Orthorhombic. The chemical symbol for sulfur is derived from the first letter of the Latin word *sulphur*. The German word for sulfur, *Schwefel*, originated from the Old High German *sweual* or *swebal*. The flammability of this element was early recognized by the ancients. This property caused the Greeks to name it *theion*, which means God-given. Homer named it "dispeller of the plague." The alchemists thought sulfur and *argentum vivum* (mercury) were the bases of all metals and introduced sulfur, along with other metals, stone, and salt, into their system of the alchemistic world order. Antoine Lavoisier (1777) was the first to recognize sulfur as an element, and the burning of sulfur as oxidation.

Under normal temperature conditions sulfur crystallizes in the orthorhombic form (alpha sulfur). Above 95.6°C sulfur crystallizes in the monoclinic form (beta sulfur), as, for example, in the fumarole zones of volcanic craters where, after cooling, sulfur quickly reverts to the alpha form. In nature sulfur is often found in well-developed crystals of a bipyramidal habit (see p. 44, Fig. 18) up to a few centimeters or more in size. It is also sometimes found in granular masses, and in thin powdery crusts. The color is characteristically yellow (sulfur yellow), but impurities can give it a brownish yellow color. Its high refractive index gives it a greasy to adamantine luster. Hardness 1½–2. Specific gravity 2.07. The thermal conductance of sulfur is so poor that even holding a crystal in the hand can cause sufficient inner stress for the crystal to emit a crackling sound and finally break apart. In air sulfur burns with a blue flame, producing sulfur dioxide (SO₂), a pungent gas. Much of the naturally occurring native sulfur is a condensate of volcanic fumaroles in many active and inactive volcanos, such as Vesuvius, Etna, and Vulcano, the result of partial oxidation of hy-

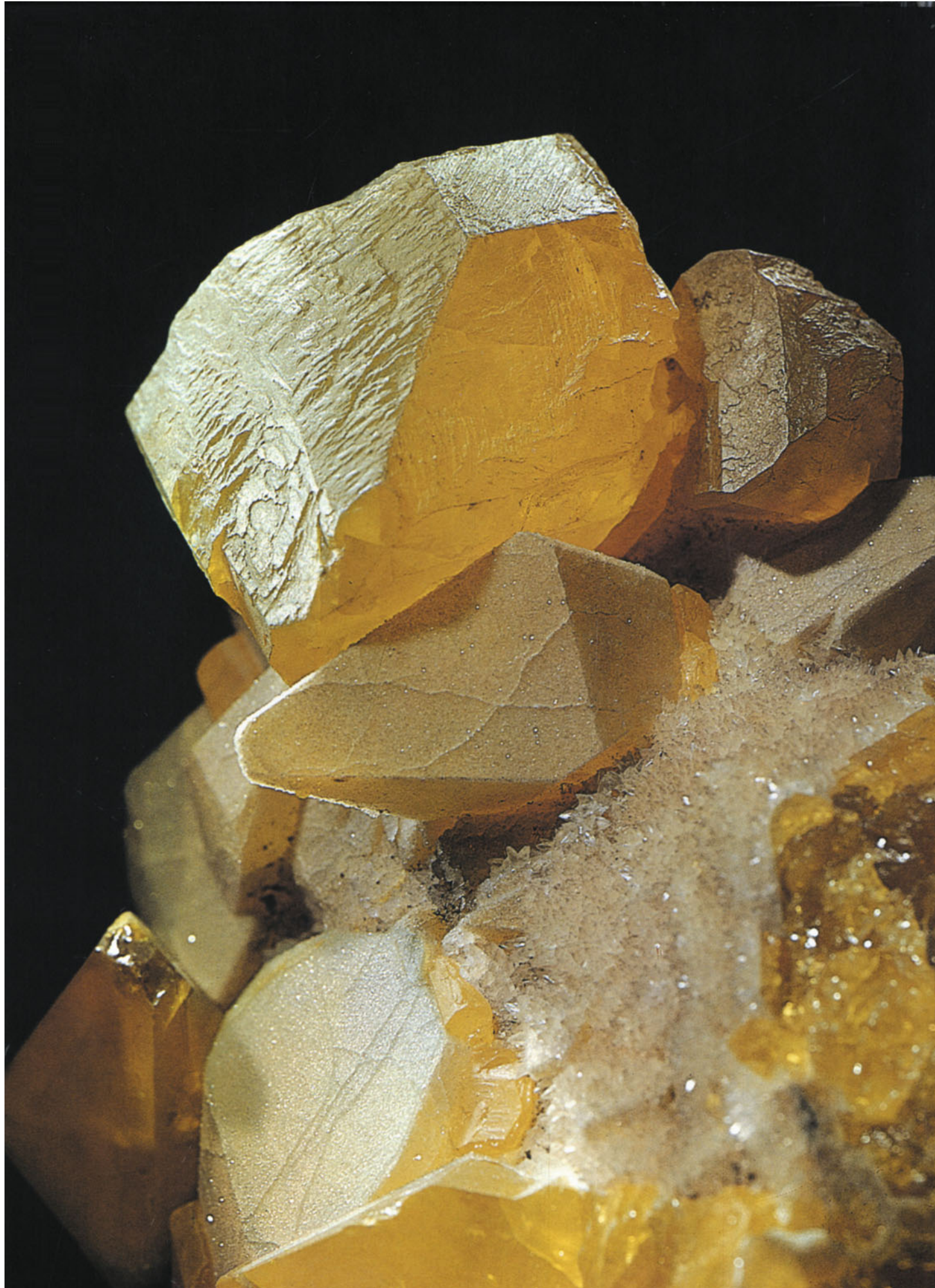
drogen sulfide (H₂S) or by reaction between H₂S and sulfur dioxide. Economic deposits of volcanic sulfur are relatively rare, occurring in Japan, Chile, and Mexico. The important deposits of sulfur in Sicily are not connected with the volcanic activity of Etna.

Sedimentary deposits are of great economic importance. Sedimentary beds of gypsum and anhydrite are first decomposed by anaerobic microorganisms which form calcium sulfide (CaS). Further reaction with percolating waters containing carbon dioxide converts the calcium sulfide to elemental sulfur and calcium carbonate in the form of calcite and aragonite. The deposits of Agrigento and Caltanissetta in Sicily, famous for their rich stores of beautiful crystals were formed in this way. Since 1250 sulfur has been mined in Sicily, where it is separated from the surrounding rock by melting. Extensive deposits of the same origin are found in Louisiana and Texas, in the U.S.A. Superheated steam is forced into the ground to a depth of about 180 m, where it melts the sulfur from the surrounding rock. In the molten state it is pumped through a double-walled pipe to the surface. Using this very economical process, the Sicilian monopoly was broken at the beginning of this century. Native sulfur is also formed through the oxidation of sulfides such as sphalerite and pyrite, but only in small quantities, and these sources are of minor economic importance.

Sulfur is important in many industries, but mainly it is used in the production of sulfuric acid, which is critical to the fertilizer industry, the vulcanization of rubber, as a disinfectant, and in the production of insecticides, fibers, and explosives.

The annual world production of sulfur, including that part derived from pyrite and natural gas, is about 32 million tons.

6 **Sulfur**
Sicilia/Italy
Original size 66 x 49 mm



7 **Sulfur** on Aragonite
Caltanissetta, Sicilia/Italy
Original size 37 x 70 mm





Diamond – C

Isometric. Diamond has been recognized with certainty only since the 4th century (B.C.). The classic diamond producer was India. In his book *Arthasastra* (economics) a teacher at the royal court, Kautilya, described the remarkable properties of the coloring of diamonds and extolled their value as a state treasure for tax and customs purposes. The six sharp points, eight evenly developed faces, and the twelve straight edges of the diamond octahedron were the standards of quality. The ideal form was of great importance because the diamond's great hardness originally allowed only the existing faces to be polished. The term for diamond in Sanskrit was *hirok*. The Greek *adamas* (=the invincible) was originally used to describe steel and then later all stones of great hardness. In his book *Peri Lithon* (About Stones), Theophrastus (372–287 B.C.) first used this term for diamond, and gave it as an example of an “unburnable stone”. In Roman times diamonds were rare. Pliny (23–79 A.D.) knew of six types of *adamas*, most of which were considered impure. The true *adamas* was thought by Pliny to be the most valuable gemstone. In his book *Historia Naturalis*, a work which retained its importance well into the Middle Ages, Pliny wrote about the legends, myths, and folklore of the diamond: “one tests the diamonds on an anvil, the genuine stones resisting the blows so that the hammer will break and even the anvil will crack. Their hardness is so great that it will also resist fire, and will not even become warm”. This monstrous strength could only be defeated with warm ram's blood, a story which returned in later years in the *Tales from the Valley of the Diamonds*, an adventure of Sinbad the Sailor, in *A Thousand and One Nights*. Another observation of Pliny is, however, apt: “If one is successful in breaking the diamond it falls apart in such small

flakes that they are hardly visible to the naked eye. These particles are eagerly sought by stonecutters. Set in iron, they are useful to drill with ease stones of any hardness.” From the earliest times diamond was associated with enchantment and mystery and especially since the 11th century it has been valued for its magical qualities. Worn on the left arm, it made its wearer invulnerable. It gave courage and helped against poisons, gout, arthritis, and gallstones. In his book *De Mineralibus*, Albertus Magnus (1193–1280) described the diamond: “Adamas, sometimes called diamas, is a very hard stone with a greasy luster, a little darker than quartz and so strong that it will penetrate iron and all other precious stones.”

Until the Middle Ages, little was known about the properties of diamond. It was prized for its hardness, but was valued less than pearls, rubies, and emeralds. Even in the 16th century Benvenuto Cellini (1500–1571), a famous late Renaissance goldsmith, placed its value at one-eighth that of ruby. The basic knowledge of the chemical nature of this unique mineral originates from Antoine Laurent Lavoisier (1743–1794), a chemist in Paris. He observed from heating experiments that, in the presence of air, diamond was changed into a fully gaseous carbon dioxide (CO₂), and therefore was composed of pure carbon. The chemical symbol for carbon was derived from the Latin *carbo* (=coal).

The most common crystal forms of diamond are octahedrons, cubes, hexoctahedrons, or tetrahedrons, sometimes in combination with much rarer crystal forms. The variety of the shapes of the crystals is only partly due to the original crystallization. It depends more upon partial dissolution in the magmatic melts. This results in stones with pronounced rounded faces, surface lines, bent faces, and etch figures, which show up as triangular pits on the octahedron faces, called trigons (see Fig.8). Diamond crystals

commonly form flat heart-shaped structures which are known as knots. Because of the difficulty of cutting these stones the South African cutters refer to them as *Duivelsteene* (devil's stones). Diamond aggregates of irregular or radial growth (ballas) are known as *bort*. In general the term bort is used to describe stones of inferior color or those that are heavily included and therefore unsuitable as gemstones. *Carbonados* are pea- to egg-sized rolled crystal aggregates, gray to black in color, due to heavy graphite inclusions. They are mostly used in drill tips, as they have no gem potential.

Diamond crystals are mostly colorless, with only slight tints of yellow, brown, or green. Brightly colored diamonds are extremely rare. These stones are known as fancy diamonds and command much higher prices than even the cleanest colorless stones. Golden yellow, orange-yellow, coffee brown, green, blue, red, and pink are some of the colors of these fancy stones. The color is caused by ordered atoms of foreign matter. Canary yellow, cognac brown, and dark brown diamonds contain iron (Fe), rare blue diamonds boron (B), and the pinkish-red manganese (Mn). Nitrogen (N) is responsible for the more or less yellowish tint in some “colorless” diamonds. A few examples of famous large colored diamonds are the 128.5 carat (1 carat = 0.2 g) canary-yellow Tiffany Diamond from South Africa, the 44.5 carat blue Hope Diamond from India, and the 23.6 carat Williamson Pink from the Williamson mine in Tanzania.

Treatment of diamonds with neutrons or electrons will cause a change of color. Neutron bombardment imparts a green color that changes to yellow or brown

8 **Diamond** in Kimberlite
Republic of South Africa
Original size 22 × 25 mm



with heat treatment; electrons cause a blue color. Diamonds range from full transparency (like pure water) to translucent and opaque. The striking diamond luster is caused by its high refractive index, the play of colors or “fire” is due to diamond’s high dispersion (the breaking up of white light into its spectral colors). Luster, dispersion, and reflection of light from an ideally cut gem (brilliant cut) work together to produce a brilliant stone.

Diamond, as pure carbon, burns at 720 °C in the presence of oxygen and at 800 °C in air to form carbon dioxide. Heating to 1200 °C in the absence of oxygen will change diamond to graphite (the hexagonal form of carbon). The reverse process of producing diamond from graphite has only been possible since 1953. This process requires temperatures in excess of 1400 °C and pressures of 50,000 to 60,000 atmospheres. The diamonds formed in this process are small, mostly under 1 mm in diameter. Large quantities of synthetic diamonds for industrial use are produced in the U.S., South Africa, Ireland (Shannon), and the Soviet Union. Since 1970 it has been possible in the U.S. to produce larger diamonds over 1 carat in size, often with beautiful colors and of cutting quality. Because of high production costs this process is not of economic importance.

In nature diamonds are found in both primary and secondary deposits. The **primary** deposits are always genetically dependent upon volcanic pipes (tubes), which penetrated older rocks and have, for the most part, been deeply eroded with time. The matrix of primary diamonds, kimberlite, is a very basic eruptive rock. It was first found in 1869 near the present town of Kimberley, South Africa. In its unaltered condition kimberlite is a bluish-green rock (blue ground) and on the surface it weathers to a yellow color (yellow ground). The diamond crystals were formed under great pressure in kimberlitic magmas at depths

greater than 50 km and were transported with explosive force, toward the end of the Cretaceous period, about 70–100 million years ago.

Secondary deposits were formed through the weathering of primary deposits. Most of the diamonds withstood the weathering process. They were transported by surface waters and, because of their high specific gravity, were deposited in stream beds and lake and ocean bottoms. Those in the ocean became concentrated in the conglomerates through wave action. The secondary deposits were the only suppliers of diamonds from the time of the old Indian sources until the discovery of primary pipe deposits in South Africa. The famous old Indian deposits were situated on the east side of the Deccan Highlands in the area of Golconda. Many important diamonds were found there: the Hope Diamond, the Kohinoor (Mountain of Light), and many others. With the discovery of new diamond deposits in Brazil in 1721, the depleted Indian deposits became unimportant. The 600-carat President Vargas was the most famous Brazilian diamond.

The first South African diamonds were found in the bed of the Orange River, near Hopetown, in 1866 by the son of a farmer, Daniel Jacobs. Numerous finds followed, first in the secondary deposits, and later in the primary pipes of Kimberley. These finds helped South Africa to become one of the leading diamond producers. In the Premier mine, near Pretoria, South Africa, the largest diamond ever found, the first-sized Cullinan, was recovered in 1905, weighing 3106 carats. It was later cut into nine large and 96 small gems which still grace the British Crown Jewels.

Other large diamond deposits in Africa include the coastal region of Oranjemund, Namibia (discovered in 1908), the Williamson mine, Tanzania (discovered in 1940), and the deposits of Tschikapa (discovered in 1907) and Bakwanga (discovered in 1918) in the Re-

public of Zaïre. Zaïre is the world’s largest producer of industrial diamonds.

Since 1829 diamonds were found in the Ural region of the Soviet Union. New secondary deposits were discovered in the area of the lower Tunguska, Siberia, in 1948, and in 1954 the first kimberlite pipes in Yakutia. From 1967 on, large quantities of diamonds have been mined from primary deposits in the U.S.S.R. One of the largest diamonds found so far in the U.S.S.R. is the Star of Yakutia, weighing 232 carats. Industrial diamonds account for 75% of the world’s production, and these are used for abrasives, drill tips, wire drawing dies, and phonograph needles. The other 25% is used for jewelry. The annual world production of natural diamonds is 50 million carats (10,000 kg). A similar quantity of synthetic diamonds is produced each year.

9 **Diamond** in Kimberlite
Republic of South Africa
Original size 28 × 32 mm



The Structure of Minerals

The uniformity of natural crystal forms led mineralogists to the belief, even in the earliest days of the science, that the reasons for this uniformity could be found in their internal structure. In 1611 Johannes Kepler, through observations of the hexagonal forms of snowflakes, theorized that these skeletal forms were the result of an ordered arrangement of equal-sized vapor droplets at low temperatures. In 1784 René Just Haüy, professor of mineralogy at the Sorbonne, also speculated on the structure of crystals. In his book *Essai d'une théorie sur la structure des cristaux* he expressed the theory that all crystals are built up of minute cleavage bodies, the “molécules intégrantes,” that produce regular but varied crystal forms during the crystals’ growth. However, many physical properties of minerals did not support the theory of growth of “integrating molecules” forming solid bodies without intervening spaces or gaps. In order to account for the compressibility and thermal expansion of crystals, the Freiburg physicist Ludwig August Seeber, in 1824, suggested that the individual crystal building blocks do not touch each other, but are spherical and arranged in a lattice. A space lattice such as Seeber proposed would have to show interference phenomena when radiation of specific wavelengths impinges up-

on it, similar to the effect of an optical grating on visible light. The proof of the lattice concept was provided in 1912 by another physicist, Max von Laue. At von Laue’s suggestion, W. Friedrich and P. Knipping, in Munich, used a hitherto unknown type of radiation discovered by Wilhelm Conrad Röntgen in 1895, and later named for him, to probe the inner reaches of a crystal. With this radiation (now called X-rays) they found that a photographic film placed behind the crystal was exposed in a pattern of symmetrically ordered dots, due to the X-rays having been deflected by the crystal lattice.

This experiment not only confirmed the lattice structure of crystals but, at the same time, the wavelength nature of X-rays. Since then the study of crystal structures using X-rays has developed into a very important aspect of crystal physics. It has many technical applications also, as in materials testing.

Using interference diagrams it is possible to determine even the smallest building block in the regular, ordered three-dimensional space lattices. These parts – atoms, ions, or molecules – are not fixed in the lattice but, due to their thermal energy, pulse swiftly about their respective space point centers. The smallest unit of the structure, when repeated in infinite

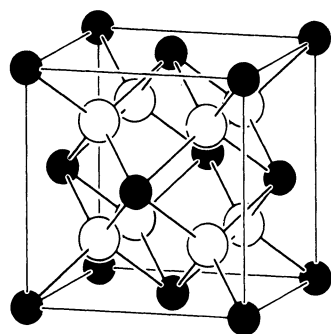
numbers in three-dimensional rows, forms a crystal visible to the naked eye. This building block is called the unit cell. All crystalline substances are based on unit cells, each with characteristic parameters. By considering all of the possible lattice positions, Bravais, in 1850, derived a total of 14 distinct types, the Bravais lattices. These may be ranked into 230 “space groups” by varying the symmetry characteristics. All of the unit cells of the countless crystal types, whether natural or synthetic, are included in this number. In contrast to the morphological measurements of crystals, the X-ray structure analyses provide a direct determination of the absolute edge lengths and angles of the unit cell. These are the lattice constants and are characteristic for every crystal type. They correlate with the crystallographic axes and angles, also discernible macroscopically, and are termed a , b , and c ; α , β , and γ , respectively. The unit cells can each be related to one of the seven basic kinds of axial intersection, corresponding to the seven crystal systems. Because the dimensions of the cells are so minute, the absolute lengths of the lattice constants are expressed in a unit of length named for the Swedish physicist Å. J. Ångström. An Ångström unit (Å) equals $1/100,000,000$ cm ($= 10^{-8}$ cm). The wave-

length of visible light lies between 4000 and 8000 Å. The X-rays used in crystal structure studies differ from visible light by their much shorter wavelengths.

In a unit cell the individual atomic components, with their inclination for symmetrical coordination during crystal growth, are ordered in a specific manner for every different type of crystal.

The unit cell of the isometric (cubic) mineral fluorite (CaF_2), as an example, is a cube with an edge length of 5.46 Å. Thus if 100 million of these unit cells were grouped with cube edges aligned, the resulting cube would measure about 5.5 cm on an edge.

In contrast to the very complex structure of silicate minerals, the symmetry of fluorite is easy to illustrate. On the corners and plane centers are found the calcium ions, while the fluorine ions occupy the $\frac{1}{4}$ and $\frac{3}{4}$ positions, measured from the unit cell corners. Every calcium ion is therefore surrounded by eight fluorine ions at the corners of a cube and every fluorine surrounded by four calcium ions at the corners of a tetrahedron. Following the discovery of the Röntgen interference by Max von Laue and the first structural determinations of diamond, sphalerite, halite and others in 1913–1914 by William Henry Bragg and Sir Lawrence Bragg,



Unit cell of Fluorite CaF_2
(black atoms: Ca, white atoms: F)

most of the structures of the minerals have been worked out. The building blocks of the crystals can be either electrically neutral atoms, such as the molecules of organic compounds, or electrically charged particles, as in metals or ionic crystals. The way in which atoms or ions are arranged in a crystal lattice is influenced, aside from physicochemical considerations, by many external factors such as pressure, temperature, and the nature of associated solutions. Crystals result from the accumulation of chemically identical substances on an existing crystal seed. In this way, provided a constant nutrient is supplied, a regularly formed macrocrystal develops through the addition of atoms, ions, or molecules, layer upon layer. If particular planes are favored during the crystallization process, distorted

crystals will result. Crystals, given identical combinations of faces (combinations between cube faces and octahedron faces, for example) can also show a very different development in the size of each face type, and thus become either more a cube or more an octahedron.

A peculiarity of growth often seen in crystals is their ability to form so-called “twin” crystals. A twin is the product of two crystals of the same crystal type having grown together in a geometrically related arrangement. The twin growth was present from the beginning of crystal growth, as evidenced mostly by the fact that a crystal with a twin partner is a mirror image of the partner. Especially common are the twin growths in feldspars. Depending on the type of twinning (law) they may be termed, for example, twins of the Carlsbad, Baveno, or Manebach law. Quartz may form Brazil, Dauphiné, and Japan law twins. A characteristic of twins is the “re-entrant angles” which are not observed with untwinned crystals.

Ordered, geometrically controlled intergrowths of more than two crystals of the same mineral are also found. This type of crystal growth may be described as a trilling (commonly seen in aragonite), fourling, etc.

Sphalerite - ZnS

Isometric. This has an interesting derivation from the original German word *Blende*, first mentioned in the 16th century (Agricola, 1546). It was used to describe a metal-free black or sometimes yellow rock which, because of its heavy weight and semi-metallic luster *blendet und betrügt* (German: blinds and deceives) the miner into believing that it contained useful metals. Not until the 18th century did the Swedish chemist Brandt (1734) discover a useful zinc ore in the *Blende*. With this discovery the name lost its original meaning, but was nevertheless retained as sphalerite, from the Greek word *sphaleros*, which means deceiving.

The most common crystal forms are dodecahedrons and tetrahedrons, often twinned, and otherwise usually massive. Layered sphalerite was called *Schalenblende* in German. It forms complex ores, associated with galena, pyrite, and marcasite. Pure zinc sulfide is white in powder form. As the iron content increases (up to 20% FeS) the color changes from yellow to brown, red, dark-green, and black (marmatite, a variety). Crystals vary from transparent to opaque. Sphalerite has a bright luster which is even adamantine on cleavage surfaces. Its high refractive index nearly equals that of diamond. Hardness $3\frac{1}{2}$ –4, specific gravity 3.9–4.2.

Sphalerite emits a characteristic odor when rubbed across an unglazed porcelain surface.

As an important zinc ore, sphalerite is always associated with galena. It often contains rarer metals such as cadmium, indium, gallium, germanium, gold, and silver, which are recovered during smelting. Many of the economically important deposits are in hydrothermal areas, such as the old deposits in Oberharz, Freiberg, in the Erzgebirge, or Schauinsland in the Schwarzwald; also Bleiberg in Carinthia and Příbram,

Czechoslovakia. A very important deposit has been the Tri-state district (Oklahoma, Kansas, and Missouri, U. S. A.). The most beautiful crystals come from Trepča, Yugoslavia, and unusually light-colored crystals from Picos de Europa, Santander, Spain. Sedimentary deposits are found near Meggen in Westphalia (with pyrite and barite), and metamorphic deposits occur at Rammelsberg, near Goslar. The annual world production of zinc is about 5.8 million tons, almost all derived from sphalerite. Technical uses for zinc are in the production of alloys (brass), galvanizing of sheet steel and iron, galvanic elements, pigments (zinc white, lithopone, zinc yellow), and in insecticides.

10 **Sphalerite** on Siderite and Quartz
Georg Mine near Willroth, Westerwald/ FRG
Original size 8 x 12 mm





Galena - PbS

Isometric. Although later called galenite in reference to the term galena (= lead ore), already used by Pliny (77 A.D.), miners of the past centuries recognized this important lead ore because of its typical metallic luster, and called it *Glanz*. The German name *Bleiglanz* was proposed by Abraham Gottlob Werner (1749–1817) as a refinement of the old miner's term. Miners also knew of its often high silver content. It commonly occurs in beautifully formed crystals, often of unusually large size, and these are found mostly as cubes, octahedrons, dodecahedrons, or combinations of these forms. The reader is referred to p.44, Figs. 1–3, 6. Twinning is common. In massive form the ore is coarse- to fine-grained.

The color is lead gray with a reddish tint. It has a strong metallic luster, especially on fresh cleavages; crystal faces and massive pieces are usually tarnished and dull. Hardness $2\frac{1}{2}$ –3, specific gravity 6–7.2.

When struck sharply, the perfect cleavage causes galena to break into fragments that are always cube-shaped. Occurrences are mainly in hydrothermal zones and in limestone replacements, but also in sedimentary and metamorphic environments. Well-known deposits are found at the now closed mines in the Oberharz (Clausthal, Zellerfeld and Bad Grund) and in the Erzgebirge (Freiberg, Saxony). Beautiful crystals came from Neudorf, East Harz and particularly large cubes on pink dolomite from the Tri-state district. Of the many other notable deposits only a few can be mentioned here: the mines of Siegerland, Upper Silesia, and near Aachen; also in the Ruhr Valley near Essen and Recklinghausen; Alston Moor, Cumberland, England; Příbram, Czechoslovakia; Bleiberg, Carinthia; Mežica (Mies) and Trepča, Yugoslavia; and Laurion, Greece. Galena formed through

metamorphism occurs along with other sulfide ores in Rammelsberg, near Goslar, and in massive quantities in Broken Hill, New South Wales, Australia. Galena is the most important lead ore. Some of the silver found in galena results from the replacement of lead by silver, but it also can be as a mechanical mixture of other silver minerals, such as proustite, pyrrargyrite, tetrahedrite, etc., and the silver content can exceed 1%. Since galena is so widely distributed and occurs in such large quantities, it is also the most important silver ore. Metallic lead is used in the production of sheet lead, lead cables and pipes, low melting point alloys, shot, and the fabrication of batteries. It is used in the glass industry for the production of lead glass "crystal"; also as a pigment for paints (white lead, red lead); and as an anti-knock compound (tetraethyl lead) in gasoline. The annual world production is about 3.6 million tons.

11 Galena

Tristate District/USA

Original size 40 x 62 mm





Symmetry of the External Crystal Forms

The outer surface of an ideally formed crystal is bounded by regular planar surfaces. The faces are bounded by straight lines, and these lines meet at exact corners. As described earlier, the external shape of the crystal reflects its atomic structure. A thorough knowledge of characteristic crystal forms is the first step toward satisfactory identification of an unknown crystal or mineral.

The first basic study of the constancy of crystal forms was conducted by the Danish doctor and naturalist Niels Stensen (Nicolaus Steno). In his study of the angles between the prism faces of quartz crystals he discovered, in 1669, that the angles between these faces are always the same, regardless of the size of the faces. This “law of the constancy of angles” means that, in general, all crystals of the same mineral, formed under identical pressure-temperature conditions and having identical chemical composition, will have the same angle between analogous faces. The law gains importance since most crystals are only rarely found in ideal, fully symmetrical form, most being more or less severely distorted. The ideal crystal form can be immediately reconstructed. To measure the crystal angles one uses a goniometer. The respective faces measured must be at right angles to the goniometer in order to

determine the interfacial angles. These are important, definitive constants that are presented in angle tables, which enable the identification of the crystal faces. The angles can be measured to an accuracy of $\pm 0.5^\circ$ with a simple contact goniometer. Two scissor-like, movable metal arms are adjusted to adjacent faces and the angle read from one of the arms which is also a protractor. Much more accurate readings can be made with a reflection goniometer, where interfacial angles are measured with the aid of light reflections from the crystal faces. The crystal, which is mounted on a measuring ring, is turned until it is oriented to the reflections and the difference between two reflections is the complement of the interfacial angle.

Through the study of ideally formed crystals it has been determined that the faces occur in a rhythmically ordered succession. This regularity of the surface forms is also known as its symmetry. There are three fundamental symmetry elements: axes of symmetry, planes of symmetry, and a center of symmetry. The **axis of symmetry** of a crystal is an imaginary line about which the crystal may be rotated a certain number of degrees, with the result that the crystal will have moved into a position indistinguishable from its original position. De-

12 **Galena** and Siderite on Quartz
Neudorf, Harz/GDR
Original size 85 × 98 mm



pending upon how many times this occurs in a full 360° rotation, the axis could be a two-, three-, four-, or sixfold axis of symmetry. These are $2 \times 180^\circ$, $3 \times 120^\circ$, $4 \times 90^\circ$, and $6 \times 60^\circ$, respectively. The rotation symmetry of crystals is determined by that of the unit cell of the space lattice. A solid lattice made up of unit cells with five-, seven-, and eightfold symmetry, as often seen in plants, sea-stars and radiolaria, is not possible.

Planes of symmetry (represented by *m*, from *mirror*) are imaginary planes that divide the crystal in half, each half the mirror image of the other. Every plane, edge, and corner is mirrored by corresponding planes, edges, and corners on the opposite side, as with the human body in which the right side is mirrored by the left.

A **center of symmetry** or center of inversion (represented by *i*, from the Latin *inversio* = inversion) is a hypothetical point in the center of a crystal through which a line may be passed from a point on some face, edge, or corner such that a similar point is found at the same distance on the other side of the crystal. Obviously a crystal can possess only one center of symmetry.

A crystal can have multiple axes of symmetry varying in number, planes of symmetry in

Chalcopyrite - CuFeS_2

Tetragonal. The modern name comes from the Greek words *chalkos* (copper) and *pyr* (fire). The German name *Kupferkies* is derived from the old miner's language. Originally *Kies* was used to describe the minerals that could not be used as ores by themselves, but found some uses as additions to smelting processes. *Kiese* all have a highly metallic luster, light color, and are mostly hard enough to generate sparks when struck by steel tools. *Kupferkies* is an exception to this rule. The mining terms *Kies* came from flint (*Kieselstein*), which also spark when struck, and was used also for pyrite and other sulfide minerals. The minerals described by Agricola (1546) as *Kies* also included both pyrite and chalcopyrite.

The crystals are often well formed and sometimes up to 1 cm in size, usually in the form of disphenoids (Greek *sphe* = wedge). The mineral is, however, mostly found as a massive ore. The color is brass yellow to greenish, the surfaces sometimes brightly colored but also tarnished black. It has a very strong metallic luster on fresh surfaces. Hardness $3\frac{1}{2}$ –4, specific gravity 4.2. It is easily mistaken for pyrite, but is softer.

Chalcopyrite is one of the most common minerals and the most important copper ore. It may be found as an "intrusion" mineral in deposits of complex origin, e.g., liquid magmatic and also in most hydrothermal deposits as an accessory or major mineral. It is rarely found in sedimentary deposits and then only when formed under oxygen-free conditions. It is also found in metamorphic deposits. Through the weathering of chalcopyrite many diverse and colorful secondary minerals are produced, such as malachite, azurite, tenorite, and limonite; these in the oxidation zone. Of the many localities mention can be made of Stora Kopparberg, Falun, Sweden (mined since

1220); Sulitelma, Norway; Rammelsberg in the Harz (mined since the time of Otto I., ca. 900 A.D.); in the Mansfeld copper shales (or slates); Ergani Maden, East Anatolia, Turkey; and Bingham, Utah, and Bisbee, Arizona, U.S.A. Fine crystals were found in the mines of the Siegerland, from Freiberg in Saxony, and elsewhere.

13 Chalcopyrite on Siderite
Georg Mine near Willroth, Westerwald/FRG
Original size 96 x 110 mm



varying orientations, and a center of symmetry. The higher the symmetry of a crystal, the greater the number of combined elements of symmetry.

There are 32 possible combinations of the symmetry elements, as first proved mathematically by Hessel, in Marburg, in 1830. All crystals having the same type and number of symmetry elements are in the same “symmetry class” or “crystal class.” Even considering the great number of crystal types, both natural and synthetic in origin, there are none that cannot be placed in one of the 32 classes.

These 32 classes can be subdivided into the seven crystal systems, through comparisons of analogous symmetry elements. Every crystal system is defined by its particular crystallographic axes and these coordinate axes are more or less fixed by the corresponding axes of symmetry. The axial ratio of the individual crystal system is a function of the lengths of the crystallographic axes a , b , and c , and also by their angles of intersection α , β , and γ . The axis from the front of the crystal to the rear is a , that from right to left is b , and that from top to bottom is c . The characteristics of the axes of the seven crystal systems, and the angles of intersection of these axes, are illustrated on p.44.

Tennantite - $\text{Cu}_3\text{AsS}_{3.25}$

Isometric. Tennantite is a mineral of the group of “gray ores” or *Fahlerze* in German. This term was used in the Middle Ages to describe ores of a pale greyish color and weak metallic luster. The chemical compositions and names of the members of this group are quite different, mostly due to the partial replacement of copper by other metals. The most common are tennantite (named for the English chemist Smithson Tennant in 1821) – arsenian tennantite, tetrahedrite (antimony replacing arsenic), and freibergite (silver replacing copper).

Crystals of these minerals often are well developed and exhibit many faces, especially those of the tetrahedron. They are also found as massive, granular aggregates. The color varies from light grey to black, but tennantite is usually paler. The crystals are commonly dull due to surface tarnish, but fresh surfaces have a metallic luster.

Hardness 3–4, specific gravity 4.4–5.4. When the silver content of tetrahedrite is less than 30%, averaging 2–4%, it is called argentian tetrahedrite. Over 30% it is freibergite. More rarely are found mercury (up to 17%) and bismuth. Tetrahedrite is one of the silver-bearing minerals found finely dispersed in galena.

Most of the minerals of this group are hydrothermal in origin and are widespread. Excellent crystals came from Freiberg, Saxony; Tsumeb, Namibia; and the Binnenthal, Switzerland.

14 **Tennantite** and Mimetite on Quartz
Tsumeb/Namibia
Original size 30 x 40 mm





Every crystal type is characterized by a set of reference axes with precisely defined lengths and angular relationships. Once these parameters have been determined from X-ray studies which yield the lattice constants, or from measurements of interfacial crystal angles using a “unit face” which intersects each axis at unit length, it is possible to refer all observed faces on a given crystal to these reference axes using the ratios of the axial intercepts: $m \cdot a : n \cdot b : p \cdot c$. The coefficients m , n and p are usually simple numbers or rational fractions, such that a “law of simple rational intercepts” may be defined. This law and the use of reference axes were introduced as early as 1816 by Christian Samuel Weiss in Berlin. Both concepts represent the foundation upon which crystallographic investigations operate. In practice, only the indices of W.H. Miller (London, 1839) are generally used today in crystal calculations, because they are much simpler to manipulate. Miller indices are derived from Weiss coefficients by introducing the reciprocal values of the latter, i.e., $\frac{1}{m} \cdot a : \frac{1}{n} \cdot b : \frac{1}{p} \cdot c$, and clearing the fractions. The indices of a face are enclosed in parentheses, and the parameters a , b , and c , which are always given in the same order, are omitted. Using the rhombic dodecahedron as an example, where each face intersects

Pyrrhotite - Fe_{1-x}S

Hexagonal. The universally used name pyrrhotite comes from the Greek *pyrrhos*, which means fire. It refers to the typical color of the mineral, but the old German term *Magnetkies* alludes to the magnetic properties of the mineral. Well-formed crystals are not common. It tends to form flat, hexagonal plates, sometimes in rosette-shaped aggregates. It is mostly found in massive bodies which may be granular or laminated, intergrown with other sulfide minerals.

The color is bronze-yellow to pinchbeck-brown, bronze with a tint of brown, and most crystal surfaces are tarnished dull. It has a metallic luster and is opaque. Hardness 4, specific gravity 4.6.

Pyrrhotite is weakly magnetic, so that small particles are easily picked up with a magnet. Because there are unfilled iron positions in the crystal lattice, all terrestrial pyrrhotite has a slight iron deficiency. It is mostly formed as a concentration in magmatic rocks and may form large deposits. Small admixtures of pentlandite ($(\text{Fe}, \text{Ni})_9\text{S}_8$) make pyrrhotite deposits the most important source of nickel. Major occurrences include Sudbury, Ontario, Canada; the Bushveld, South Africa; and Petsamo, Finland. The deposits at Bodenmais and Waldsassen in East Bavaria are metamorphic in origin. It is found as an included mineral in many meteorites and in this case is called troilite. Apart from its importance as a nickel ore, it is used in the production of sulfuric acid and a polishing rouge.

15 **Pyrrhotite** with Quartz
Trepča/Yugoslavia
Original size 55 x 86 mm





two axes of equal length but is parallel to the third, one obtains the Weiss coefficients $1a:1b:\infty c$, and the Miller indices (110). Octahedral faces, on the other hand, intersect all axes at equal length and yield the Miller indices (111). The hexoctahedron, with the axial intercepts $1/3a:1/2b:1c$, leads to (321). The simplest form in the isometric crystal system, the cube, possesses the Miller indices (100).

Stibnite - Sb_2S_3

Orthorhombic. The ore and the metal it contains were known very early in Egypt, and also by the Greeks and Romans. The steel-gray mineral was used in salves, eye makeup for brows and lashes, and as a medicine for eye ailments. Pliny (77 A.D.) called the ore *stibium*, taken from the old Greek-Latin name *stimmi* or *stibi*. *Stibium* is still the Latin name for antimony (Sb).

In old German mining the mineral was called *Spiessglas*, from about the 15th century. Stibnite was greatly coveted by alchemists. It was used in the refining of gold and to manufacture *vitrium antimonii*, an antimony glass that was used pharmaceutically as a laxative and purgative. *Spiessglanz*, *Grauspiessglanz*, and *Antimonglanz* are modern synonyms derived from the name used in the Middle Ages. *Antimonium* in late Greek means flower or blooming. In the 18th century the term was used only to describe the ore, the metal itself was called *regulus antimonii* by the alchemists, also *Spiessglaskönig* or simply *Spiessglasmetall*.

The many-faced crystals are almost always spear-shaped or rod-like and typically form divergent sprays. The color is lead gray to dark gray, with a metallic luster. Hardness 2, specific gravity 4.7.

A characteristic of stibnite is cross-hatching on cleavage surfaces.

Stibnite is the most important antimony ore. It forms under low temperature hydrothermal conditions and is found in stibnite-quartz veins or as an associated mineral in lead and silver ore veins. Especially beautiful crystals with many terminal faces, in groups of crystals up to 0.5 m in length, were found in the old mines of Ichinokawa, on the Island of Shikoku, Japan. Crystals of similar size (to 1 m) came from Stolica and Lesnica, in Yugoslavia. The most important economic

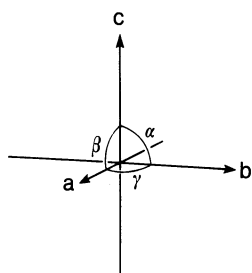
deposits are in South Africa, Lake Titicaca in Bolivia, in China, and in Mexico.

Antimony is used as an alloy constituent in hard lead used for bearings and type-setting metal, as an impregnating and fireproofing material for textiles, and as a filler and coloring agent in rubber. Antimony compounds are used in the paint and ceramic industry to heat-proof colors, and are further used in the manufacture of pharmaceutical preparations. The annual world production of antimony is about 80,000 t.

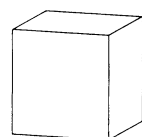
16 Stibnite

Herja, Baia Mare/Romania
Original size 43 × 51 mm

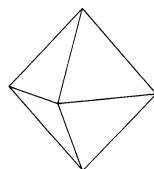




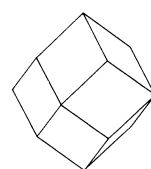
cubic
 $a = b = c$
 $\alpha = \beta = \gamma = 90^\circ$



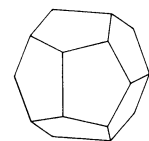
1. Cube



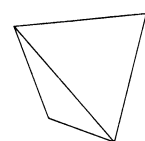
2. Octahedron



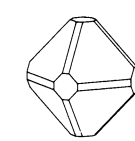
3. Rhombic dodecahedron



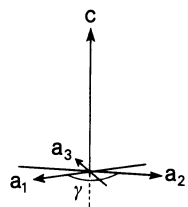
4. Pyritohedron



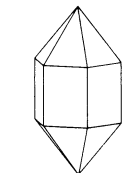
5. Tetrahedron



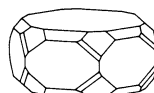
6. Galena



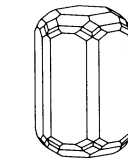
hexagonal
 $a_1 = a_2 = a_3 \neq c$
 $\alpha = \beta = 90^\circ; \gamma = 120^\circ$



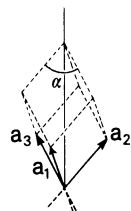
7. High quartz



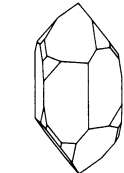
8. Apatite



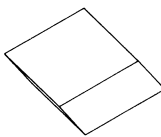
9. Beryl



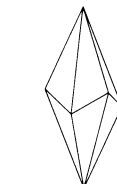
trigonal
 $a_1 = a_2 = a_3$
 $\alpha_1 = \alpha_2 = \alpha_3 \neq 90^\circ$



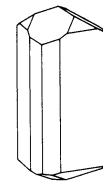
10. Quartz



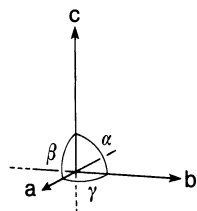
11. Rhombohedron



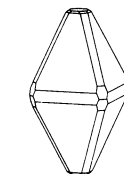
12. Scalenohedron



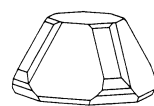
13. Tourmaline



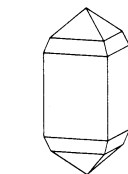
tetragonal
 $a = b \neq c$
 $\alpha = \beta = \gamma = 90^\circ$



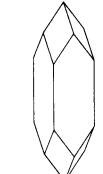
14. Anatas



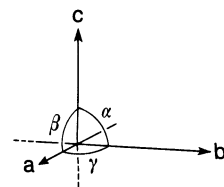
15. Wulfenite



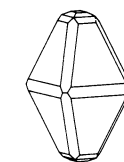
16. Zircon



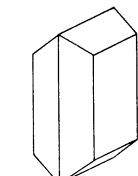
17. Apophyllite



orthorhombic
 $a \neq b \neq c$
 $\alpha = \beta = \gamma = 90^\circ$



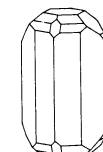
18. Sulfur



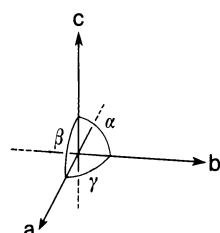
19. Aragonite



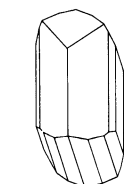
20. Barite



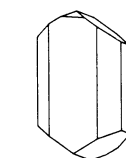
21. Topaz



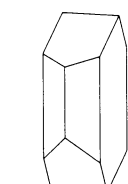
monoclinic
 $a \neq b \neq c$
 $\alpha = \gamma = 90^\circ; \beta \neq 90^\circ$



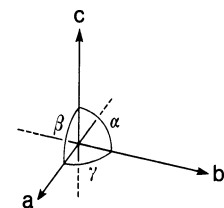
22. Orpiment



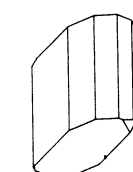
23. Augite



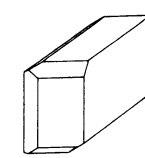
24. Orthoclase



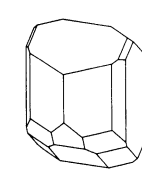
triclinic
 $a \neq b \neq c$
 $\alpha \neq \beta \neq \gamma \neq 90^\circ$



25. Chalcantite



26. Rhodonite



27. Plagioclase

17 **Pyrite** on Calcite
 Trepča/Yugoslavia
 Original size 24 x 27 mm



Pyrite - FeS

Isometric. The name *pyrites* was given to the mineral by Dioskurides (50 A.D.) and means firestone in both Greek and Latin. The ancients thought that the mineral contained fire that was released in the form of sparks when it was struck. In antiquity the term was also used for other minerals. Therefore Pliny, in his *Historia Naturalis*, described pyrite as a metallic gold-yellow to silver-white substance, whereby only the former could be descriptive of pyrite or chalcopyrite. Other names such as common pyrites are probably derived from the Germanic firestone or flint. Aside from the proper pyrite, Pliny also knew of a black *piritis* precious stone that allegedly possessed the power to burn when rubbed by the fingers. Agricola (1494–1555), the founder of mining technology and mineralogy, and also Henkel (1725) in his books *Pyritologia* or *Kieshistorie*, grouped many similar ores under the name pyrite, and only later were these found to be separate, distinct minerals.

Along with the Greek *pyrites*, the old German names *Schwefelkies* and *Eisenkies* are still in use today. Pyrite is often found in large and ideally formed crystals. Of the more than 60 known crystal forms, pyrite is most often found in cubes, pyritohedrons (see p.44, Fig.4), and diploids, either in single forms or in combinations of two or more forms. The cube faces nearly always show typical (for pyrite) striations parallel to the edges, caused by the alternating growth of the cube and pyritohedron surfaces. Of great interest are the so-called “iron cross” twins, consisting of interpenetration twins of two pyritohedrons. Excellent examples are found in the Keuper marls of Vlotho, near Minden, F.R.G. Pyrite is most often found in granular masses and also in bulbous or kidney-shaped masses with a radial structure.

The color is light brass yellow. Occasionally the crystal surfaces are coated with a rust-brown coating of iron hydroxide (limonite). Pseudomorphs of limonite after pyrite occur when the sulfur in the pyrite is fully replaced by hydroxyl, yet the original form of the crystal is preserved. Strong metallic luster. Hardness 6–6½, specific gravity 5.0–5.2. When struck with steel or quartz, pyrite throws sparks and emits a strong pungent odor of sulfur dioxide.

Pyrite is found in deposits widely different in type and age around the world. It is also found in nearly every kind of rock formation. For this reason it was referred to by the early German miners as “Hans in allen Gassen” (Jack in all streets). Many deposits are hydrothermal in origin, others contact metamorphic, sedimentary, regional metamorphic, and even primary magmatic. Important deposits are in Rio Tinto, Huelva Province, Spain, probably the largest deposits, some of which were mined by the Phoenicians for their copper and gold; Alemtejo Province, Portugal; Falun, Sweden; Sulitelma, Norway; Rammelsberg, near Goslar (Harz); and Meggen on the Lenne (Westphalia). Most deposits also produce chalcopyrite and are important copper sources. Pyrite is also locally important as the main carrier of gold, especially in the gold veins of the Witwatersrand conglomerate in the Transvaal. Exceptionally beautiful crystals come from Rio Marina, Isle of Elba, Brosso and Traversella in Piedmont, Italy; and Cassandra on the Chalkidike Peninsula, Greece. Small quantities of the mineral are also present in most crystalline rocks, and they are common in brown coal. Rocks chosen for their attractiveness for facades or decoration in the building industry must be absolutely free of pyrite, for it weathers easily under atmospheric conditions to soluble and corrosive iron sulfates and further iron hydroxide. When this occurs, all light-colored rocks such as marble are irreparably discolored with unsightly

brown stains. The sulfuric acid formed in the process is destructive to the stone and even the concrete. Many historic buildings such as the cathedrals of Cologne and Regensburg are in danger of corrosion by smoke, called acid corrosion. Minimal amounts of sulfuric and sulfurous acids that form when coal containing pyrite is burned in the presence of humid air have, over the course of many years, attacked the artistic stone ornaments. Pyrite is used in the production of sulfuric acid which is formed when pyrite is roasted in the presence of air, through oxidation. The residue is iron oxide (Fe_2O_3), which is used as a red pigment, a polishing agent, and an iron ore. Because of its gold content, pyrite may at times be an important source of gold. Pyrite was once a popular jewelry stone in France, faceted and polished and sold as marcasite. Today beautiful single crystals of pyrite are used in modern jewelry in their natural unaltered condition.

18 **Pyrite** oriented overgrowths on Calcite
Lindenberg Mine near Münster, Taunus/FRG
Original size 20 × 23 mm



Physical Properties

Just as a morphologically distinct macrocrystal reflects the symmetry of the internal crystal structure, so the physical properties of crystals are determined by their atomic structure. In contrast to glasses, fluids, and gases, which have a disorderly structure, crystals are composed of fixed and orderly structural units that occupy the crystal lattice in regular, but varying, proportions. This causes many physical properties to vary with direction in a crystal. Crystals show an “anisotropic” (Greek *anisos* = unlike, *tropos* = direction) character, while glasses, etc. are “isotropic”.

Consequently, differentiation is made between vectorial properties depending on direction and nondirectional properties that are unrelated to crystal direction. Vectorial properties are the optics, hardness, cleavage, thermal conductivity, and pyro- and piezoelectric characteristics. Nondirectional properties are specific gravity (density), specific heat, melting point, etc. Through the determination of the physical property characteristics of unknown crystals, it is often possible to identify a mineral quickly, and without destroying the crystal. This is of special importance in the study of gemstone minerals in the rough and, especially, cut form. Some physical properties such as color and luster can be ascertained simply by

visual observation; others such as hardness, cleavage, or specific gravity are relatively easy to determine with simple tests, so that an unknown mineral may be identified with very little equipment.

Color of Minerals

Apart from the manifold crystal forms, color is the most conspicuous and interesting characteristic of minerals. Not without reason, the minerals with the most pleasing colors have been used from the earliest times as gemstones. Many minerals occur in only one characteristic color, others in a wide variety of shades. A good case in point is the quartz family, members of which are found in many different colors, even being named for their color varieties: colorless as rock crystal, smoky brown as smoky quartz, violet as amethyst, and others. The same mineral can therefore be found colorless as well as colored. White light, consisting of electromagnetic waves, is composed of the spectral colors red, orange, yellow, green, blue, indigo and violet, and is unchanged in its color character on passing through a colorless crystal. Depending on the degree of turbidity, the **transparency** of a crys-

tal may vary from water clear, milky white, cloudy or opaque.

With the presence of various coloring agents, such as titanium, vanadium, chrome, manganese, iron, cobalt, nickel, and copper, some wavelengths of the visible light spectrum are more or less strongly absorbed. The minerals then appear colored to the eye and the color is that of the wavelengths that are not absorbed. The “chromatic” elements can be present in the crystal as an integral part of its composition or as trace elements in the most minute quantities. The former condition is described as an idiochromatic (own color) and the latter an allochromatic (foreign color) mineral.

Idiochromatic minerals are always colored in a characteristic manner. They are distinctive in the intensity of their colors. In the following table examples are given of idiochromatic minerals, together with the elements responsible for their colors.

Vanadium		
Vanadinite	$\text{Pb}_5[\text{Cl}](\text{VO}_4)_3$	Orange-red
Chrome		
Uvarovite	$\text{Ca}_3\text{Cr}_2[\text{SiO}_4]_3$	Green
Crocoite	PbCrO_4	Yellow-red
Manganese		
Rhodochro- site	MnCO_3	Pink
Spessartine	$\text{Mn}_3\text{Al}_2[\text{SiO}_4]_3$	Orange-yel- low
Rhodonite	$\text{CaMn}_4[\text{Si}_5\text{O}_{15}]$	Dark pink
Iron		
Andradite	$\text{Ca}_3\text{Fe}_2[\text{SiO}_4]_3$	Red
Olivine	$(\text{Mg,Fe})_2[\text{SiO}_4]$	Green
Cobalt		
Erythrite	$\text{Co}_3[\text{AsO}_4]_2 \cdot 8\text{H}_2\text{O}$	Red
Copper		
Azurite	$\text{Cu}_3[\text{OH} \text{CO}_3]_2$	Blue
Malachite	$\text{Cu}_2[(\text{OH})_2 \text{CO}_3]$	Green
Diopase	$\text{Cu}_6[\text{Si}_6\text{O}_{18}] \cdot 6\text{H}_2\text{O}$	Green

Other minerals with idiochromatic colors are sulfur (yellow), cinnabar (red), realgar (red), and orpiment (yellow). The ore minerals with metallic luster are also always the same in their colors but sometimes may appear different because of surface tarnish colors.

Allochromatic minerals do not show any specific colors. They are normally colorless, but when colored, owe their colors to minute amounts of foreign atoms contained within them. Many minerals with essentially uniform chemical composition occur in numerous and variable hues. A particularly good example of a mineral that is found in many colors is fluorite. When absolutely pure it is colorless, but in most cases it is either yellow, green, violet, blue, or pink, and of varying intensity. The different colors are caused by various foreign atoms. The elements that cause color in idiochromatic minerals also produce the same coloring in allochromatic minerals. Chrome is thus responsible for the red of rubies, spinal, pyrope, and pink topaz; and also the green color of emerald, alexandrite, jade, demantoid, and some tourmaline.

Radiation coloring is fairly common in nature. It is caused by natural radioactivity (α -, β -, γ -rays) from the surrounding rocks or neighboring radioactive minerals. This is the cause of

the color of smoky quartz and amethyst, and also the deep violet color of fluorite and blue halite. Diamonds of poor color may be irradiated with neutrons from atomic reactors to change them to green, yellow, or brown, and they may be changed to blue by accelerated electrons from a van-de-Graaff generator.

Some special **light effects**, not dependent upon color, but emphasizing it, should also be mentioned here. These are caused by numerous oriented thin hollow channels, oriented precipitates of included foreign crystals, or are interference phenomena in lamellar structures.

Chatoyance, or the cat's-eye effect, is the reflection of light in the form of a lighter-colored line that may be observed on the curved surface of some cabochon-shaped stones. The effect is caused by parallel tubes or crystals of microscopic thickness. It is commonly seen in chrysoberyl – and the chrysoberyls are the best known cat's-eyes. It is also observed in quartz, beryl, and tourmaline. **Asterism**, known as the star effect, is mostly found in rubies and sapphires, which are then called star rubies and star sapphires. The cause of the stars is the same as that in the cat's-eye, oriented inclusions of foreign crystals. In this case, however, extremely fine needles of rutile (TiO_2) per-

meate the corundum “host” in three crystallographic directions and cause the six-rayed star. The star in rose quartz is produced in the same way, and also due to rutile inclusions. Asterism is very evident on spheres of rose quartz, sometimes even showing twelve-pointed stars. The rays become sharper when the light source is pointshaped.

Labradorescence is the bright color display in certain feldspars, particularly labradorite. The colors change from blue to yellow-green as the direction of the light source changes. In *adularia*, a potassium feldspar, the similar effect is called **adularescence**, and is due to interference effects. In labradorite the interference is caused by alternating thin layers of slightly differing composition. The phenomenon of adularescence is particularly strong in moonstone, which in certain directions shows a blue-white internal shimmer. **Opalescence** is the play of varied colors observed as an opal is moved about under a light. All the colors of the rainbow may appear in opals. Opalescence is caused by the diffraction of light from layers of silica spherules of varying size. The layers of smaller spherules appear violet and blue, the larger ones yellow and red.

Aventurism is the product of light reflected from tiny platy crystals distributed uniformly

Marcasite - FeS₂

Orthorhombic. Additionally to the isometric form of iron disulfide pyrite, the same compound occurs in nature in another form, marcasite. The mineral's name is Arabic in origin, *markaschatsa*, which means firestone. The alchemists of the Middle Ages used the term equally for the “pyrite of the ancients” and for general sulfur-sulfide compounds. Based only on the crystal form *Speer kies* and *Kamm kies*, the ores of the old mineralogists and miners can be recognized as the marcasite of today. Since 1845 the name marcasite has been limited to the orthorhombic form of FeS₂. For a time, especially in the 18th and 19th centuries in France, pyrite was faceted and sold in inexpensive jewelry as marcasite.

Single crystals, especially the tabular- or spear-shaped, are rare. Normally the crystals occur in parallel and scale-like aggregates or twins and the shapes of these aggregates have caused them to be described as spear-shaped or cocks' combs. Marcasite is also often found in botryoidal or reniform radiating masses, crusts and stalactitic masses over other minerals, or as irregular knobs and radiating spheres.

The color is similar to pyrite, brass-yellow, but with a tinge of green. The luster is somewhat less than in pyrite. Hardness 6–6½, specific gravity 4.8–4.9. As with pyrite, sparks are generated when it is struck with steel and it releases the SO₂ odor.

Marcasite forms mostly in low-temperature acid water solutions and is found extensively in hydrothermal metasomatic deposits, as at Aachen, Upper Silesia, or in ore veins, as in the Oberharz, Freiberg. It is found as concretions in formerly muddy sediments such as clays, marls, and brown coal, beautiful examples being the radiating flat discs up to several centimeters in diameter in a blue shale at Sparta, Illinois, U. S. A.

Marcasite is unstable at normal temperatures, and above 400 °C it changes to pyrite. Its resistance to weathering is considerably less than pyrite, so that it more easily alters to limonite and sulfuric acid. Therefore rocks containing marcasite are absolutely unsuitable for construction purposes.

19 Marcasite

Christian Levin Mine, Essen/FRG
Original size 30 × 35 mm



throughout clear quartz or feldspar. Green aventurine is quartz containing green mica (fuchsite) and reddish brown aventurine feldspar is colored by hematite flakes within it.

Streak

When a mineral is dragged over an unglazed porcelain surface, it usually leaves a trail (streak) of its own components in powder form. The exceptions are those minerals, often silicates, that are harder than the porcelain. For most minerals the streak color is more distinctive than the true color of the mineral, and may therefore be used as one of its diagnostic properties. Many idiochromatic minerals have body colors and streak colors that are nearly identical; for example, cinnabar, malachite, and azurite, although the body colors tend to be darker. Other minerals, however, especially the metallic and allochromatic ones, have a streak that is not the same as the body color. Thus, the streak for brassy yellow pyrite is black, that of black hematite is barn red, and sphalerite, even when deep black, leaves a brown streak. The many colored crystals of allochromatic fluorite always give a white streak.

Luster

This term refers to the appearance of the surface of a crystal in reflected light. Several factors influence the amount of light reflected from a crystal. One of these is the angle of incidence of light that falls on a face. Others are the reflective and refractive characteristics of the crystal. Minerals with a low refractive index (fluorite and quartz, for example) have a glassy luster. Those with higher indices (zircon and diamond) appear adamantine (brilliant), and those with very high indices appear semi-metallic (rutile). Minerals with an extremely high refractive index possess a metallic luster. They are not transparent to visible light and their crystal faces reflect the light strongly. The degree of luster may be described as strong, lustrous or weak. Powdery minerals or aggregates with a rough break do not have a luster but show a matte surface, such as massive magnesite or earthy limonite. Other appearances may be described as greasy, pearly (gypsum), porcellaneous, or silky (asbestos).

Stephanite - $5\text{Ag}_2\text{S} \cdot \text{Sb}_2\text{S}_3$

Orthorhombic. This mineral received its name in 1845 in honor of Archduke Stephan of Austria. Originally, because of its black color and difference from red silver ore, it was referred to as brittle silver ore (*Sprödglasserz*) or black silver ore (*Schwarzgültigerz*). The German miners in Hungary called the mineral *Röschgewächs*, after the Middle High German word *rösch*, which means hard or brittle.

Stephanite is a mineral of the silver antimony group and an important ore of silver. Crystals are mostly prismatic, thick tabular, often pseudo-hexagonal, in rosettes, and they have a lead grey to black color. Hardness $2\frac{1}{2}$, specific gravity 6.2.

Stephanite is found in many hydrothermal silver ore veins along with other silver minerals, as in the Comstock lode, Nevada, U.S.A.; Zacatecas and Guanaquato, Mexico; Příbram, Czechoslovakia; Freiberg, Erzgebirge; St. Andreasberg, Harz; and Wolfach, Schwarzwald.

20 Stephanite

Himmelfahrt Mine, Freiberg, Sachsen/GDR
Original size 30 × 35 mm



Refraction of Light

The way in which minerals refract light is an important diagnostic property in the study of minerals. The refractive index is the ratio between the speed light travels in a vacuum and its velocity in the crystal or liquid being studied. The former is always $300,000 \text{ km s}^{-1}$. In a diamond light travels at $124,000 \text{ km s}^{-1}$, that is to say that the refractive index (expressed as n) is:

$$n = \frac{300,000}{124,000} = 2.42$$

These velocities cannot be measured directly because of their great magnitudes. However, due to the differences in velocity, the direction of the light changes when it passes inclined from one medium to the next; that is, from the “thinner” medium (vacuum or air) to the “denser” medium (crystal). It is “bent” toward the perpendicular to the crystal face. From the ratio of the angle of the incident and the angle of the “bent” ray the refractive index can be calculated (refraction laws of Snell, 1662). An apparatus that measures the refractive index in this manner is the refractometer. The index is dependent upon the wavelength of light. Normally, monochromatic light with the wavelength of sodium light is used.

Boulangerite - $5\text{PbS} \cdot 2\text{Sb}_2\text{S}_3$

Monoclinic. The mineral was named in 1837 by the chemist Moritz C.J. Thaulow after the French engineer and mine superintendent C.L. Boulanger, the man who first discovered and described it in 1835. Single crystals of boulangerite are quite rare. When found they form thin acicular, fibrous or prismatic aggregates. More often it is found in granular or fibrous masses of radiating crystals, which resemble crystalline galena or stibnite. Crystals of fibrous hair-like forms, such as the “plumosite” from Trepča, Yugoslavia, sometimes reach the considerable length of 1 m. The color is mostly lead gray with a metallic luster. Hardness $2\frac{1}{2}$, specific gravity about 6. Boulangerite is hydrothermal in origin and is found at most lead ore deposits, such as Clausthal, Harz; Příbram, Czechoslovakia; and Boliden, Sweden.

21 **Boulangerite** on Dolomite
Ramsbeck, Sauerland/FRG
Original size 18 x 28 mm





Isometric crystals, glass, and fluids transmit light at the same speed in all directions. These substances are termed singly refractive (optically isotropic). Their index is not dependent upon orientation, and they always have only one refractive index.

Water	n = 1.333
Fluorite	n = 1.433
Halite	n = 1.544
Sphalerite	n = 2.396
Diamond	n = 2.418

All other crystals break light into two components. This phenomenon, “**double refraction**”, is especially noticeable in rhombohedral cleavages of calcite from Iceland (Iceland spar) and the observation was first described by Erasmus Bartholinus in Copenhagen in 1669. If one looks directly into such a cleavage, one sees a doubling of any image placed behind the cleavage. With most other crystals the double refraction is less clearly distinguishable, and optical aids are required in order to observe it. The light rays entering a doubly refracting crystal are broken up into two rays, the ordinary and the extraordinary. These are polarized, i.e., their oscillations are confined to only one plane each. Before entering the crystal the light rays pulsate in all di-

Realgar - As_4S_4

Monoclinic. The name realgar has its origins in the Arabic *rahj al ghâr*, which means “dust of the mines,” and was introduced into the mineralogical vocabulary in 1747 by Joh. Gottschalk Wallerius. Other names used earlier included *sandarach*, from the *sandarake* of Theophrastus and probably derived from the Sanskrit word *candarâga*, “having the color of the moon.” The Germans used terms *rotes Rauschgelb*, then later *Rauschrot* or *rote Arsenblende*. Rauschgelb is now called orpiment and it and realgar are two related arsenic sulfides. They almost always occur together. In ancient times they were used as pigments and for medication.

The normally small crystals of realgar are often prismatic and striated on the prism faces. Otherwise it is found massive in small granules and as thin coatings. Realgar is translucent and has an adamantine luster. It is red to orange in color, and in the presence of sunlight it alters to earthy orpiment. Hardness $1\frac{1}{2}$, specific gravity 3.5–3.6.

Realgar is formed from low temperature hydrothermal solutions and is found in veins, associated with orpiment, stibnite, or arsenic, lead, silver, or gold ores. It is sometimes formed from weathering of arsenic-bearing ores. Large and beautiful crystals come from the Binnenthal, Switzerland; Baia Sprie (Felsöbánya), Kapnic, and Sacaramb (Nagyág), Romania; Jáchymov (Joachimsthal), Czechoslovakia; from the large borate deposits of Emet, near Bigadis, Turkey (Fig. 22); and from the Getchell mine, Golconda, in Nevada, U.S.A.

22 **Realgar** on Colemanite- $\text{Ca}[\text{B}_3\text{O}_4(\text{OH})_3] \cdot \text{H}_2\text{O}$
Monoclinic
Emet/Turkey
Original size 23 × 27 mm



rections. Upon entering the crystal the directions of oscillation of the ordinary and extraordinary rays become perpendicular to one another.

Doubly refractive crystals, unlike the isotropic media, have more than one refractive index. These may be divided into two groups:

1. Uniaxial Crystals. To this group belong members of the hexagonal, trigonal, and tetragonal crystal systems. They possess two indices: n_e (R.I. of the extraordinary ray), n_o (R.I. of the ordinary ray).

Refractive indices of uniaxial crystals
(Na light)

	n_o	n_e
Quartz	1.544	1.553
Beryl	1.570	1.566
Tourmaline	1.640	1.620
Apatite	1.646	1.642
Calcite	1.658	1.486

2. Biaxial Crystals. These are in the orthorhombic, monoclinic, and triclinic crystal systems and have three refractive indices: n_α , n_β , n_γ or n_x , n_y , n_z .

Halite - NaCl

Isometric. Rock salt, commonly known as salt, has been indispensable to mankind from primitive times. As a useful raw material, rock salt was easily the first mineral to be produced through mining. It was being mined in the easily entered salt deposits of Hallstadt, Salzburgerland, Austria, during the Bronze Age. The word *Salt* comes from the earliest German usage. It is related to the Latin *sal* and the Greek word *hals*, from which latter we have the modern name halite (Glocker, 1847). Depending upon the manner of production of the salt, whether by underground mining, evaporation of sea water in "salt gardens", or from brine in salt springs, a distinction was once made between rock salt, sea salt and spring salt. The earliest salt springs were Lüneburg (956), Reichenhall (1163), and Hallein (1177). Because of the many brine springs in Germany, there was an early growth of international trade. Crystals that have grown in fractures and cavities are almost always cubic, rarely with combinations of octahedrons and dodecahedrons. Rock salt is usually massive and granular, but may be fibrous in clefts. Salt is usually colorless, with iron oxide impurities coloring it red or yellow. Blue or violet colors, in part concentrated in zones or isolated flecks, are due to admixtures of colloidal metallic sodium which, under the exposure to radioactivity, is present in the form of the isotope K^{40} . It is transparent to translucent with a glassy luster. Hardness 2, specific gravity 2.1–2.2. Rock salt has a perfect cubic cleavage and is easily soluble in water. Sea water contains an average of 3.5% soluble salts, three-fourths of which is NaCl. By far the largest quantity of rock salt is found in massive deposits of marine sedimentary origin. Sea basins, when separated from the oceans by land barriers, in arid climates, will, through evaporation and replenishment of sea water, enrich the salt content of

the water to a saturated state. The dissolved salts crystallize from the solution with the least soluble precipitating first – limestone, anhydrite, and gypsum. Then thick layers of rock salt form, and finally the most soluble potassium and magnesium salts ("trash salts") – sylvite, carnallite, kainite, and polyhalite. These conditions have occurred at various times in the geologic past and have led to the formation of immense salt deposits, as in northern and middle Germany (Thuringian time); in Reichenhall, Berchtesgaden, Salzkammergut (Lower Triassic); Friedrichshall, Heilbronn, Schwäbisch Hall, in Württemberg (shell limestone), and on the Oberrhein (Oligocene). In arid countries (Mediterranean area) rock salt is produced by evaporation of sea water in the so-called "salt gardens." More than half the production of halite is used in the chemical industry for the production of soda, sodium hydroxide (lye), and hydrochloric acid. Approximately one-fourth is used for cooking and animal feed salt. The once ignored "waste salts" are indispensable in the agricultural fertilizer industry. The yearly production of salt from rock salt and sea salt is about 148 million tons.

23 **Halite**
Neuhof near Fulda/FRG
Original size 59 x 68 mm



Refractive indices of biaxial crystals (Na light)

	n_α	n_β	n_γ
Gypsum	1.521	1.523	1.531
Aragonite	1.530	1.682	1.686
Topaz	1.612	1.614	1.621
Barite	1.636	1.637	1.648
Sulfur	1.960	2.040	2.248

Because of their double refraction, thin transparent plates of uniaxial and biaxial crystals show intense interference colors in polarized light. If one uses a prepared section of uniform thickness, such as a thin section of 0.02 mm to 0.03 mm, the characteristic interference colors can be used to identify the minerals which compose a rock. Isometric crystals and glass, on the other hand, remain dark in color. This kind of study is made with the help of a polarizing microscope. Polarization microscopy is one of the most important techniques in mineralogy and petrology.

Pleochroism

The coloring of numerous nonisometric crystals is dependent upon the axial directions in which they are viewed; which is the product of

the crystal's ability to absorb various wavelengths of white light differently in different crystallographic directions. This effect is known as **pleochroism**. In uniaxial crystals the colors are limited to two changes with direction and this is known as **dichroism**. Biaxial crystals can show up to three different colors. In this case we speak of **trichroism**. Many crystals reveal these color changes to the unaided eye as they are rotated. Strongly dichroic minerals are represented by benitoite (with a color change from colorless to greenish-blue), tourmaline (from dark to light green or blue), and ruby corundum (from dark red to yellowish-red). Especially strong trichroism is shown by cordierite (erroneously named dichroite at one point in its history) as it varies from pale yellow to grey blue to violet. Less noticeable is trichroism of red topaz, which changes from red to yellowish- to pinkish red.

Luminescence

The emission by some crystals of light that is not caused by heating is luminescence. These crystals have the ability to convert certain forms of invisible energy into visible light. If a crystal glows under ultraviolet rays (black

light), we call this **fluorescence**. The effect begins and ends with the appearance and disappearance of the energy source. In some cases the response is brought on with shortwave ultraviolet light (2537 Å), in others it is longwave ultraviolet light (3650 Å) that produces it. Common fluorescent colors are violet, blue, green, yellow, orange, red, and white. The ultraviolet component in sunlight can cause crystals, such as diamond and fluorite, to fluoresce. Certain minerals tend to fluoresce most intensively in characteristic colors: many secondary uranium minerals glow in yellow or green, fluorite in green, blue, violet, and white, and calcite in red and orange.

If this effect persists for a time after the ultraviolet source has been removed, we call it **phosphorescence**. Sphalerite, diamond, fluorite, and calcite commonly show this property.

Other forms of luminescence include:

thermoluminescence – light effects caused by heating a crystal (fluorite)

triboluminescence – the product of mechanical action such as rubbing or percussion (sphalerite, halite, fluorite)

crystalloluminescence – light effects generated while certain materials are actually crystalliz-

ing (sodium hydroxide crystallizing in a melt)

Chemically pure crystals do not luminesce. The phenomenon is caused, in part, by a defect in the crystal lattice, or may be due to the presence of foreign elements in trace amounts in the crystal (rare earths in fluorite, manganese in sphalerite).

Hardness

Hardness is the resistance of a crystal to mechanical abrasion. It is one of the simple tests that can be used to aid in identifying an unknown mineral. We make a distinction between a mineral's resistance to scratching, being cut, and its brittleness. In mineralogy the scratch test has been most widely used. As early as 1822 the German mineralogist Friedrich Mohs (1773–1839) devised a scale for hardness comparison based on ten relatively common minerals. Each mineral in the Mohs hardness scale can be scratched by the next

24 Halite

Heringen on the Werra/FRG
Original size 150 × 110 mm



highest in the scale. The members, in order of increasing hardness, are:

1. Talc	$\text{Mg}_3[(\text{OH})_2 \text{Si}_4\text{O}_{10}]$
2. Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
3. Calcite	CaCO_3
4. Fluorite	CaF_2
5. Apatite	$\text{Ca}_5[\text{F}(\text{PO}_4)_3]$
6. Orthoclase	$\text{K}[\text{AlSi}_3\text{O}_8]$
7. Quartz	SiO_2
8. Topaz	$\text{Al}_2[\text{F}_2 \text{SiO}_4]$
9. Corundum	Al_2O_3
10. Diamond	C

If a mineral can be scratched, for example, by # 6 orthoclase, which, in turn, can scratch # 5 apatite, the hardness of the unknown lies between 5 and 6. A fingernail will scratch # 2 gypsum, a piece of copper will scratch # 3 calcite, and the steel blade of a pocket knife has a hardness of 5 to 5½. Window glass is about 5. Even though the determination of hardness in this manner is not very exact, it does provide information useful in helping to identify a mineral. The intervals from one mineral on the scale to the next are not uniform. In absolute terms the difference in hardness between # 9 corundum and # 10 diamond is greater than the difference between # 9 corundum and # 1 talc, but few minerals have a hardness be-

Fluorite - CaF_2

Isometric. This mineral was in use in the earliest times as an additive in the smelting of ores. It was used as a flux to reduce the melting temperature of the ore, thus generating a liquid slag. Until the middle of the 18th century, when a differentiation between the various types of "spar" minerals was made, fluorite was referred to under the general term spar (or *spat*) and *Fluß* (German for flow). The German name *Flußspat* first appeared in 1770 in a description of "fluores minerales" by the Stockholm mining official Baron A. F. Cronstedt. *Fluor* (plural *fluores*), the Latin term for melting or fluid, had already been used as a mineral name by Agricola in 1529. From this term the name fluorite was derived, a term that has become the most widely used name for the mineral since the 19th century.

The mineral is found in well-developed crystals in open fractures in rocks, almost always in the form of cubes, and less commonly as combinations of the cube with the octahedron, dodecahedron, or both and also as independent octahedrons. It is also commonly found in interpenetrating cubes which are the most prevalent type of twin. In massive deposits, fluorite is in more or less coarse, crystalline, cleavable aggregates, sometimes with a very beautiful banding of colors.

Fluorite is a mineral with great color varieties: rarely water-clear and colorless, it is most often yellow, green, violet, and blue. Some crystals contain zonal color variations. The color of the dark violet fluorite from Wölsendorf, Bavaria, was produced by the effects of radiation from associated uranium minerals. The coloring agents responsible, finely divided metallic calcium and free fluorine, are present in the crystal lattice. When this fluorite is struck a pungent gas is released, hence the name in German *Stink-*

spat. Fluorite is more or less transparent, with a glassy luster and low refractive index. Hardness 4, specific gravity 3.2–3.3. Many fluorite crystals glow when exposed to ultraviolet light, the property having been named fluorescence after the mineral. Due to the perfect cleavage parallel to the octahedral planes, the corners of cubic crystals are often accidentally broken off.

Fluorite is common in pneumatolytic desposits in the tin ore paragenesis. Major economic deposits are high- to low-temperature hydrothermal veins such as at Wölsendorf, Bavaria; Liebenstein, in Thuringia; Schwarzwald; Stolberg, in the Harz; and also in Cumberland and Derbyshire, England; Illinois, U.S.A.; the Urals, U.S.S.R.; Namibia; and others. Beautiful crystals come from Göschenen, Switzerland, and Val d'Ossola, Piemonte, Italy.

Fluorite is an important fluxing agent in metallurgical processes, and is used in the production of hydrofluoric acid and synthetic cryolite for the electrolytic production of aluminum, in the enamel and glass industry, and to reduce the temperature required to make cement. Clear and colorless crystals are cut into lenses and prisms for the optical industry.

25 **Fluorite** on Aurichalcite
 $(\text{Zn}, \text{Cu})_5 [(\text{OH})_3|\text{CO}_3]_2$
 Mina Ojuela, Mapimi, Durango/Mexico
 Original size 12 × 14 mm



tween 9 and 10. Hardness is a vectorial property and depends upon the crystallographic direction in which the test is made. With precise measurements on a sclerometer (hardness instrument) one can differentiate variations in hardness on a single crystal face. In some cases this hardness anisotropy is so pronounced that it can be observed with the simple scratch test. An especially good example is provided by kyanite (also known as disthene; from the Greek *dis* = twofold and *sthenos* = hardness). The hardness of these tabular crystals is $4\frac{1}{2}$ in the long direction of the crystal (can be scratched by a steel needle) and 7 in the cross direction (cannot be scratched). This hardness anisotropy is also present in isometric crystals, which is why diamonds can be cut and polished with their own powder.

Cleavage

The structural strength (cohesion) of a crystal can, by means of external mechanical pressure, be strained to the point that the crystal will break. The resulting surfaces may be completely irregular, as with quartz, or they may appear as flat "cleavage faces," always in the same crystallographic orientation for a given

Cryolite - $\text{Na}_3[\text{AlF}_6]$

Monoclinic. The mineral was discovered in relatively recent times, although it was first brought back to Copenhagen toward the end of the 18th century, and was first described there in 1799 by Peter Christian Abildgaard. It was named for its appearance after the Greek word for "ice stone" (*kryos* = ice, *lithos* = stone).

Cryolite is usually found in massive, coarsely crystalline aggregates, rarely as idiomorphic crystals of pseudocubic form. The single crystals are colorless, the cloudy masses are snow white, but it is also reddish, grey, or black. It has a glassy luster and a very low refractive index. Hardness $2\frac{1}{2}$ –3, specific gravity 2.95. At a temperature of just over 560°C the monoclinic cryolite changes to a cubic modification. Minerals such as cryolite which reveal evidence of melting or mixing and also of changing their modification at elevated temperatures, are known as geologic thermometers. Thus we know that clear crystals of cryolite were formed at a temperature below 560°C , and the more common cloudy masses above this temperature.

Cryolite is almost always pegmatitic in origin, the transparent crystals having formed in fractures in the massive material are hydrothermal in origin. The only commercially important deposit for this useful fluorine mineral is Ivigtut, on the Arsukfjord, in South Greenland, worked since about 1850. Mining was halted in 1962 due to the depletion of the deposit. It has some importance as a clouding agent in the glass and enamel industry, but is most important in the electrolytic production of aluminum. The melting point of raw Al_2O_3 is above 2000°C , but with the addition of cryolite it drops to little more than 1000°C . Since the demand can no longer be met with natural cryolite, it is synthetically produced from fluorite today.

26 Cryolite

Ivigtut/Greenland

Original size $90 \times 103 \text{ mm}$



mineral. Depending on the cause of the break, we may have percussion cleavages, pressure cleavages, and tensile cleavages.

Cleavage is related to the structure of the crystal. Cleavage planes are always lattice planes that are relatively dense with atoms, while the distances between the planes are great enough that the bonds holding them together are not strong.

As with hardness, cleavage is a property that may be used to differentiate between many minerals. It is not always necessary to break a crystal in order to observe its cleavage. Cleavage “tears” can often be seen in a crystal, often so small that magnification is required. The cleavage of some minerals is so obvious that early miners named them “spars” and even today we see such terms as fluorspar (fluorite), calcspar (calcite), and manganese spar (rhodochrosite) in use. The ease of cleavage is described as very perfect, distinct, good, difficult, or absent. Two minerals with very perfect cleavage are gypsum and muscovite (mica). They can be cleaved into paper-thin plates and they show a pearly luster on the cleavage faces.

More than one cleavage direction of different distinctness may exist in one and the same single crystal of some minerals; they are, how-

Cuprite - Cu_2O

Isometric. The early name *Rotkupfererz* (red copper ore) comes from the mining language of the Middle Ages and was in use by Abraham Gottlob Werner. Even older terms were *Rotkupferglas* (red copper glass) and *Kupfer Lebererz* (copper liver ore), so called because of the red to liver-brown color and resemblance to sealing wax. In 1845, Wilhelm Haidinger introduced the name cuprite which superseded the older terms. The crystals found in numerous localities are uniformly dominated by the octahedron or the dodecahedron, in addition to truncated cubes and rarer forms. It is also found massive, granular, or mixed with earthy limonite (*Ziegelerz* = brick ore). Very thin acicular crystals, the axes parallel to cube edges and extremely elongated, are known as chalcotrichite, or *Kupferblüte* (Fig. 29). Very beautiful pseudomorphs of malachite after cuprite are known, especially from Chessy, near Lyon, France; or from the more recent find at Onganja, Namibia (Fig. 28).

The color of cuprite is dark red and particularly in massive specimens red-brown to metallic gray. The hair-like variety, chalcotrichite, is usually a brilliant carmine red. It is transparent to translucent, with an adamantine to slightly metallic luster due to its high refractive index, which is much higher than that of diamond. Hardness $3\frac{1}{2}$ –4, specific gravity 5.8–6.2.

Cuprite is found in many types of copper ore, chiefly in the oxidation zones, usually in the upper levels of ore deposits, and it is an economically important copper ore in some localities throughout the world. It is almost always associated with native copper and copper carbonates. Handsome crystals come from Bisbee, Arizona, U.S.A.; Tsumeb, Namibia; and Chessy, near Lyon, France. A new finding of excellent formed crystals was made in Onganja, near Otjison-gati, about 80 km northeast of Windhoek, Namibia. At

this locality, in mid-1973 during preparation work, at a depth of 75–100 m, a fracture was uncovered that produced a very large quantity of the most beautiful cuprite crystals ever found, for a short time. The largest weighed about 2100 g and measured 14 cm in diameter. Here the crystals were covered with malachite up to 1 mm thick. The malachite may be removed with phosphoric acid, exposing the original cuprite form, but the faces are somewhat rough due to having altered to malachite. Because of their deep red color and extremely high index of refraction, many of these crystals have been faceted, but their use in jewelry is limited by its extreme softness.

27 **Cuprite** with Malachite and Mimetite on Dolomite
Tsumeb/Namibia
Original size 18 × 21 mm



ever, redundant always geometrically related to the crystallographic axes. There are even minerals with three or more cleavage directions (each of which can also be a natural crystal face) such that crystal pieces may be completely bounded by cleavage faces. Thus a cleavage “cube” of halite may be produced. Fluorite, which almost always crystallizes in cubes, has octahedral cleavage. It is common to see a cubic fluorite crystal with cleavage “tears” at the corners and in many cases the corners have been cleaved off completely. Calcite, noted for its varied and complex crystal forms, always breaks into rhombohedral cleavages.

Break

When minerals that lack cleavage are broken, uneven surfaces result. These too may be useful in helping to distinguish certain minerals. Not only is the absence of cleavage noted, the break surface may vary from hackly, to splintery, conchoidal, smooth, even, or uneven. A hackly fracture is found in many native metals, such as copper silver, gold, and platinum, conchoidal in quartz, opal, and some very dense fine-grained aggregates. Mineral aggregates

can have a granular, columnar, fibrous (gypsum), or earthy (chalk) fracture. Cleavage and fracture are some times both seen in the same mineral.

Specific Gravity (Density)

Specific gravity is a property that does not change with direction, as does refractive index, and is a precise measurement which aids greatly in mineral identification. Since it is nondestructive, it is a good test for faceted gemstones.

The specific gravity, also known as density (abbreviated as D), is the ratio of the weight of an object to the weight of an equal volume of water. It is the weight in grams(g) of one unit of volume (cubic centimeter = cm³):

$$D = \frac{m}{V} \left[\frac{g}{cm^3} \right]$$

Various methods may be used to determine specific gravity. A very accurate measurement can be made with a hydrostatic balance. One needs an accurate analytical balance and a method for determining the exact volume of the object being tested. The weight is obtained by normal means. The volume determination

28 **Cuprite** with Malachite overgrowth
Onganja/Namibia
Original size 61 × 70 mm



utilizes the fact that a body immersed in water loses exactly the same amount of weight as the weight of the volume of water it displaces (Archimedes Principle). The object is suspended on a fine thread and weighed in air, then in water. The difference gives the weight of the water displaced. The density is calculated with the following formula:

$$\frac{\text{Weight in air}}{\text{Weight in air} - \text{Weight in water}} = D \text{ g cm}^{-3}$$

Another method is by suspension using heavy liquids, which requires only very small fragments of test material. The mineral is immersed in a “heavy” (high density) liquid in which it floats. By mixing in another, lighter liquid the density of the solution is adjusted until the mineral is suspended at the midpoint of the solution, indicating that the mineral and the solution have the same density. Then the density of the liquid (and thus the mineral) is measured with a Westphal balance or a pycnometer. Only a few dilutable heavy liquids are necessary.

Bromoform – density 2.90, can be thinned with alcohol or xylol

Thoulet’s solution (potassium mercury iodide)
– density 3.20, thinned with distilled water

29 **Cuprite** (Chalcotrichite) on Calcite
Tsumeb/Namibia
Original size 8 x 11 mm





Methylene iodide – density 3.32, thinned with benzol, xylol

Clerici's solution (thallium formate-malonate) – density 4.15, may be thinned with distilled water

Densities over 4.15, as in many ore minerals for example, cannot be determined by the suspension method.

To make an exact determination the measured mineral must be free of inclusions or attached foreign matter which would change the results. The densities of minerals range between $D=1$ and $D=22$. Metals, particularly platinum ($D=21.45$), have the highest densities. Those greater than 2.9 are known as heavy minerals, including rutile, garnet, zircon, and tourmaline. They are frequently found in alluvial deposits, and may be used as guide minerals to help determine the origin of the sediments.

Magnetite – Fe_3O_4

Isometric. A stone called *magnetis* was reported by Theophrastus to have been known by the ancient Greeks. In Pliny a reference is found to a *magnes*, so named after a shepherd, who discovered the stone on Mount Ida when the nails in his shoes and the tip of his cane were caught fast on the ground. More probable, however, is the interpretation that the mineral was named after Magnesia, a region of Thessaly, or perhaps after Greek Asian towns of the same name. Pliny made a distinction between various *magnes*, in particular a masculine and a feminine. The masculine had the power to attract iron and therefore was identical with the real magnetic iron ore. It is believed that the feminine *magnes* referred to manganese ore, which was similar in appearance to the iron ore, magnetite. It could also have applied to the white-colored mineral which was later named magnesite (MgCO_3). The term magnet is derived from the accusative form of the Latin *magnetum*, as is also the name from the Middle Ages *Magneteisenstein* and the modern mineral name magnetite, which was introduced in 1845 by Wilhelm Haidinger.

Magnetite crystals are predominantly octahedral in form, less commonly dodecahedral. Twins are also often formed on the octahedral plane. Dense, granular masses often appear as magnetite ore, loose granules as sedimentary magnetite sands. The black crystals have a dull metallic luster. Hardness $5\frac{1}{2}$, specific gravity 5.2. The crystals are attracted to a magnet, and dense masses are often themselves magnets, attracting small iron objects. The magnetism is lost after heating to about 600°C , but returns after cooling.

Finely divided magnetite is a constituent of many basic rocks, such as basalt and gabbro, and it may be concentrated in basic magmas to form important deposits as at Kirunavaara, Gellivare, and Loussavaara,

north Sweden, the largest iron ore concentration in the world. Other major deposits include Grängesberg and Taberg, also in Sweden, Otanmäki, Finland, and the Lydenburg district in the Transvaal. Contact pneumatolytic magnetite is found in many localities, as in Magnitogorsk, Urals, U.S.S.R., and Berggiesshübel in Saxony, among others.

It may also be metamorphically formed from the sulfide, oxide, or carbonate iron minerals and may form beautiful crystals such as those in the chlorite schists of the Tyrolean Alps.

Magnetite is an important and widespread iron ore. The total world production is about 496 million tons annually.

30 Magnetite

Kollergraben, Binnental/Switzerland
Original size 18×21 mm



Hematite - Fe_2O_3

Trigonal. The name of the mineral comes from the Greek *haima*, meaning blood, and in appearance many of the reniform masses of hematite are of a red-brown color (Fig.31). From the earliest times it was popular with the Babylonians and Egyptians for jewelry or amulets. When it was sliced on a saw or ground upon a wheel it began to "bleed", because the mixture of the powdered mineral and water looked like dark red blood. Theophrastus, in his famous *Lapidarien*, called the mineral *haemetitis*, or bloodstone, in 315 B.C. *Haemetitis* was used as a medicine for many illnesses by the ancient Egyptians, as well as by the Greeks. They used it in the treatment of eye disorders, for which it was finely ground and mixed with honey. Moreover, since it was thought to stop bleeding and to heal bloody wounds, it was the protective stone of all warriors of the time. Even throughout the Middle Ages bloodstone was still believed to possess these powers.

Hematite crystals have a particularly rich variety of form and are tabular, lens-shaped, but also rounded, rhombohedral, and even columnar. Beautiful crystals come from the Alpine clefts, as at Cavradi, Tavetsch, Switzerland, and from the Isle of Elba. Compact masses of hematite are granular, micaceous (*Eisenglimmer*), or they form earthy non-metallic, often bedded, deposits (*Roteisenerz*, *Roteisenstein*, *Eisenrahm*). The radially fibrous form of the mineral with reniform surfaces is known as kidney ore. The German name is *Glaskopf* (Fig.31). Coarsely crystalline hematite has a semi-metallic luster and a grey to black color. Other forms are non-metallic, dull, and dark-red.

Hardness 6, specific gravity 5.2–5.3. The earthy forms are much softer. Unlike the massive magnetite, often similar in appearance, hematite is non-magnetic, and

on an unglazed porcelain surface it gives a red-brown streak.

Hematite is an important iron ore and is widely distributed worldwide. The localities are of many different types. Metasomatic action produced the multi-faceted crystals at Rio Marina, Elba; pegmatitic processes formed the iron roses in the Alpine clefts in the Gotthard region; and drying of gels at low temperatures led to the formation of the kidney ores. Metamorphic hematite occurs in large, economically worked deposits known as itabirite in Brazil and in Krivoi Rog, the Ukraine, U.S.S.R. As a result of submarine volcanic action, the *Roteisenerz* deposits in the Lahn-Dill region, F.R.G., were formed, and these are counted among the largest iron deposits in the world. Magnetite is often found as pseudomorphs after hematite, which are known as martite, and these are found in great quantities in the Urals and elsewhere.

31 **Hematite (Reniform)**
Cumberland/England
Original size 44 x 68 mm





Quartz – SiO₂

Trigonal. Quartz is one of the most common minerals in the crust of the earth. In its great variety of appearance it is exceptional among all the minerals. Its name is attributed to the Slavic root for hard, a name which comes to us from the Bohemian mines of the 14th century. This is also the origin of the old German term *Quertz*, which means the quartz is a hard and dead substance of no value in mining which often appeared in the ore veins.

In its purest water-clear and colorless form, quartz is known as mountain crystal or rock crystal (*Bergkristall*). In old legends it was believed that nymphs and fairies lived in palaces made of glittering rock crystal deep within the mountains. The Greeks called the transparent quartz *krystallos*, “the ice.” Pliny had written “In any case it is only found where the winter snow brings the most cold, therefore it must be formed from crushed ice and pure snow.” The view that the *krystallos* was petrified ice which could not be melted by the hottest rays of the sun was widespread in ancient times. Johannes Kunckel, chemist and discoverer of ruby glass, reported that rock crystal was nothing more than coagulated ice, in 1689 in his book *Ars Vitria* (The Art of Glassmaking), even though the physicist and chemist Robert Boyle effectively discredited this legend in 1672 in his work *Essay on the Origins and Properties of Precious Stones*. He determined that the specific gravity of *crystall* was three times that of ice and that the two, therefore, could not be identical.

For thousands of years the term *crystal* was used only to describe rock crystal quartz. Only later, after Nicholas Steno in 1669 first used quartz to discover the principal of the constancy of the angles between crystal faces, was the term expanded to include other symmetrically formed crystalline objects. The science

that dealt with these properties in particular was from that time called crystallography.

Quartz, especially as rock crystal, is found in beautifully formed crystals, often with complex terminations. These are usually bounded by the faces of six-sided prisms, which are almost always striated horizontally. Very often they are doubly terminated. One characteristic of such crystals is that there are two different rhombohedrons composing each end, or termination, resulting in six triangular faces, alternate ones being larger or smaller than its neighbor (see p.44, Fig. 10). An asymmetrical arrangement of so-called trapezohedral faces leads to the development of left-handed and right-handed quartz crystals. Quartz crystals are often distorted and most are twinned, although the twinning is not obvious from the external morphology. When not in well-defined crystals quartz forms compact masses, and is occasionally cryptocrystalline or in fibrous aggregates.

In addition to being colorless or white, quartz is found in numerous colors. The colored varieties usually have distinctive names. The various colors of quartz are caused by the presence of foreign atoms occupying positions in the crystal lattices, but they may also be the product of the coloring effects caused by natural radioactivity from closely associated rocks. Quartz is transparent to (rarely) opaque, with a glassy luster on crystal surfaces and a greasy luster on broken surfaces. Hardness 7, specific gravity 2.65. At a temperature of 573 °C quartz changes to a hexagonal high quartz polymorph (see p.44, Fig. 7), which makes it a useful geological thermometer. At 870 °C it will change to tridymite, and at 1470 °C to cristobalite, the melting point of which is 1715 °C.

Quartz is, after the feldspars, the second most common mineral and accounts for about 12% of the earth's upper crust. As a major rock-forming component it is found in numerous magmatic, sedimentary,

and metamorphic rocks. Examples are granites, rhyolites, gneisses, sandstones, and quartzites. Quartz, in masses weighing many thousands of tons, often forms the main core of pegmatites, or is a dominant mineral of hydrothermal vein fillings. The highly coveted beautifully crystallized varieties like the water clear rock crystal, the brown smoky quartz, and the violet amethyst are formed in cavities and vugs under moderate hydrothermal conditions. During and after weathering of rocks quartz, because of its chemical and mechanical resistance, remains almost unchanged. It can, therefore, be transported and rounded, over thousands of years, by water, ice, and wind and ultimately deposited in broad and frequently massive accumulations of boulders and sand. Very often when surrounding rocks are weathered away, remnants of quartz in giant blocks will be left behind. One such impressive geologic phenomenon is the “Bavarian wall”, a hydrothermal fissure filling that traverses the countryside for more than 150 km and, at many places, towers above the landscape in craggy, bizarre walls and cliffs.

Quartz, with its diverse forms, finds many uses in a variety of technological applications. Clear, untwinned quartz crystals serve as oscillators to stabilize the broadcast frequencies of radio stations and wireless signals. It is used in electro-acoustics to produce ultrasonic signals or to drive electronic oscillators (quartz clocks). In all but a few localities, such as Brazil and Madagascar, most natural quartz crystals, including those of the Swiss Alps, are twinned and are not, therefore, useful as piezo-electric quartz. For this reason we produce huge quantities of synthetic

32 Quartz

Arkansas/USA

Original size 90 × 103 mm



crystals. High quality quartz is also used in the manufacture of optical instruments, especially as lenses and prisms. Quartz glass, formed by melting natural quartz, is very resistant to chemical agents, is not sensitive to extreme temperature changes, and is very transparent to ultraviolet light. For these reasons it is used widely in the manufacture of chemical apparatus and ultraviolet lamps.

Pure quartz sand or vein quartz are the most important raw materials in the glass and porcelain industries, and they are also important in the production of ferrosilica and carborundum (silicon carbide, SiC), which is an excellent cutting abrasive due to its extreme hardness of 9½. Impure quartz sand is widely used in the construction industry as an additive in cement and mortar, in the metallurgical industry as a molding material for steel and iron castings and for sandblasting, and also as a filtering agent in preparing drinking water. The varieties of quartz remain popular today for their decorative and jewelry value, as they were in ancient times. Both their beautiful crystal formations and their lovely colors account for this popularity. The quartz varieties are referred to as crystalline (phanerocrystalline) when individual crystals are readily observable, or as microcrystalline (cryptocrystalline) when the crystallinity is so minute that individual crystals can be recognized only under very high magnification.

Crystalline Varieties

Rock crystal, the colorless transparent form is found in crystals of microscopic dimensions as well as in crystals as large as 5 t. The largest crystals come from Minas Gerais, Brazil. Today Brazil is the most important supplier of rock crystal; apart from Minas Gerais, important deposits may be found in the states of

Goyaz and Bahia. Rock crystal, along with many of the other varieties, is found in clefts and cavities in massive rocks, the open spaces of which allow the crystals to grow unhindered. Famous for the specimens they have produced are the “crystal cellars” of the French and Swiss Alps. Especially prolific cleft systems occur at Dauphiné, near Bourg d’Oisans, and on Mont Blanc in the Aare-Gotthard Massif, in upper Valais and Tessin. Others are found in the Zillertal Alps and the Hohen Tauern. The largest quartz crystals from Alpine clefts reach a size of more than 1 m. The guild or fraternity of *Strahlers* is an old tradition in the Alps. Under the most difficult conditions, in almost unreachable regions of the high Alps, the *Strahlers* still bring in many of the most beautiful crystal specimens. Beautiful rock crystal is also found in Madagascar. Water-clear fully developed crystals of small size are found in cavities in marble at Carrara, Italy (Fig. 33), and in the sandstones near Herkimer in New York state, U.S.A. These are called Herkimer “diamonds.” Rounded, abraded rock crystals, most probably originating from the Gotthard massif, once found in the Rhine River, were the original “Rhinstones.” The “Rhinstones” that are sold today are simply sparkling iridescent imitations made of glass.

Rock crystal is seldom used as a faceted stone, more often it is used for matte-cut bead necklaces, often in combination with beads of other very colorful minerals, such as lapis, sodalite, and chrysoprase. Rock crystal with included crystals of other minerals, such as hairlike rutile needles (aptly called Venus’ hair) and even without inclusions is widely used for carved figures and artistic objects.

Rock crystal had already been used in a similar fashion as early as 3000 B.C. Jewelry, bowls, and cosmetic containers were found in ancient Egyptian graves. The stone was also highly valued by the Romans.

Emperor Augustus consecrated on the Capitol the largest rock crystal known at that time, and Emperor Nero favored drinking from rock crystal cups. According to the writings of Pliny, the Roman doctors of the day used rock crystal spheres as “burning glasses” to concentrate the sunlight for burning out wounds. With the aid of “magic spheres” of rock crystal one could allegedly see into the future.

Smoky quartz is colored light to dark, smoky-grey and brown. In the 18th century it was always falsely referred to as smoky *topaz*, a practice that unfortunately continues today. Almost black smoky quartz is called **morion** (Greek *moróeis* = dark). The color of smoky quartz can be removed by heating to 200° to 400 °C. Exposure to X-radiation will restore the original color. It is widely believed that the cause of the color is due to exposure to natural radiation from the surrounding rocks. The localities are the same as for rock crystal. Especially large crystals, up to over 130 kg in weight, come from the Tiefengletscher on the Furka Pass in Uri Canton, Switzerland, and crystals of over 3 t come from Minas Gerais, Brazil.

Amethyst, because of its attractive color, takes a favored position among the multiple varieties of quartz. It was coveted in ancient times. According to the second book of Moses 28, the Hebrew High Priests carried amethyst as one of the twelve precious stones in their breastplates. In Greek *améthystos* means the unintoxicated. Throughout the centuries it was thought that this stone would protect its wearer from the consequences of drinking. The amethyst is still thought of as the stone of abstinence. It is found among the badges of office of the Catholic Church

33 **Quartz** on Marble
Carrara/Italy
Original size 40 × 46 mm





and, mounted in rings, is worn by bishops and cardinals.

Crystals of amethyst are generally densely clustered on the walls of clefts and vugs, so that the individual crystals show only the points of the rhombohedral terminations. These continuous plates of amethyst points are frequently found as fillings in cavities (amygdaloids) in basic eruptive rocks. Those containing amethyst and agate in the Nahe region, F.R.G., were mined by the Romans. Except for occasional finds, these deposits have been depleted from the beginning of the 19th century. Today amethyst is produced in great quantities in the states of Bahia, Minas Gerais, Rio Grande do Sul, all in Brazil; and near Artigas, Uruguay, where amethyst is the national stone. Other important localities are in Zambia, Madagascar, Namibia, and the U.S.A. Highly desirable are the amethyst points, which crystallize in columnar form. When sawn in thin slices they show a beautiful zonal development with an inner core of chalcedony (Fig.36). Well-formed individual crystals of amethyst are exceptionally rare; beautiful specimens are expensive and come from the states of Guanajuato and Guerrero, in Mexico (Fig.35).

The color of amethyst can vary from the faintest lilac to an intense reddish-purple color. Especially prized are deeply colored crystals of full transparency. Such amethysts were once valued as highly as diamonds, rubies, and emeralds. Catherine the Great, lover of

34 Smoky Quartz

Arkansas/USA

Original size 95 x 70 mm

35 Amethyst

Guanajuato/Mexico

Original size 52 x 60 mm



beautiful Russian amethysts, sent thousands of her subjects into the Urals to seek and to mine them for her. A valuable amethyst jewel that belonged to Queen Charlotte of England was valued at 2000 British pounds in the 18th century. It was not until major deposits of amethyst were discovered at the beginning of the last century in Brazil and Uruguay that the value of amethyst dropped substantially.

The violet coloring in amethyst is not uniform. The color is usually most intense in the crystal points, and is due to natural radiation of quartz which contains minute quantities of iron. The amethyst color is not stable at higher temperatures. Amethysts from some localities, such as Rio Grande do Sul and Bahia, turn to a brilliant yellowish red to brownish red when heated to 250° to 450 °C. Stones from other localities may become colorless or milky white. Amethysts from Montezuma in the Rio Pardo district, Minas Gerais, Brazil, when “burned” become green and are called praseolite (Greek *prasinos* = leek green). All burned amethysts regain their original color upon exposure to X-radiation. Yellow burned amethyst is commercially often falsely called topaz, or gold-, madeira-, and palmeira topaz. These stones are not to be confused with the precious topaz, a mineral of the silicate group, but should be called citrine, just as the naturally occurring yellow quartz is citrine.

Citrine is naturally yellow quartz and is much rarer than amethyst. Its name is derived from the Latin and it means lemon-colored. The yellow color of citrine is due to the presence of trivalent iron, and it varies between light and deep yellow, at times with slight tinges of green or golden yellow. Unlike burned amethyst, natural citrine does not show a red-brown shade, or zonal coloring. It is, instead, usually homogeneous and is at times cloudy. The mode of formation and the localities are much the same as those for amethyst. Naturally colored citrine is produced most-

ly in Brazil and Madagascar, but in earlier times the most beautiful stones came from the provinces of Córdoba and Salamanca, in Spain, where, even at the beginning of this century religious processions would call upon the Holy Virgin for a plentiful supply of stones.

Rose quartz almost always occurs in pegmatites in massive crystalline bodies which do not show crystal faces. The usually pale rose color, occasionally an intense rose red, gave the variety its name. These large masses are practically never transparent, in fact they are usually intensely fissured and transected by milky quartz stringers. The rose color is caused by a small titanium content. For the same reason almost all rose quartz specimens contain oriented inclusions of the mineral rutile, titanium dioxide, in needles so fine that they cannot be seen even under a microscope. These inclusions are responsible for the milkiness of rose quartz. Where this material is cut into spheres, and light, coming particularly from a point source, is directed onto the sphere, a star of six or more rays may be seen. The position of the star appears to change as the sphere is rotated. This optical effect is known as asterism, a phenomenon better known in rubies and sapphires. Massive rose quartz comes mostly from Brazil, Madagascar, Namibia, and the U.S.A. Early localities in the Bayerischen Wald near Arnbrück and Zwiesel now have only historic significance. Rose quartz in euhedral crystals is extremely rare and has been known in significant amounts only since about 1960. The crystals, rarely more than 1 cm in size, are of hydrothermal origin. They are found growing on colorless quartz, and sometimes overgrown with bladelike crystals of eosphorite in the pegmatites of Sapucaia and Aracuai, Minas Gerais, Brazil (Fig.37).

Ferruginous quartz (Fig.38) is also a crystalline quartz variety that is colored red, brown, or yellow by

the inclusion of iron oxide. Another crystal habit that is typical of some quartz is **scepter quartz** (Fig.39). Still another is **milky quartz**, the product of countless inclusions (Fig.41). **Blue quartz** is usually opaque, its color is attributed to inclusions of rutile or hornblende. **Aventurine** is green in color because it contains many oriented mica flakes, which reflect light and give the mineral a light shimmer. Quartz varieties that have the appearance of being fibrous are usually pseudomorphs of quartz after a fibrous, asbestiform mineral. In the case of **cat's-eye quartz**, the fine fibers are oriented in parallel within the mineral, reflecting a linear light as in a cat's eye when the stone is cut with a domed shape. In this case a line of light is reflected selectively off of the inclusions, and the light line moves as the stone is moved. While these are usually yellow to grey-green, a similar effect is shown by the grey-blue **falcon's eye**, and the golden-yellow **tiger's eye**. Both were formed through the silicification of the asbestos mineral crocidolite, the fibers of which cause a magnificent silky luster. The yellow-brown color is due to the inclusion of iron oxide, which was formed during weathering of the crocidolite.

Finely Crystalline Varieties

The quartz varieties covered in this group look completely solid and homogeneous to the eye and have no outward manifestations of crystal form. However, under the microscope it can be seen that they are formed of the finest fibers and granulets. On the atomic level they are identical in structure and composition to the other varieties of quartz. While they do

36 Amethyst Rosette

Brazil

Original size 90 × 103 mm



not have their own species name, the fibrous varieties are known collectively as chalcedony, a group which is further divided into varieties largely on the basis of color.

Chalcedony is named for the former Greek town of *Chalkedon* across the Bosphorus from old Byzantium (Istanbul). This town was either a locality or a transit point for early supplies of the material. The term chalcedony is used to describe botryoidal, kidney-shaped and sinter-like crusts or stalactitic formations (Fig. 42) that are usually formed in vugs and clefts in basic rocks. It is deposited from aqueous solutions at temperatures of about 120 °C in the uppermost earth layers. The color of the waxy luster chalcedony is usually light gray. It is sometimes also pale sky blue, yellowish, or reddish. In antiquity chalcedony was important in the carving of cameos and all forms of vessels. Johann Kunckel reported "The best use of this stone is for signets and seals, because it seals very well and does not stick to the wax."

Of the many varieties of chalcedony the most widespread and best known is **agate**. It owes its name to a small river in Sicily, in which it was rolled and polished by stream action. It was discovered and utilized as colored stones by the Greeks. In the earliest times it was greatly desired because of its varied patterns. Theophrastus (372–287 B.C.) referred to it in his famous lapidary book *Peri Lithon* (About Stones), and Pliny told of an agate ring stone belonging to King Pyrrhus which had a naturally occurring picture of Apollo and the nine muses. Agate was also one of the "precious stones" contained in the badge of office of the high priests.

As is the case with chalcedony, agate is formed in low temperature hydrothermal solutions as coatings and fillings in former gas cavities which are produced when lavas have lost their dissolved gases. In the

agate geodes the chalcedony built up a succession of layers of various colors and thicknesses. The first was deposited along the inside surface of the cavity and additional layers were precipitated upon this, with the agate coating growing toward the center of the cavity. White quartz is often interspersed between agate layers, and the final portion to grow near the center is often white quartz as well (Fig. 43). It is common in these amygdaloids to have a cavity in the center, into which grow crystals of amethyst, the last layer to be precipitated. These crystals may also be smoky quartz or rock crystal. Such cavity fillings are known as druses. The colors of the various layers of agate are mostly white and gray, but they may also be black, brown, yellow, red, or even blue. Cryptocrystalline quartz varieties such as chalcedony and agate have a lower specific gravity than pure quartz. They are, to a certain extent, porous, and therefore can be colored by dye solutions. This dyeing of agate was known as early as Pliny's time. The agates that are dyed are mostly those of an unattractive gray color. In this case organic and inorganic solutions are introduced into the pores of the agate and by subsequent treatment the color is enhanced. As the white quartz layers are not colored in the process, they form a particularly impressive contrast with the dyed ones. Agate which is artificially dyed black, in analogy to the natural black material, is called **onyx**. Many other colors may also be introduced. From the various patterns found in agate, a number of names have been introduced: eye agate, banded agate, fortification agate, coral agate,

37 **Rose Quartz** with Eosphorite
(Mn, Fe²⁺)Al[(OH)₂]PO₄ · H₂O
Orthorhombic
Aracuai, Minas Gerais/Brazil
Original size 34 × 53 mm







and scenic agate, to name but a few. Agate with straight parallel layers, the so-called *lagenstein*, are especially valued for use in engraving cameos, crests, and monograms. Moss agate and dendritic agate are chalcedony with inclusions of green hornblende, chlorite, or iron hydroxide dendrites which look organic.

From the time of the Romans to the beginning of the last century the most important, and in the Middle Ages the only, locality for agates was in the melaphyres and porphyries of Idar-Oberstein, F.R.G. They were the reason for the development of the lapidary industry and gem dealing in the area. Today most of the agates cut here come from the state of Rio Grande do Sul, in Brazil, as well as from northern Uruguay. In addition to its uses in cameos, agate is used extensively for making many jewelry products and for artistic ornaments, especially thin and delicate bowls and other containers such as ash trays, and a variety of animal figurines. It is important in technology and science where it is used as a material for mortars and pestles and bearings for scales and other precision instruments.

Among the colored varieties of translucent chalcedony are **carnelian** which is colored red by iron oxide, **sardonyx** is brown and is colored by iron hydroxide, and **chrysoprase** which is green and derives its color from the inclusion of nickel silicate. At one time chrysoprase was the most valuable gemstone found in Germany, and today it is still the most valuable of the chalcedony varieties. In Greek the name means golden leek. Its locality is Frankenstein, in Silesia, and it lies in a weathered zone of a nickel deposit. It was known as early as the 14th century, but now is more or less exhausted. Chrysoprase was the favorite stone of Frederick the Great. Although he was so frugal that he melted down the silver decorations of his furniture, he used chrysoprase copiously to decorate

38 **Ferruginous Quartz** on Hematite
Cumberland/England
Original size 105 x 81 mm

39 **Scepter Quartz** (Amethyst)
Zillertal/Austria
Original size 31 x 22 mm



his Sansouci Palace, as it was the stone of his Silesian Province. Today it is found in Brazil, the U.S.A., Madagascar, and especially in Australia.

Jasper is a cryptocrystalline granular quartz. Its many colors are the products of pigmentation by oxides and hydroxides of iron and manganese, or of other inorganic and organic substances. Jasper is always opaque, and the favorite color is red.

Many "precious" stones – and that applies to quartz with its numerous varieties in particular – were believed by the ancients to possess supernatural powers. They were considered to be protective stones against all dangers. They were supposed to protect the wearer from harm, aid in healing, and give special powers to the wearer. In the mysticism of astrology, the stones were allied with the stars and planets. From this we see moonstone and the stones of the Zodiac, for which even today their wearers claim a certain power. Of all the stones thought to possess magical powers, quartz has a favored place. Hildegard, the Abbess of Bingen (1098–1179), described quartz as having many healing properties, influencing glands, gallstones, and heart disorders, as well as worn in the lumbar region for kidney diseases. The Arabian doctor Ibn al-Beithar believed that rock crystal was a protection against nightmares. It was also thought to guarantee a safe journey across the seas, protect against travellers' diseases, prevent frostbite when worn on the finger, keep bad luck and enemies away, and build endurance.

The amethyst not only served as protection against intoxication, delirium, and its consequences, but since antiquity, has been used as a talisman against every type of phobia. When placed under the pillow it was even believed it would drive away nightmares. Hildegard recommended the use of the stone, moistened with spit, as a remedy against pimples and skin problems, tumors, insect stings, and viper bites. Also

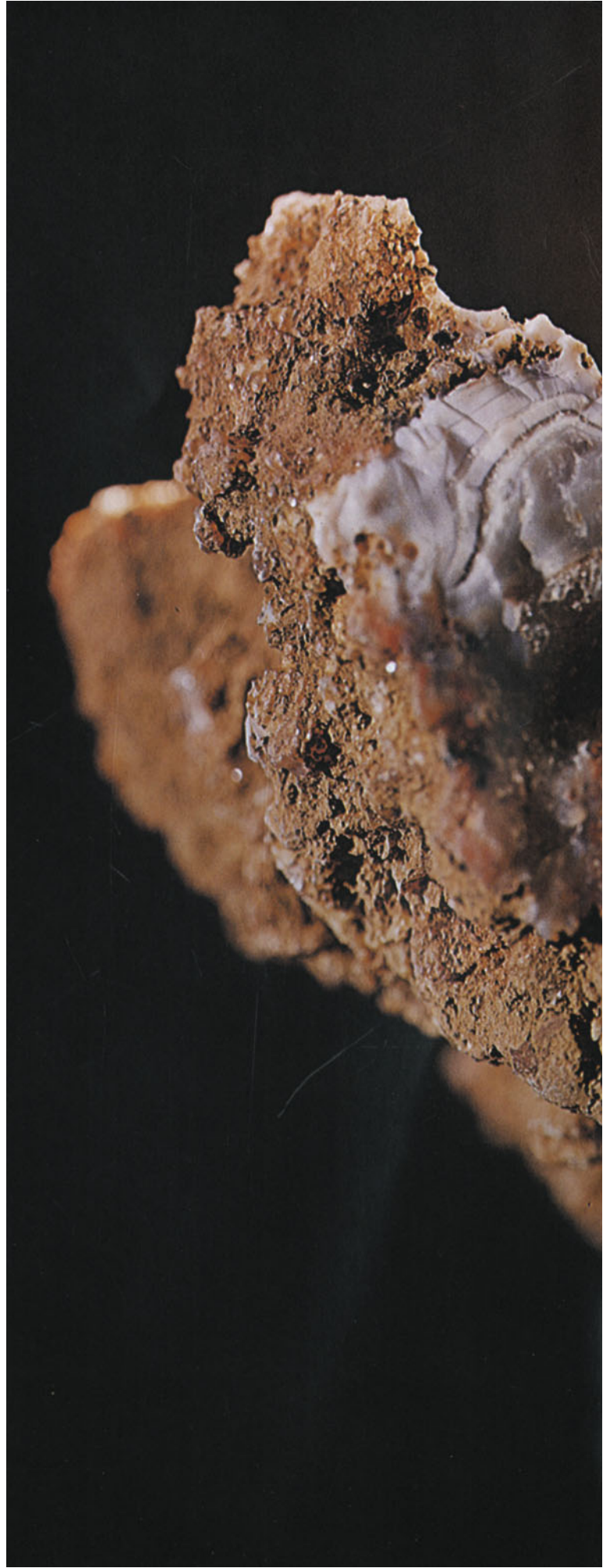
in ancient times it was thought that rose quartz, with its lovely color, brought its wearer happiness in life, provided gracefulness and luck in love, and promoted the power to understand.

From the earliest of recorded history chalcedony was used as a talisman against debility and discontent. Marbod, the Bishop of Rennes in the 12th century, recommended its use as a healing agent for diseases of the gall bladder. Albertus Magnus believed that it relieved depression and melancholy. In Adamus Lonicerus' herbal book was written: "Its power is against bad ghosts, sorrow, and fear, and makes men triumphant." The stone, when laid on the tongue or breathed upon, was thought to impart eloquence. The agate was also bestowed with healing and protective powers. Pliny tells us that it served as a protection against storm and lightning, or stilled the thirst of a fevered man when it was placed upon his tongue. It was thought to cure headaches and sharpen the eyesight. According to Konrad von Megenberg it gave the wearer a pleasing appearance and imparted fertility. Agate "has great virtues, especially that which is the color of a lion's hair or skin" wrote Adamus Lonicerus. "Agate is good against a scorpion's sting, when rubbed upon or tied to the wound, with water, it immediately removes the pain. Thrust upon the wound, or given in a drink of wine, it cures the snake's bite."

40 Quartz Druse

Asnî/Morocco

Original size 90 x 140 mm







41 **Milky Quartz**
Rocher de Sel de Djelfa/Algeria
Original size 68 x 60 mm

42 **Chalcedony**
Naila near Hof/FRG
Original size 48 x 56 mm





43 **Agate**
Brazil
Original size 200 × 380 mm



Manganite – MnOOH

Monoclinic. The name is a reference to the metal manganese and it was proposed by the Viennese mine official Wilhelm Haidinger in 1827. Older, obsolete, terms such as *Graubraunstein* or *Braunmanganerz* remind us of its use in the glass-making and pottery arts as a brown coloring agent for glass melts and glazes. The often beautiful crystals are found as fillings in fissures and cavities. They usually occur as long simple prisms or shorter prisms with many faces. The crystals commonly show striations parallel to the long direction. It may form twins in knee-shaped or cross-shaped pairs. The color is brownishblack, but in thin splinters it is translucent red and the luster is semi-metallic. Hardness 4, specific gravity 4.3–4.4.

Manganite in pure form is rare. It is usually partially or completely altered to pyrolusite (MnO_2). The color changes with this alteration from a brownish black to a steel-gray, and the semi-metallic luster intensifies to a strong metallic luster. A large portion of the specimens in collections labeled as manganite are in reality pseudomorphs of pyrolusite after manganite.

In hydrothermal veins manganite is found in independent seams alongside calcite and barite. This type of deposit, with uniquely beautiful crystals, was once found in the south Harz in porphyry, near Ilfeld (Fig.44), and in the Thüringer Wald in the porphyry and melaphyre near Elgersburg, Ilmenau, and Oehrenstock. The relatively high manganese content of the surrounding eruptive rocks apparently concentrated in the veins after leaching. The high manganese content (62.5%) made manganite locally a very important manganese source. The old mines were shut down because of depleted ore reserves. An interesting locality for manganite is in the vicinity of Nicopol in the Ukraine. The manganese are here had been concentrated in the surf zone of a former sea in the form of oolites, small spherical aggregates.

44 **Manganite** on Barite
Ilfeld, Harz/GDR
Original size 77 × 120 mm





Smithsonite - ZnCO_3

Trigonal. Smithsonite is a zinc carbonate, named after the English chemist and mineralogist James L.M. Smithson by Francis S. Beudant, in 1832. In the German mineralogical literature one most often finds the term *Zinkspat*, a name first used by the Prussian mines superintendant Justi, in 1757, for a poorly characterized mineral. The name smithsonite came into use during the second half of the 19th century. In the old usage, the mineral was included under the general term calamine (Greek *kadmeia*; Arabic *kalmeia*, *kalimija*), the name for zinc ores that were necessary for the production of brass. Both the zinc carbonate and the zinc silicate now known as hemimorphite were called calamine. They are similar in appearance and were found together in many of the zinc-rich deposits. Calamine (in German *Galmei*) is still used today as a general term for unspecified zinc ores that are either the carbonate, the silicate, or both.

Single crystals of rhombohedral form (see Fig. 11, p. 44) are rare and usually small. Smithsonite almost always forms compact, radiating, or stalactitic aggregates or shells of banded crusts with reniform or botryoidal surfaces (Fig. 46). The color is very variable – colorless, gray, yellow, or brown as well as green, green-blue to sky blue, and pink. It may have a bright to dull luster. Hardness 5, specific gravity 4.3–4.5.

Smithsonite is formed from the decomposition of primary zinc minerals, notably sphalerite, in which solutions carrying the intermediate zinc sulfates react with limestones or dolomites. Its occurrence, therefore, is largely dependent upon these carbonate rocks being nearby.

45 Smithsonite

Tsumeb/Namibia

Original size 18 x 35 mm







Especially beautiful and plentiful smithsonite specimens are known from Broken Hill, New South Wales, Australia, and Tsumeb, Namibia (Figs. 45 and 47). Compact kidney-shaped specimens with lively yellow bands of color from Iglesias and Monti Poni, Sardinia, and rich green specimens of a shell-like form from Laurion, Greece, are particularly famous. Important old localities are Altenberg, near Aachen; Wiesloch, in Baden; and Upper Silesia. It is also found in numerous localities in the U.S.A. and Mexico. Smithsonite is an important ore of zinc. Blue-green material from Mexico is referred to as Aztec stone and is used occasionally for jewelry.

46 Smithsonite
Anatolia/Turkey
Original size 120 × 90 mm

47 Smithsonite
Tsumeb/Namibia
Original size 14 × 16 mm



Rhodochrosite - MnCO_3

Trigonal. The name was given to the mineral in 1813 by the Göttingen mineralogist Joh.F.L.Hausmann, and is derived from the Greek *rhodochroos*, meaning rose-colored, even though the mineral was probably unknown in ancient Greece. In the course of time many thought the name "sounded unpleasant" and was difficult to pronounce, so new names such as *Himbeerspat* and an older name proposed by Abraham Gottlob Werner, *Manganspat*, were used as synonyms, but did not prevail. *Manganspat* alluded to the chemical composition and the excellent cleavage of the mineral.

The crystals, usually small, are confined to the interiors of vugs. They are sometimes curved into lens shapes or in parallel growths. Larger, and especially beautiful crystals, such as those from Colorado, U.S.A., are rare. Rhodochrosite is frequently compact, granular, "sparry", or built up into radial reniform crusts. The rose red color, the typical color of the divalent manganese ions, sometimes appears in alternating dark and light bands and creates a delightful decorative appearance. Rhodochrosite is mostly translucent, but can be transparent, and it has a glassy luster. Hardness 4, specific gravity 3.3–3.7.

As a typical vein mineral, rhodochrosite is found in the hydrothermal gold, silver, and zinc veins, as for example at Kapnic, Romania, and Trepča, Yugoslavia. Particularly magnificent crystals come from the silver mines of Alma, Alicante, and Gladstone, Colorado, U.S.A. Relatively young growths are found in the oxidation zones of ore bodies (gossans), some very well crystallized, as at Horhausen, in the Siegerland. Also formed in recent time are the crystalline shell-like growths widely used for decorative purposes. This material comes from Capillitas, near Andagala, Argentina, an abandoned mine that was worked by the

Incas in the 13th century for copper and silver. In 1938 the locality was rediscovered. In the 700-year interval while the mine lay idle, massive stalactitic growths of rhodochrosite had formed in the old workings. The material was called Inca rose for the Indians of the Andes, who believed that the blood of the unforgotten rulers of their Inca kingdom had turned to stone there. Further occurrences of the banded rhodochrosite are found near San Luis and in the Catamarca Province, also in Argentina.

In the compact crystalline banded form, rhodochrosite is finding more and more use in the production of reasonably priced modern jewelry and artistic articles.

Along with other manganese oxide minerals, rhodochrosite is an important ore of manganese at various localities. As one of the metals related to iron, it finds use as a component of manganese steel, as an oxidizer in chemical processes, in the glass and ceramics industries, and in the production of dry cell electrical batteries. The yearly world production of manganese is more than nine million tons.

48 Rhodochrosite

Wolf Mine near Herdorf, Siegerland/FRG
Original size 27 x 42 mm







49 **Rhodochrosite**
Waldalgesheim/FRG
Original size 61 x 45 mm

50 **Rhodochrosite** on Quartz
American Tunnel Mine, Gladstone, Colorado/USA
Original size 34 x 39 mm



Gypsum - $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$

Monoclinic. The mining of the mineral and the means of processing it were known in ancient times. From its fine-grained variety, known as alabaster, the Egyptians and Etruscans fashioned statues, salve jars, and burial urns. In earliest Egypt it was known that when the powdery form of the mineral was "burned", and mixed with water, it would quickly harden. Having the same knowledge, the Greeks called the mineral *gypsos*, which meant burned earth (Theophrastus 315 B.C.). According to the writings of Pliny, gypsum was also burned by the Romans and used to produce impressions. The name was used, as today, for both the mineral and the "burned" stone. Neither Theophrastus nor Agricola (1546) made a distinction between the calcined products of gypsum and limestone. A clear-cut differentiation was first made by the Stockholm mining official Alex F. Cronstedt in the mid 18th century: "limestone bubbles with acidic spirits, gypsum does not." For a while the "heavy spar" (barite) was also counted as a gypsum, but the Swedes Scheele and Gahn recognized the true identity of the mineral in 1774 when the name gypsum was first used in its current sense.

Idiomorphic gypsum crystals are often formed along the surfaces of clefts, especially in massive gypsum deposits, and these have been known to reach sizes in excess of 1 m in length. The individual crystals are preponderantly tabular stalky or prismatic in form, often curved into lenticular shapes. They may also form interpenetrating groups of platy crystals and sometimes groups of rosettes. Compact gypsum in large masses is common, more rarely are the fibrous varieties, and translucent compact alabaster. Twins are very common which, because of their form, are called swallow-tail twins. Similar in appearance but twinned after a different law are the interpenetrating and

sometimes lenticular Montmartre twins. Single crystals of gypsum are mostly colorless and transparent. Compact masses, on the other hand, are white to gray and translucent. Minor impurities can cause yellowish or reddish shades to occur. The crystals are easily split into thin leaves with a knife. This type of transparent cleavage has been called Marienglas in Germany. The surfaces of cleavages show a distinct pearly luster, while they appear glassy on other surfaces. Hardness $1\frac{1}{2}$ –2, specific gravity 2.3. Gypsum is easily recognized by its softness; it can be easily scratched with the fingernail. Also notable is its poor thermal conductivity. Alabaster, therefore, feels warm, a while marble, which often looks similar, will feel cool to the touch. In this way one can easily distinguish between the two substances in antique sculptures.

The precipitation of gypsum from concentrated water solutions can occur only at relatively low temperatures. At temperatures above 40°C , the water-free calcium sulfate known as anhydrite is formed. In the presence of other salts in higher concentrations, such as in the evaporation of sea water in isolated bodies of sea water, the formation of anhydrite is possible even at lower temperatures. For this reason gypsum cannot be a primary mineral in high temperature hydrothermal veins or can crystallize in highly salt-rich sea water. Marine gypsum deposits are possible only at the beginning of the concentrating of salt in the sea water and form, therefore, the bed that is the underlying layer in salt deposits. With increasing salinity anhydrite is favored instead of gypsum. Together they often form alternating layers of massive proportions. Subsequent absorption of water can convert anhy-

51 Gypsum

Eisleben, Harz/GDR

Original size 90 x 140 mm





drate to gypsum, which causes the volume to expand as much as 60%, often distorting the beds into wave-like form resulting in the formation of "serpentine alabasters." Massive gypsum deposits are found worldwide, having formed under varying geologic conditions: in Thuringian time in north and middle Germany, the alpine Triassic in Bavaria, and in the Tertiary in the Paris Basin and in Sicily. While gypsum is usually found in compact masses in the salt deposits, it may form beautiful and very large crystals in the weathering zones of sulfide ore bodies as sulfate-bearing solutions react with available calcium. A similar mode of formation produces the concretionary gypsum in clays and marls following the decomposition of pyrite. Fibrous aggregates form in fissures in adjoining rocks or beautifully crystallized in old abandoned mines or gypsum caves (Thüringer Wald) from such sulfate-bearing waters. Such crystals, clear and of the best morphological development, come from the sulfur deposits of Sicily. The often bizarre aggregates of crystals in rosette-like groups are known as sand roses or desert roses. They are always full of and covered with reddish yellow sand, and in many localities were formed from circulating sulfate solutions in desert regions (Fig. 52). The area near Volterra in Tuscany, Italy, is famous for the quality of the alabaster found there. Volterra is the old Volaterrae of the Etruscans. The mines that provided the Etruscans with the finest materials for statues, urns, and vases are still in production.

By far the largest proportion of gypsum is used in the building industry. In "burned" form it finds use in the production of plaster. By heating to about 130 °C gypsum loses the greatest proportion of its water and forms the "half hydrate" $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ which, when mixed with water, produces many micro crystals quickly and hardens. Since plaster weathers readily outside, it is used almost exclusively for interior work

(partitions, ceilings, moldings, etc.). Above 200 °C, gypsum loses all of its water and forms anhydrite. When heated to about 900 °C, a plaster is produced, which combines with water at a much slower rate and is used mostly in the construction of floors. "Burned" gypsum also finds use in the manufacture of simulated marble, for molds in the ceramic industry, in medicine as casts, and all kinds of molds in dentistry. Ground gypsum serves as a fertilizer and as an additive in mortar to delay the hardening process. It is used as a filler for paper and textiles and in the manufacture of sulfuric acid. The yearly world production of this technically important mineral is about 50 million tons.

52 Gypsum Rose
El Goléa, Sahara/Algeria
Original size 73 x 110 mm





Calcite - CaCO_3

Trigonal. *Chalis* in Greek means lime, chalk, or plaster, also small stone or gravel. Borrowed from this word is the Latin *calx, calcis*, which in ancient times was pronounced by the Romans as a k instead of a c, and influenced the old German language. At the time of Christ's birth the Romans mastered the technique of burning lime and preparing plaster. *Calx* to the Romans was both the raw stone and the slaked lime. The burned, unslaked lime (quicklime), was known by them as *calx viva* (=living lime) because of its unusually active reaction with water.

A notable characteristic of the mineral is its perfect cleavage. In general all of the easily cleavable minerals were known as spars and thus we have the name Kalkspat from middle old German mining terminology. Clear, transparent calcite shows especially well the property of double refraction, a phenomenon that was first observed by Erasmus Bartholinus (1669) in Icelandic double spar (Iceland spar). When light enters such a crystal it is broken into two rays. Because of this property, images observed through the parallel faces of a cleavage appear doubled, even without the help of other optics. Goethe, versed in many facets of natural science and an enthusiastic mineral collector, described in his theory of colors in 1813 the "double images of rhombohedral calcite" and he tried, with the means at his disposal, to explain the phenomenon. As early as 1775 calcite and lime were known to be compounds of carbon dioxide. In 1808 the English chemist and physicist Davy, with the help of electrolysis, discovered the metal contained therein, which he named calcium. The name calcite, earlier used only for the calcite pseudomorphs from Sangerhausen, on the southern side of the Harz Mountains, was finally adopted to cover the entire mineral type by Wilhelm Haidinger, a Viennese mining official, in 1845. Today

both names, calcite and kalkspat, are used equally.

Calcite is a mineral that is often found in excellent crystals, the largest of which may attain lengths of more than 2 m. With perhaps 600 different crystal forms in more than 2000 combinations, calcite is unique in the rich variability of its crystal shapes. Calcite is unique in its great variety. The simplest crystal forms are steep and flat rhombohedrons (see p.44, Fig.11) and numerous scalenohedrons (see p.44, Fig.12). Additionally, the hexagonal prisms are often combined with a flat rhombohedron or with a basal termination, which is known as cannon spar. Crystals with dominant basal forms are extremely tabular and are known as paper spar (Fig.53).

Calcite has a propensity to form twins. When scalenohedral forms are involved, the twin is in the shape of a butterfly or heart. Compact aggregates of calcite are granular, cleavable, columnar, fibrous, massive or even earthy. Calcite is usually colorless or white but foreign atoms and mechanical mixtures of other minerals can cause infinite variations of colors. Clear and usually colorless glassy crystals show a noticeable double refraction, but most crystals are only translucent. Hardness 3, specific gravity 2.6–2.8. Calcite has a perfect cleavage, so that when broken it always forms perfect similar rhombohedrons. When heated to between 900 °C and 1000 °C, calcite forms calcium oxide (CaO, burned lime, quicklime) and carbon dioxide (CO₂). This step is used in the construction industry in the manufacture of burned lime which is important in plaster.

Calcite is a very common mineral and occurs in nature in extremely large amounts. It may be formed

53 Calcite

Andreasberg, Harz/FRG

Original size 78 x 120 mm





magmatically in the so-called carbonatites, as at Alnö, Sweden, or Phalaborwa, northeast Transvaal. As a vein mineral it is found in numerous hydrothermal ore deposits. From vugs in such veins come the most beautiful calcite crystals in a myriad of combinations of forms. One of the best known localities is the now abandoned St. Andreasberg, Harz (Fig. 53 and 56); Freiberg in the Erzgebirge; Derbyshire and Egremont in Cornwall, England (Fig. 55); Příbram, Czechoslovakia; and, in especially large crystals, from Joplin, Missouri, U.S.A. Beautiful crystals are also found in vugs in volcanic rocks, as in the Nahe area around Idar-Oberstein, or as water-clear "double spar" in the basalts of Helgustadir on the Eskifjord, Iceland.

The greatest amount of calcite is of sedimentary origin and, in the form of **compact limestone**, constitutes the major portions of many mountains such as the Kalk Alps, and the Swabian and Fränkischer Jura. These are marine sediments that are mostly relicts of sea organisms (mollusk shells, corals, and other life forms) or precipitates from inorganic processes in warm shallow seas. The rocks are cemented through subsequent partial solution and recrystallization. Foraminifera shells make up the impressive chalk cliffs of Rügen, G.D.R. **Travertines** or **lime tufas**, on the other hand, are cellular porous sinter formations that are created in areas of lime-bearing thermal waters, especially the multi-colored terraces of Mammoth Hot Springs in Yellowstone National Park, U.S.A. Through the action of waters containing carbon dioxide, a remarkable amount of calcium carbonate can be leached from neighboring rocks and deposited in suitable areas. As a result many places on earth are endowed with caves containing fantastically shaped stalactites (growing down from the ceiling) and stalagmites (growing from the ground up).

If limestone is exposed to elevated temperatures, as when in contact with ascending magma, it is recrystallized into larger granules of calcite. This type of metamorphism produces **marble**. Especially clean white marble is quarried in immense amounts in Carrara, Italy, and at Pentelikon, near Athens, Greece. The term marble is used in the technical and business sense to describe everything from polishable, cryptocrystalline to massive limestone and dolomite.

The uses of calcite, because of its great variety of occurrence, are varied. The increasingly rare clear double spar is used in the optical industry for the manufacture of polarization prisms. White marble has been used from the earliest times for carving the most exquisite sculptures. Marble, as well as the often colorful and beautifully figured limestone, is used in the building industry in the form of flat polished plates for decorative stones. From these are made façades, wall and floor coverings, window frames and sills, and even steps. The extremely fine-grained material from Solnhofen also finds use in the printing industry as lithographic plates. The small stones of sidewalks in many localities are made of limestone, and blocky limestones are still used today for monuments and building stones. Burned lime CaO , when mixed with water, makes slaked lime Ca(OH)_2 which, when combined with gravel or sand, is used as construction mortar. As the mortar "sets", the slaked lime and carbon dioxide "remake" the calcite and in combination with sand produce a hard cement. Limestone also finds widespread use in the chemical industry in the manufacture of calcium nitrate, calcium fertilizers, calcium carbide, and calcium chloride. In the glass industry it is used to homogenize melts and in blast furnaces it is used as an additive to ores containing SiO_2 .

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54 **Calcite** on Quartz
Col de Forclaz/Switzerland
Original size 20 × 23 mm



Occurrence and Origin of Minerals

Through deep core drilling or mountain building processes coupled with erosion, the chemistry and distribution of elements in rocks is known to us as far into the earth as the top of the subcrustal layer, marked by the Mohorovičić discontinuity, or at least to a depth of about 16 km. In 1924 Clarke and Washington, after studying some 5000 rock analyses, were able to describe the relative abundance of the most important elements in the earth's crust. They discovered that only a small portion of the 92 elements found in crustal rocks are important constituents. Nearly 99.5%, by weight, of the earth's crust is made up of only 12 elements, of which two, oxygen and silicon, comprise 75% of the total weight. Expressed in percent by volume, the oxygen content alone is over 94%. Consequently, the most important minerals in the crust are the oxygen-silicon compounds, the silicates. The silicate portion, including quartz, accounts for more than 90% by weight.

The most common minerals are the plagioclase feldspars, with 40.2%, and orthoclase, which is 17.7% by weight. Feldspars are present mostly in fine granular form but also occur as larger, relatively pure masses which are of economic interest. The third most abundant mineral is quartz. As with the pyroxenes, am-

The most common elements in the earth's crust (percent by weight)			
Oxygen	O	46.60	
Silicon	Si	27.72	
Aluminum	Al	8.13	
Iron	Fe	5.00	
Calcium	Ca	3.63	
Sodium	Na	2.83	
Potassium	K	2.59	
Magnesium	Mg	2.09	
Titanium	Ti	0.44	
Hydrogen	H	0.14	
Phosphorus	P	0.12	
Manganese	Mn	0.10	
Total		99.39	

phiboles and micas, it occurs as a major component of many rocks. The minerals that are important in technology (ores and industrial minerals) constitute only a very small percent of the total.

The genesis of minerals is the product of a combination of a variety of chemical, physical, and geological factors operating over extremely long periods of time throughout vast geographical areas. Mineral concentrations of

Major minerals of the earth's crust (percent by weight)	
Feldspar	57.9
Pyroxene, amphibole, olivine	16.4
Quartz	12.6
Magnetite, hematite	3.7
Muscovite, biotite	3.3
Calcite	1.5
Clay	1.0
Limonite	0.3
Dolomite, magnesite	0.1
All other minerals	3.2
Total	100.0

55 **Calcite**
Egremont, Cornwall/England
Original size 48 x 55 mm



economic importance are known as deposits. Aside from ore deposits, there are numerous nonmetallic deposits of raw materials such as salt, fluorite, and clay deposits. The origin of these concentrations is closely related to the genesis of rocks. We divide the rocks into three main types:

1. Igneous
2. Sedimentary
3. Metamorphic

Of the rocks in the earth's crust, those of igneous origin comprise 92% by weight. The sedimentary and metamorphic rocks each make up about 4%.

Igneous Mineral Formation

Magmas (Greek = plastic) are molten fluid silicates, or rock melts, present in the crustal zone. Their principal components are oxides of the elements silicon, aluminum, iron, calcium, sodium, potassium, and magnesium, plus large quantities of volatiles, especially water vapor, sulfur dioxide, hydrogen sulfide, carbon dioxide and fluorine. Depending upon where these melts cool and crystallize, within the crust or on its surface, the rocks that are formed will be markedly different. If gas-rich

magmas rise through the crust along fissures, the reduction in pressure will allow the volatile components to escape. If they flow to the surface they are known as lavas. Rapid cooling occurs and very fine-grained and often porous rocks result. These are referred to as **extrusive** or eruptive. In some cases extrusive rocks contain larger crystals dispersed through them which began to crystallize before the magma reached the surface. Examples are quartz crystals in rhyolite, known as quartz porphyry, or olivine in basalt.

Volatile components escaping from magma near the surface, as at volcanic areas such as Etna or Vesuvius, are exhalations and these may form minerals such as sulfur, realgar, orpiment, sal ammoniac, halite, hematite, and opal in volcanic vents. Except for sulfur, cinnabar, and sassolite, these are of no economic importance. Magmas that solidify within the crust cool slowly under greater pressure so the volatile component cannot escape. This slow crystallization of the individual minerals favors the formation of much larger crystals. These are deep-seated, or **plutonic**, rocks and examples are granite, which is composed of feldspar, quartz and mica, and gabbro, which contains feldspar and pyroxene (augite) or amphibole (hornblende).

56 **Calcite**
Andreasberg, Harz/FRG
Original size 50 × 58 mm



The crystallization of minerals from a magma and the assemblage of minerals that results is the **paragenesis** (Greek *para* = next to, beside, and *genesis* = origin) and it follows a characteristic order of precipitation. Very high temperature melts of about 1500 °C while still in a molten condition can separate silicate and sulfide portions because of their different densities (**liquid magmatic segregation**). The heavier sulfide portions settle to the lower part of the magma, a phenomenon which has produced valuable concentrations of nickel, pyrrhotite, or chalcopyrite ore deposits, often with a surprisingly high platinum content. In the early phase of crystallization, between 1200° and 900 °C, the magnesium-iron silicates olivine and pyroxene (augite), and plagioclase, plus oxides such as chromite, titanomagnetite, and ilmenite, are the minerals which form first. With this crystallization basic and ultrabasic deep rocks are formed, sometimes including commercial ore deposits. During the next **major crystallization** phase, with temperatures now down to about 600 °C, the darker rock-forming minerals pyroxene (augite), amphibole (hornblende), and biotite, then lighter silicates such as plagioclase, alkali feldspars, and quartz crystallize from the remaining melt. Among these are found the elements whose

Ankerite - $\text{CaFe}(\text{CO}_3)_2$

Trigonal. In 1825 this mineral was found by W. Haidinger, through chemical analysis, to be a species distinct from siderite (FeCO_3) and dolomite $\text{CaMg}[\text{CO}_3]_2$ and was named after Matthias J. Anker, the curator of the Johanneum in Graz at that time. Curiously another derivation of the name is given, from the Greek *an* (= perhaps, well) and *keros* (= wax), alluding to the yellowish waxy look of the compact massive material.

Ankerite is similar in appearance and crystal form to dolomite, a very widespread mineral (Dolomite Mountains). The crystals often form rounded rhombohedrons, sometimes mosaics of numerous smaller rhombohedrons. The color of the usually translucent crystals is yellowish brown. Hardness $3\frac{1}{2}$ –4, specific gravity 2.9–3.8.

Ankerite is found mostly in hydrothermal veins of carbonitic type. Under the influence of thermal waters earlier formed iron carbonate FeCO_3 is dissolved, calcium is added, and ankerite crystals are deposited. In this way ankerite, along with calcite, quartz, chalcopyrite, pyrite, and many other sulfides, was formed in the siderite veins of Siegerland. Good crystals are also found in the enormous iron ore deposits of the Steieran ore mountains near the town of Eisenerz. Here the ankerite is formed as an intermediate product where the limestones have been replaced by siderite. Well-formed crystals are also known from many other localities, such as Freiberg, in the Erzgebirge, and Traversella, in Piemonte, Italy.

57 **Ankerite**

England

Original size 85 × 132 mm





Aragonite - CaCO_3

Orthorhombic. The mineral was named after a locality in the Spanish province of Aragon by Abraham Gottlob Werner in 1788. Prior to this it was known as "aragonitic calcite" or "spathic aragon". Aragonite is the orthorhombic form of CaCO_3 , but under the pressure-temperature conditions at the earth's surface it is unstable and tends to revert to the more stable trigonal form, which is calcite. Under suitable conditions aragonite can form under atmospheric pressure and will remain stable.

Ideally formed crystals on matrix are prismatic acicular and elongated along the vertical axis, or they may be tabular; they most often form cyclic twins rather than single crystals. These appear to be hexagonal prismatic crystals but their twinned nature is easily recognized due to the presence of long sutures on each prism face, and the characteristic striations on the basal faces (Fig. 59). The mineral is often found in compact masses in the form of columnar aggregates, as radially fibrous spheres, and coral-like stalactitic growths (Fig. 58). It also occurs in sinter crusts as well as sphaerolitic forms in "pea stone". Aragonite is found in many colors from colorless to white, yellowish, greenish, pink, and violet. It is transparent to translucent with a glassy luster which appears greasy on broken surfaces. Hardness $3\frac{1}{2}$ –4, specific gravity 2.95. Like calcite, it displays strong double refraction, but not such an excellent cleavage. Aragonite can be differentiated from calcite by the Meigen test. When cooked in a cobalt solution, the powder of orthorhombic aragonite assumes a violet color while the trigonal calcite remains white.

Unlike calcite, aragonite is more rare in nature and is not a rock-forming mineral. Well-formed crystals of hydrothermal origin are usually found in clefts and gas pockets in basalts and basalt tuffs, as at the

Blauen Kuppe, near Eschwege, and near Sasbach in the Kaiserstuhl; Hořenec (Horschenz) in Bohemia; and Nugsuak, Greenland. In normal ore veins aragonite is rare and is essentially restricted to the upper levels of very few localities, such as Leogang at Salzburg, or Alston Moor in Cumberland. More often the mineral forms sinter deposits from hot springs in interestingly translucent mottled masses and in varying colors, especially greenish, yellowish, or beige in large deposits in Mexico. This material, known as Mexican onyx or often simply onyx, is used for decorative table tops, sculptures, and other artistic articles. This is not real onyx, which is black and white banded agate. Some sinter formations consist of concretions that are formed of single radially structured concentric spheres and are locally known as Karlsbader Sprudel or Erbsenstein (pea stone) in allusion to a famous locality in Czechoslovakia. Leaching processes result in stalactitic or coral-like masses, as in the limonite deposits at Kamsdorf, in Thuringia. Very beautiful are the bizarre branching growths known as Eisenblüte from the Styrian Erzberg (Fig. 60), and from Hüttenberg in Carinthia. Here the action of surface waters has dissolved the primary iron ore in clefts and vugs, replacing it with manifold "blooms" of aragonite. Fine pseudohexagonal twins of reddish or gray color come out of the clayey sediments of Molina, in Aragon, Spain. Colorless or blue aragonite twins also are found in the sulfur deposits in Sicily, having been formed, along with sulfur, through the reduction of sulfates, especially gypsum and anhydrite. Aragonite is the basic substance in pearls and mother-of-pearl in many mollusk shells.

58 Aragonite

Kamariza, Laurion/Greece
Original size 63 × 98 mm





ionic radii are too large or too small to be incorporated in the earlier minerals. These are mostly lithium, cesium, beryllium, boron, tin, zirconium, hafnium, niobium, tantalum, molybdenum, tungsten, uranium, and the rare earths (cerium, etc.). The crystallization of this residual melt occurs in a temperature range of 700 °C to 550 °C. The presence of the volatiles results in the formation of crystals of exceptional sizes, and the resulting rocks made up of these giant crystals are known as **pegmatites** (Greek *pegma* = framework). Single crystals in pegmatites can attain a mass of many tons, especially quartz, potassium feldspar, and mica. These rocks may also contain concentrations of economically important minerals including tantalite (ore of tantalum), wolframite (ore of tungsten), amblygonite and spodumene (lithium), beryl (beryllium), apatite, nepheline, and cryolite. Pegmatites are also the source of many beautiful gemstones: rose quartz, topaz, aquamarine, and tourmaline. In most cases the gem quality crystals of these minerals were recrystallized through later hydrothermal activity. In pegmatites the volatile-rich melts had the fluidity and a very long time to form superb crystals at extremely high pressures. If these highly mobile and chemically reactive solutions forced their way into fissures in

neighboring rocks the volatile components would be released. The released gases permeate the surrounding rocks and react readily with the minerals they encounter. This process is known as the **pneumatolytic mineralization** phase (Greek *pneuma* = gas, *lyein* = solution), the products of which are difficult to distinguish from pegmatitic rocks.

Fluorine reacts with feldspars to form topaz and lithium transforms feldspar to zinnwaldite, a mica. When limestones and dolomites are the neighboring rocks they may be “metasomatically” replaced. If iron is introduced, iron ore deposits result, with beautiful crystals of magnetite or hematite as well as various calcium iron silicates. Valuable economic deposits that are often pneumatolytic in origin include cassiterite SnO_2 , molybdenite MoS_2 , beryl, apatite, and wolframite. With a further temperature reduction, to about 500° and 400 °C, the remaining water-enriched melts, enter the **hydrothermal mineral formation** phase. These hot solutions, carrying carbon dioxide, CO_2 , and hydrogen sulfide, H_2S , also contain sodium chloride, NaCl , silicic acid, H_4SiO_4 , and various dissolved heavy metals. Due to the mobility of the solutions they can readily force their way through fissures and clefts as ascending waters to very near the

59 **Aragonite**
Minglanilla/Spain
Original size 27 × 31 mm



60 **Aragonite**
Erzberg, Steiermark/Austria
Original size 63 x 120 mm





earth's surface. As they travel farther from the magma "oven" they continue to cool so that they precipitate the dissolved solids they have been carrying. The mineralized clefts are called hydrothermal veins, or ore veins when they contain valuable minerals. The mineral formations found in many gas pockets in rocks are also of hydrothermal origin. They typically contain amethyst and agate, varieties of quartz, and are described as druses or geodes.

Depending upon the distance from the magma, the hydrothermal veins are known as perimagmatic (Greek *peri* = near to) when in the same rock complex; apomagmatic (*apo* = farther away) when a direct connection to the magma is obscure; and telemagmatic (*tele* = remote) when the solutions have traveled far from the magma before crystallization occurred. Depending on the temperatures of crystallization, various parageneses can form in the hydrothermal veins. We differentiate between high temperature hydrothermal (kathothermal) at temperatures from the solidifying point of the rock melts to about 350 °C; middle temperature hydrothermal (mesothermal) from 350° to 200 °C; and low temperature hydrothermal (epithermal) under 200 °C. Examples of each are: katathermal – iron, cobalt,

Cerussite - PbCO_3

Orthorhombic. The original name, used long ago by Werner, was Weissbleierz (white lead ore), a synonym still used in Germany today. W.Haidinger (1845) named the mineral cerussite after the Latin *cerussa*, a term used by Pliny, apparently, to describe various lead compounds and roughly translated as "white lead."

The crystals are tabular or prismatic, but may also be acicular or spearlike. It may also form pseudohexagonal crystals as a result of cyclic twinning. In tabular form the crystals are commonly found in star- or comb-like growths (Fig. 61). Cerussite is also found in reniform masses, and highly impure earthy masses are known in German as Bleierde (lead earth).

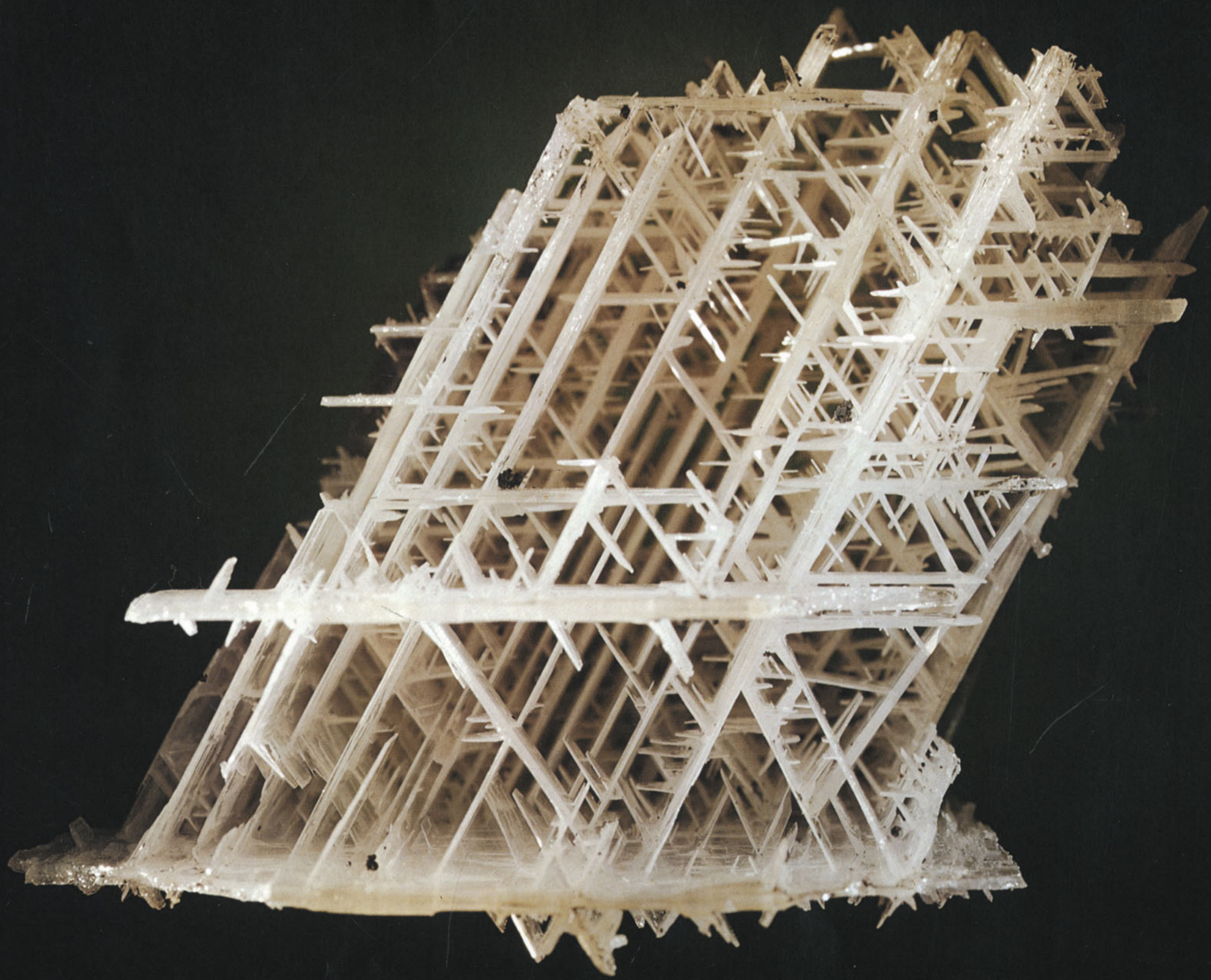
Cerussite usually is colorless to white, and more or less transparent with a strong adamantine luster resulting from its high refractive index. Inclusions of finely divided galena can color the mineral black and this type is called Schwarzbleierz (black lead ore). Hardness 3–3½, specific gravity 6.4–6.6.

Cerussite is an important lead ore. It is most often found in carbonate veins in the oxidation zone of lead deposits. Particularly beautiful crystals with extraordinary groupings occur at Tsumeb, Namibia. It is also widely found at other localities such as Broken Hill, New South Wales, Australia; Leadville in Colorado, U.S.A.; Iglesias in Sardinia; Příbram, Czechoslovakia; and Bleiberg, Carinthia. Older mines famous for cerussite, now closed, include Oberharz, Mechernich where it is found in sandstones, and the lead and zinc ore veins of Ems in the Lahn region. Cerussite is sometimes found as a post-mine alteration product on old mine dumps.

61 Cerussite

Tsumeb/Namibia

Original size 78 x 90 mm



nickel, uranium, bismuth and gold; mesothermal – zinc, copper, and lead sulfide ores; epithermal (most distant from the magma) – ores of silver, antimony, mercury, and arsenic.

Sedimentary Mineral Formation

All minerals and rocks at the earth's surface are subject to alteration and are eventually ravaged by weathering processes. Various factors play roles in the weathering of rocks and minerals. **Physical weathering** is mechanical rock disintegration. Causes include strong sun's rays and splitting by expansion of freezing water. **Chemical weathering**, with the aid of water as a solvent when it contains carbon dioxide, CO₂, and sulfur dioxide, SO₂, reacts with and drastically changes the mineral components of rocks. Biological or **organic weathering** involves the decomposition of rocks by animal and vegetable organisms. This occurs through the pressure of plant roots or the dissolving action of acids generated by plants. An example of chemical weathering can often be seen in exposed granite masses. The alkali metals are leached from the feldspars and micas and transported away in solution. The feldspars are altered to clay (kaolin) and form,

Azurite – Cu₃[OH|CO₃]₂

Monoclinic. The name azurite, derived from the Latin *azurius*, was introduced in 1824 by Francois S. Beudant, the French mineralogist and geologist in Marseilles and Paris. The names azurite and lazurite (*lapis lazuli*), the latter a complex silicate, both originate from the same root, the Persian term for blue. From the Arabic *lazaward*, the middle Latin *lazurius*, *lazulus* and lastly *lapis lazuli*, the German term *lazurstein* was derived. The basic copper carbonate was called Bergblau, or Kupferblau (blue copper) by the miners. From the Middle Ages and still later the name Kupferlazur was used, a term introduced by Abraham Gottlob Werner.

The often complex crystals are short columnar or tabular, but now and then form spherical aggregates (Fig. 62). Azurite is also found as compact reniform or earthy masses. Through hydration and reduction of the carbon dioxide, azurite can alter to malachite. As a result one frequently finds many crystals having the azurite form, but partially or completely replaced by green malachite. These are known as malachite pseudomorphs after azurite. This alteration can also be observed on specimens that are preserved in collections. Joh. Kunckel (1689) had observed this transformation:

"This is a sky blue stone, in the family of the lazursteins, however, very brittle, and it loses its color in fire; when a tablet is painted with this bergblau, the color changes in time to green."

Such color changes can also be seen in some paintings from the Middle Ages. The original blue sky, painted with azurite as a pigment, has often taken on a greenish color.

The crystals have a glassy luster, they are brilliant azure blue or deep blue-black and sometimes transparent. Hardness 3½–4, specific gravity 3.7–3.9.

Azurite is commonly found, along with malachite, in the oxidation zones of sulfide copper deposits. Under the influence of groundwater containing oxygen, soluble copper sulfate is formed from the primary copper ores, and this in turn reacts with the calcite and dolomite of the surrounding rock to form colorful secondary minerals. Crystals of unusual size and beauty, often as pseudomorphs, come from the copper deposits of Tsumeb, Namibia; Chessy, near Lyon, France; Bisbee, Arizona (Fig. 63), and Magdalena, New Mexico, U.S.A.; and Calabona, near Alghero, Sardinia.

62 **Azurite** on Dolomite
Altenmittlau, Spessart/FRG
Original size 9 × 11 mm



Malachite - $\text{Cu}_2[(\text{OH})_2\text{CO}_3]$

Monoclinic. The name alludes to the green color of the mineral and it comes from the Greek *malche* or *moloche*, which mean mallows. According to Pliny (77 A.D.) *molochitis*, an opaque and saturated green colored mineral, was useful for cleaning wounds when burned, pulverized, and mixed with oil and wax. It was used in the Middle Ages as an emetic, and for the treatment of colic, in ancient Egypt as cosmetic and eye shadow.

Large crystals of malachite are rare, most occur only in small acicular spars. The most common and characteristic form is as radially fibrous stalactitic and reniform aggregates that, like much agate, are extremely decorative when cut into flat pieces and polished, due to the variegated color banding in various shades of green.

Malachite is often seen as pseudomorphs, for example after cuprite at Chessy, near Lyon, and Onganja, Namibia (Fig.28). Also after tennantite at Bieber, Hessen, and calcite, azurite, and cerussite at Tsumeb, Namibia. The color of the glassy lustrous crystals is dark green, but in massive aggregates it varies in the individual layers from a luminous, sometimes slightly bluish green to a dark blackish green. Compact pieces have a silky to dull luster and are essentially opaque. Hardness 4, specific gravity 4.

Malachite, like azurite, forms in the oxidation zones of copper deposits and is valued as an associated mineral.

Almost legendary, because of their enchanting beauty, are pieces from the rich old malachite localities in the Ural Mountains, as at Mednorudjansk, near Nishni-Tagil, and Gumeschewsk, south of Sverdlovsk. Masses weighing many tons came from these areas. In the early 1820's a giant mass was found at Mednorudjansk which produced about 250 tons of

the finest cutting quality malachite. The old Russian centers for malachite were Sverdlovsk and Leningrad. The cutting plants of Leningrad, especially, produced many works of art in malachite, often given as tokens of friendship by the Czars to other princes. Witness to the old Russian traditional artwork are the columns in the Isaaks Cathedral in Leningrad covered with malachite, countless polished tables and urns in the Hermitage, and the malachite room in the Winter Palace. The localities in the Ural Mountains have since been shut down; what remains is the Russian legend that any one who drinks from a malachite goblet will understand the language of the animals. Malachite is still a coveted material for jewelry and artistic sculptures. The finest gem quality malachite now comes from Kolwezi, in the province of Katanga, now Shaba, Zaïre, and also from Mkubwa, Zambia. Handsome pieces of malachite are also found in the Tsumeb mine in the Otavi Bergland, Namibia, and in Bisbee, Arizona. Chile and Australia also produce fine gem malachite. Just a few years ago, during prospecting work in Onganja, Namibia, a new occurrence of the most beautiful idiomorphic malachite crystals was discovered. These are in a tabular form, mostly twinned, and in more than 1 cm in length.

63 **Malachite** with Azurite
Bisbee, Arizona/USA
Original size 31 x 48 mm





either in place or in distant basins where deposited after being carried by streams, economically important clay deposits. Similarly formed from basic rocks, under suitable conditions, are bauxite and lateritic iron ores. In the course of granite weathering, quartz, because of its resistance to chemical attack, remains unaltered. Such residues of quartz grains produce quartz sands which, with natural cementation, become sedimentary sandstones.

There are other minerals besides quartz that are resistant to weathering. They usually have high specific gravities so that they settle to the bottoms of river courses and just beyond the shore lines of sea coasts and lakes to form mineable deposits. Important examples of this type are gold placers, as in the Sacramento River in California and the Yukon River in the Klondike region, Alaska. Extensive diamond placers are found in the coastal conglomerates (cemented round rocks and sand) near Oranjemund in Namibia. Other placers contain platinum, cassiterite, and monazite.

The dissolved minerals derived from chemical weathering are usually carried by rivers to the sea. Under favorable conditions, such as dry climate zones and the separation of parts of sea beds from the ocean, the salts are concen-

Barite - BaSO_4

Orthorhombic. In German mines in the Middle Ages this mineral was included along with the other "spars" and was known as one of the Bergarten (gangue minerals), that constituted unproductive rock and thus was not of interest to the miners. It was also believed at that time to be a heavy form of gypsum and was therefore called "heavy spar". The name barite is derived from the Greek *barys* (= heavy). At first the name was only used to describe an "earth" (earth alkali oxide) discovered by the Swedes Scheele and Gahn in 1774. The mineral itself was known as sulfate of baryt. Since about 1800 the name barite was used more and more as the mineral name, in addition to its original meaning. The earth alkali metal, first produced in pure form in 1901, was named barium.

Barite often occurs in beautifully formed crystals. With its more than 200 known forms it is one of the multifaceted minerals. The crystals may be tabular parallel to the basal face, or prismatic and elongated in various crystallographic directions (see p.44, Fig. 20). Often the tabular crystals are arranged so as to form rose shapes. In economically workable deposits the mineral is found as coarsely crystalline or fine granular aggregates. The sometimes clear, often translucent to nearly opaque, pieces are usually turbid white or colorless, but with inclusions of iron oxide or hydroxide they may be yellowish, reddish, and brown. Bitumen or finely divided sulfides cause it to be gray or black. It is also found in greenish shades. Transparent crystals exhibit a glassy luster. Hardness 3-3½, specific gravity 4.5. Characteristic identifying

64 **Barite** on Dolomite
Dreislar, Sauerland/FRG
Original size 58 x 90 mm





features of the mineral are its excellent cleavage and very high density.

As gangue, barite is found in almost all low temperature hydrothermal ore veins. The more complex crystals are usually found in open clefts and fissures. The most beautiful crystals come from Dufton in Westmoreland, and Alston Moor, Egremont, and Frizington, in Cumberland, England. Other localities include Příbram, Czechoslovakia (Fig.65), as well as some classic occurrences in the Harz and the western Erzgebirge. Compact barite veins up to 10 m in thickness are mined for the mineral. This type of deposit is found near Wölsendorf, in east Bavaria, commonly in beautiful crystals associated with fluorite, and also at Oberwolfach in the Black Forest, Sontra in the Werra area, and Bad Lauterberg in the Harz, among others. Platy or rosette crystals come from Dreisler in the Sauerland (Fig.64). The so-called barite roses are found in sandstones and other sediments at, for example, Münzenberg-Rocken, Hesse. Economically important sedimentary barite deposits occur at Meggen an der Lenne, Westphalia. The barite found here is mixed with sulfidic ores and bitumen and is almost black in color.

Barite has various uses in modern technology. It is important in deep drilling, as with oil wells, to add weight to the drilling muds to suppress the escape of oil and gas. It is used in large quantities in the production of smooth printing papers. It is a constituent of heavy concretes and also a filler in the phonographic record industry. Due to its ability to absorb radioactive radiation and X-rays it is used for protective shields and as a contrast material in the X-ray examination of the digestive tract. Barite is also used in the chemical industry for the production of many barium compounds and metallic barium. Once it found extensive use in the paint industry as a white pigment but has been almost totally replaced by the more suitable white titanium pigment.

65 Barite
Příbram, Bohemia/Czechoslovakia
Original size 27 x 42 mm





trated and eventually crystallize to form deposits of evaporites which are the often economically valuable marine deposits. Chemical and bio-chemical processes have formed massive limestone mountains.

Hydrothermal veins rich with ore minerals that are near the surface of the earth may be acted upon by oxygen-rich surface waters, leading to the formation of oxidation zones. When iron ores are oxidized in this zone limonite is formed, which has a rust-brown color and is known as an “iron hat” or gossan. In the oxidized zone the most varied and colorful minerals, especially the copper minerals azurite and malachite, are typically found. Under the gossan below the groundwater level is the zone of secondary enrichment, where descending solutions precipitate valuable ores such as chalcocite (Cu_2S) and argentite (Ag_2S).

Metamorphic Mineral Formation

By geological processes, igneous and sedimentary rocks may be changed by the transformation of their mineral content when subjected to higher pressures and temperatures. The processes which create these conditions are known as “metamorphism” (Greek *metamor-*

66 **Cyanotrichite**- $\text{Cu}_4\text{Al}_2[(\text{OH})_{12}|\text{SO}_4] \cdot 2 \text{H}_2\text{O}$
Orthorhombic
Moldova, Banat/Romania
Original size 8 x 12 mm





phosis = transformation) and the products are **metamorphic rocks**.

There are two fundamentally different forms of metamorphism:

1. Those confined to specific or local areas, such as direct contact with ascending magmas, constitute **contact metamorphism**.
2. Those that are active over broad areas are known as **regional metamorphism**.

Contact metamorphism is caused by melting brought on by the penetration of magmatic melts into other rocks. The high temperature of the magma heats up and alters the minerals in this zone up to a distance of a few hundred meters (the contact zone). In addition to the high temperatures, vapors and solutions are given off and these, too, may alter the neighboring rocks, forming new minerals. Depending upon their composition, whether calcic, clayey, or siliceous, and the degree of metamorphism, various suites of minerals may be formed. Rather coarsely crystallized marbles are formed from limestones. Quartz-rich rocks form the silicate wollastonite $\text{Ca}_3[\text{Si}_3\text{O}_9]$, and with alumina present we see the appearance of calcium aluminum silicates such as garnet, epidote and vesuvianite. Argillaceous (clayey) sediments form hornfels, with mineral compo-

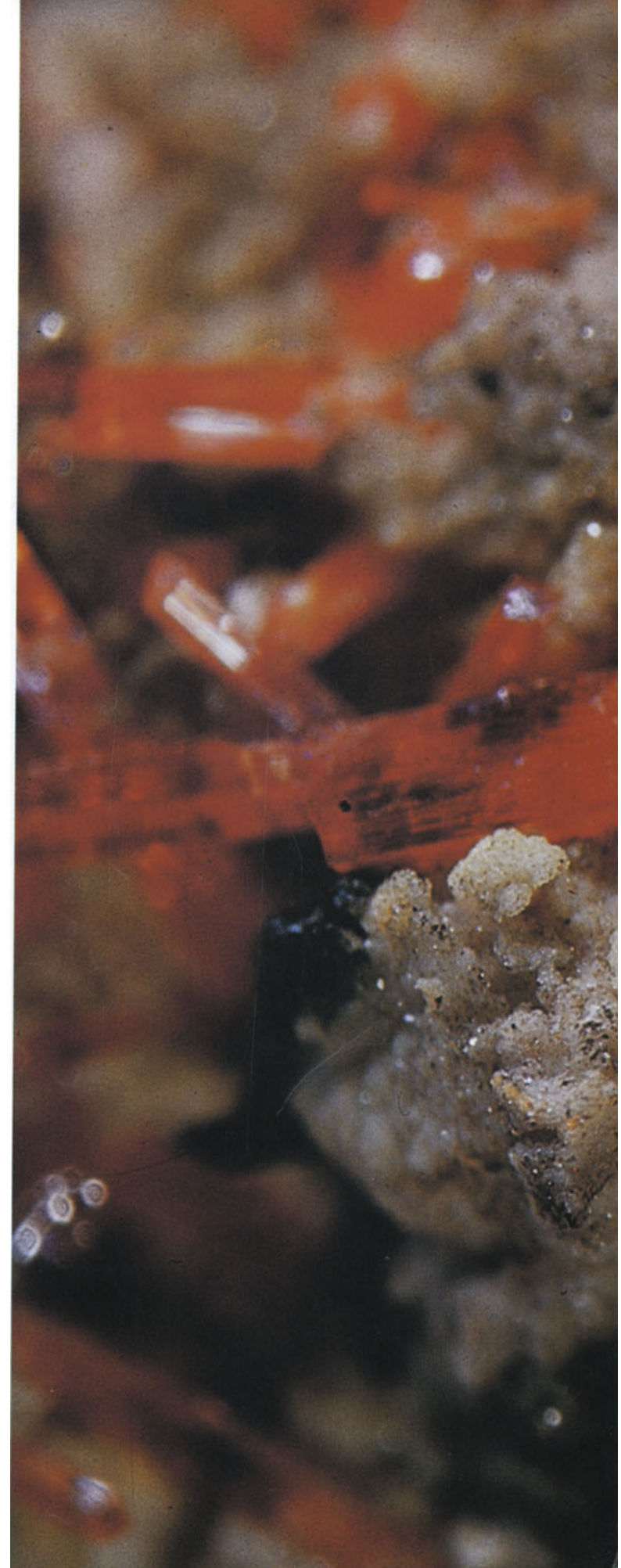
Crocoite - $\text{Pb}[\text{CrO}_4]$

Monoclinic. The mineral was named by the French mineralogist F.S. Beudant in 1832, in allusion to its distinctive red-yellow color. The name is derived from the Greek *krokos* = saffron. The old German name, *Rotbleierz*, refers to its color and the lead content of the mineral. The first crystals of this mineral were found in the southern Ural Mountains. In this material the Parisian chemist Louis Nicolas Vauquelin, in 1797, discovered a hitherto unknown metal which he named chromium (Greek *chroma* = color) after the variety of colors of its compounds. Crystals of crocoite form elongated prisms and acicular needles. Normally they are found in randomly intergrown individual crystals in cavities or on the walls of vugs. The largest crystals reach a length of more than 12 cm. Crocoite is translucent, with a greasy adamantine luster and a glowing yellowish red color. Hardness $2\frac{1}{2}$ –3, specific gravity 6.

The crystallization of this relatively rare mineral is possible only where lead ores are in the immediate vicinity of chrome ores or rocks containing chrome, and where Pb- and Cr-bearing solutions can come in contact with one another. These conditions produced the remarkably beautiful specimens from the famous, but now depleted, occurrence in the Dundas district in Tasmania, Australia (Fig. 67). The same is true for the Sverdlovsk deposit in the Urals, U.S.S.R., and Congonhas do Campo and other localities in the state of Minas Gerais, Brazil.

67 Crocoite

Dundas, Tasmania/Australia
Original size 12 x 19 mm





Wulfenite - $\text{Pb}[\text{MoO}_4]$

Tetragonal. In 1845 Wilhelm Haidinger named the mineral after the Austrian Baron Franz Xaver von Wulfen (1728–1805), a Jesuit and professor in Klagenfurt, who was the first to describe the mineral in detail in his *Abhandlung vom Kärnthner Bleispath* (Treatise on Carinthian Lead Ores) in 1785. The older German name *Gelbbleierz* (yellow lead ore) was given by A.G. Werner (1817) and served to differentiate this mineral from other colored lead minerals, such as white lead ore, green lead ore, etc. The characterization of the mineral as lead molybdate is credited to Martin Heinrich Klaproth (1743–1817), a pharmacist and chemist in Berlin, on the basis of a chemical analysis.

It is often found in groupings of flat square tablet-shaped crystals or stubby columnar pyramids. It is also found in compact aggregates and crusts. Especially obvious is the often intense color of the crystals, waxy yellow, orange-yellow, and more rarely bright red or even colorless. It has an adamantine to pitchy luster. Hardness 3, specific gravity 6.8.

The formation of wulfenite is limited to the oxidation zones of lead sulfide deposits. In some oxidation zones wulfenite is found in quantities sufficient to be economically important, as in the lead zinc deposits of Bleiberg-Kreuth in Carinthia, Austria, and Mežice (Mies) in north Slovenia, Yugoslavia. Beautiful yellow crystals are known from these localities. Colorless, blue, and also yellow crystals come from the Tsumeb mine, Namibia (Fig. 68). Other well-known localities include Mindouli, Congo-Kinshasa; M'Fouati, Congo-Brazzaville; Příbram, Czechoslovakia; Sierra de los Lamentos, Chihuahua, Mexico, as yellow, handsomely formed pseudocubic crystals on white dolomite; and the Red Cloud mine, Yuma County, Arizona, U.S.A., where the crystals are a striking orange-red color on a limonite matrix (Fig. 69).

68 **Wulfenite** on Dolomite
Tsumeb/Namibia
Original size 46 x 72 mm





nents of quartz, cordierite, andalusite and biotite. Farther from the contact various slatelike rocks are formed. Rocks very high in aluminum, such as bauxite, are altered to corundum-rich rocks.

Regional metamorphism operates on the sedimentary rocks of massive basins (geosynclines) as they are buried to greater and greater depths. As they sink from the weight of overlying sediments they are subjected to increasing temperature and pressure which is uniform over broad expanses. In the lower temperature range (below 300 °C) diagenesis occurs, which is a form of solidification of the sediments through moderate recrystallization of their components. At higher temperatures (300° to 900 °C) they are subjected to rock melting, or anatexis. The formerly randomly ordered sediments recrystallize in a parallel fashion, especially platy minerals such as micas, and a rock known as schist or gneiss is produced. These rocks are collectively termed crystalline schists.

In regional metamorphism also, there are zones of intensity. In the epizone both temperature and pressure are relatively low; they are intermediate in the mesozone and relatively high in the katazone. An argillaceous slate will be metamorphosed to different rocks under

69 **Wulfenite**

Red Cloud Mine, Yuma County, Arizona/USA

Original size 44 x 68 mm





the conditions of the three zones. Thus it would become a phyllite in the epizone, a schist in the mesozone, and a gneiss in the katazone. The various degrees of metamorphism are recognized by the presence of certain characteristic minerals. The mineral associations in each are referred to as facies (Latin *facies* = face), and the varieties carry such names as greenschist facies, amphibolite facies, etc.

Typical rocks produced through regional metamorphism are gneiss and mica schists, quartz schists, talc schists with their names derived from the dominant mineral component. Other examples are serpentine, eclogite, and marble. Economically important concentrations of graphite are often found in regionally metamorphosed graphite gneiss.

Pyromorphite - $\text{Pb}_5[\text{Cl}(\text{PO}_4)_3]$

Hexagonal. From the Greek *pyr* = fire and *morpho* = form. The name was introduced in 1813 by the Göttingen mineralogist Joh. Friedr. Hausmann after he observed that the mineral, when melted by fire, assumed its crystal form upon cooling. This phenomenon had already been observed in 1770 by the Swede Cronstedt in his examination of certain *Bleispäte* (lead spars), as minerals of this type were called. Hausmann recognized that only the lead phosphate had the property of crystallizing from melts. Originally the mineral had been called *Grünbleierz* (green lead ore). The color intensity of many lead minerals was responsible for the early names given them. Names such as white, red, or yellow lead ore are synonyms still in use today in Germany. They refer to clearly defined mineral types. The old term *Grünbleierz* was, on the contrary, not strictly limited, as it was also used for the lead arsenate mineral mimetite.

Pyromorphite crystals are ordinarily found grown upon matrix and they form characteristic barrel-shaped six-sided prisms. They are also found as clusters of kidney-shaped aggregates and crusts. Because of its many different colors the mineral also carries the name *Buntbleierz* (colored lead ore). Most common are yellow, green or brown; more rare are orange-red, colorless, or white crystals. Pyromorphite, like most lead minerals, possesses a high index of refraction and, as a result, a distinct adamantine luster. The crystals are translucent. Hardness $3\frac{1}{2}$ –4, specific gravity 6.7–7. Pyromorphite is formed as a secondary mineral in the oxidation zones of lead deposits, as at the Friedrichsseggen mine at Ems and at similar localities in this region (Rosenberg, near Braubach; Holzappel). Highly prized for their interesting crystal form are the so-called Emser barrels. Other localities,

to name but a few, are: Badenweiler and Hofgrund, in Baden; Příbram, Stříbro (Mies), Banská Štiavnica (Schemnitz), Olovi (Bleistadt), Czechoslovakia; Broken Hill, Zimbabwe; and Phoenixville, Pennsylvania, U.S.A. (Fig. 70).

70 Pyromorphite

Phoenixville, Pennsylvania/USA
Original size 13 x 15 mm



Vanadinite - $\text{Pb}_5[\text{Cl}|\text{VO}_4)_3]$

Hexagonal. The mineral is named after the element vanadium and the name vanadinite was first used in 1838 by the mineralogist Franz von Kobell. The discovery of vanadium is credited to the Swedish chemist Nils G. Sefström (1830). He named the element *vanadis*, another name for the Nordic goddess Freya. As early as the beginning of the last century the Mexican mineralogist Andreas M. del Rio believed that he had found a new metal in the lead ores of Zimapán, but he did not finish his studies of it. Only later, when Alexander von Humboldt brought ore samples to Europe, was chemical analysis performed by Friedrich Wöhler, confirming del Rio's findings. Vanadinite crystals form short hexagonal prisms, pointed di-pyramids, or complex needles, as well as kidney-shaped radial aggregates. They are orange-red, yellow, or brown and of adamantine luster. Hardness 3, specific gravity 6.8–7.1. Insignificant concentrations of vanadinite occur in the oxidation zones of lead deposits, as in Obir, Carinthia, Austria; Mežice (Mies), Yugoslavia; the Apache mine, Gila County, and the Old Yuma mine, Pima County, Arizona, U.S.A. Especially beautiful crystals come from Mibladen in Morocco (Fig. 71). In larger enriched deposits vanadinite is an important ore of vanadium, especially at Abenab, Namibia. Ores are economically interesting if they contain about 2% of the metal, or even slightly less. Vanadium is used as an alloy metal in steel and as a catalyst. The yearly world production is almost 20 000 t; 60% of the vanadium needed, for example, in the Federal Republic of Germany comes from South Africa.

71 Vanadinite

Mibladen/Morocco

Original size 15 × 28 mm





The Names of Minerals

Unlike the usual practice in botany or zoology, the naming of minerals follows no set rules. The large number of about 6000 mineral names, while not even close to the number of species in either the plant or animal kingdom, results from the unfortunate fact that there may be more than one name in use for one and the same mineral – often superfluous and obsolete synonyms. Most are names for color variations in the same mineral and over hundreds of years of usage have become deeply entrenched. The red variety of the mineral corundum (preferred name) is ruby, while the blue variety is known as sapphire. Water clear, colorless quartz is called rock crystal and the colored varieties are amethyst (violet), rose quartz (pink), smoky quartz (brown), and citrine (yellow). Similar examples can be found in numerous other cases. Eliminating the synonymy reduces the total number of well-defined species to about 3000.

Many mineral names originated in antiquity, while others are derived from a variety of languages, especially Greek, Latin and the oriental tongues. There are also variations in the names for a given mineral from one language to another. From the English names chalcopryite, galena, and sphalerite, we see in the German names modifiers such as *Kies*, *Glanz*,

Blende and *Fahlerz* combined with a metal to form terms like Kupferkies, Bleiglanz and Zinkblende, all names from middle old German mining terminology. There is a whole group of the so-called “spars,” minerals characterized by exceptional cleavage, and these carry such names as calcspar and feldspar. The name diamond is derived from the Greek *adamas*, which means invincible, and alludes to the extreme hardness of the mineral. Graphite (Greek *graphein* = to write) got its name because it is so soft that it will leave black marks on paper. Other obvious external properties are indicated by some mineral names. The metallic luster (*Glanz* in German) of many ores, the characteristic coloring of many minerals, cohesive properties, hardness, and other features like the magnetism of magnetite, all sometimes find their way into the naming of minerals.

Another common practice is to name minerals for their chemical composition – iodargyrite is iodine and silver (Greek *argyros* = silver). Still others are named for original localities – ilvaite (Latin *ilva* for the Island of Elba where it was first found), or brazilianite. Some are even named in honor of their discoverers or important mineralogists or famous people – goethite and paulingite. Very often the mineral names

Mimetite – $\text{Pb}_5[\text{Cl}(\text{AsO}_4)_3]$

Hexagonal. *Mimetes* in Greek means imitator (impersonator). Since mimetite is easily confused with pyromorphite, the Greek name was introduced by the Frenchman François S. Beudant, and later the ending “ite” was added to complete the name.

The crystals are similar to those of pyromorphite. They are also found in short columnar or barrel-shaped forms, but sometimes in pyramidal or elongated prisms. The color is predominantly honey-yellow to brown, as well as greenish, reddish, or colorless. Hardness $3\frac{1}{2}$ –4, specific gravity about 7.

Mimetite is formed under the same conditions as pyromorphite but occurs only in deposits that have arsenic ores in close proximity to lead ores. Especially beautiful are the transparent yellow crystals from Tsumeb, Namibia. Other important localities are Chihuahua and Zacatecas, Mexico; Dry Gill in Cumberland, England; Příbram, Czechoslovakia; and Johanngeorgenstadt in the Erzgebirge, F.R.G. (Fig. 72)

72 Mimetite

Johanngeorgenstadt/GDR
Original size 50 × 58 mm



end in -ite or -lite, the latter from the Greek word for stone, *lithos*.

One of the tasks of mineralogists and crystallographers is the identification of new, previously unknown, mineral species and the assigning of names to them. The discovery of new minerals has been hindered to some extent by modern mining methods, which carry ore directly from the mine to the crusher without anyone having an opportunity to examine the minerals in the rocks. On the other hand, modern technology has put such research instruments as the electron microscope, electron microprobe, and the single crystal X-ray diffractometer at the disposal of today's scientists, tools which permit the determination of the chemistry, crystallography, and other physical properties in order to identify or charac-

terize unknown crystals, even when the samples are as small as a few thousandths of a millimeter in size. Every year, therefore, many new minerals are discovered, described, and given names. To avoid further superfluous synonymy, a commission of scientists from more than two dozen countries, under the auspices of the International Mineralogical Association, reviews abstracted descriptions of all candidates for new mineral status and votes to accept or reject both the description and the name proposed by the describer. Annually this commission approves some 80 to 90 new species. Occasionally, a mineral that has been long established is found to be identical with an already existing mineral, so that it then loses its name.

73 **Variscite** – $\text{Al}[\text{PO}_4] \cdot 2 \text{H}_2\text{O}$
Orthorhombic
Reust near Ronneburg, Vogtland/GDR
Original size 24 × 28 mm



Apatite - $\text{Ca}_5[\text{F}(\text{PO}_4)_3]$

Hexagonal. The mineral was named in 1786 by Abraham Gottlob Werner and the name comes from the Greek *apatáo* = to deceive. The similarity with other prismatic minerals such as beryl, quartz, diopase, and calcite caused confusion, as did the appearance of the many variations in color. Even Werner himself was deceived and believed the yellow-green “asparagus stone” and the microcrystalline phosphorite to be separate and distinct species. The crystals are very often found in superb morphological development, and vary in size from the thinnest of needles to individual crystals weighing many hundreds of pounds. They are mostly bounded by the hexagonal prism as well as the hexagonal dipyramids of many inclinations, and the basal form. All modifications between long prismatic simple crystals to tabular complex forms exist. It is also found in compact, sometimes dense granular or radial, aggregates.

Apatite occasionally forms transparent, but more often translucent, crystals of the greatest variety of colors from colorless, yellow to oily-green (asparagus stone), brownish, deep red, blue-green (moroxite), and violet. Hardness 5, specific gravity 3.16–3.22.

As an abundant and widespread mineral with a phosphorus content of 41% P_2O_5 , apatite is the most important source of phosphoric acid in both the organic and inorganic worlds. In the form of microscopic crystals it is a component of almost all magmatic rocks, although in concentrations of only about 1%. Through differentiation of magmatic melts it may be enriched and may form important deposits. One such locality of massive size is found in a nepheline-syenite complex in the Khibina-Tundra on the Kola Peninsula, U.S.S.R. This deposit has, since 1932, supplied all of the needs of the Soviet Union for use as phosphate fertilizers. Large amounts of apatite are also con-

tained in the magmatically formed magnetite iron ores of Kiruna, in north Sweden, and in the carbonatites of Alnö, Sweden, and Phalaborwa, Transvaal. Large crystals, only rarely of economic value, as in Renfrew, Ontario, Canada, come from pegmatites. Well-formed complex crystals are found in clefts and veins of hydrothermal origin. The magnificent apatite crystals from the alpine clefts such as those of the Gotthard massif and the Rhône Glacier, in the Dauphiné and Austrian Alps have long been known. Famous old localities for numerous purple crystals are the now abandoned quarries in the area of Greifenstein, near Geyer, and the tin ore veins at Sauberg, near Ehrenfriedersdorf in Saxony, G.D.R. Large apatite crystals, sometimes violet but also in other colors, come from Panasqueira, near Fundao, Portugal (Fig. 74). Apatite may be found in transparent crystals that are of cutting or gem quality. The best locality for these in beautifully formed greenish yellow crystals is in the magnetite deposits of Cerro de Mercado, Durango, Mexico (Fig. 75). The best deep purple crystals come from the pegmatite at Mount Apatite, near Auburn, Maine, U.S.A.

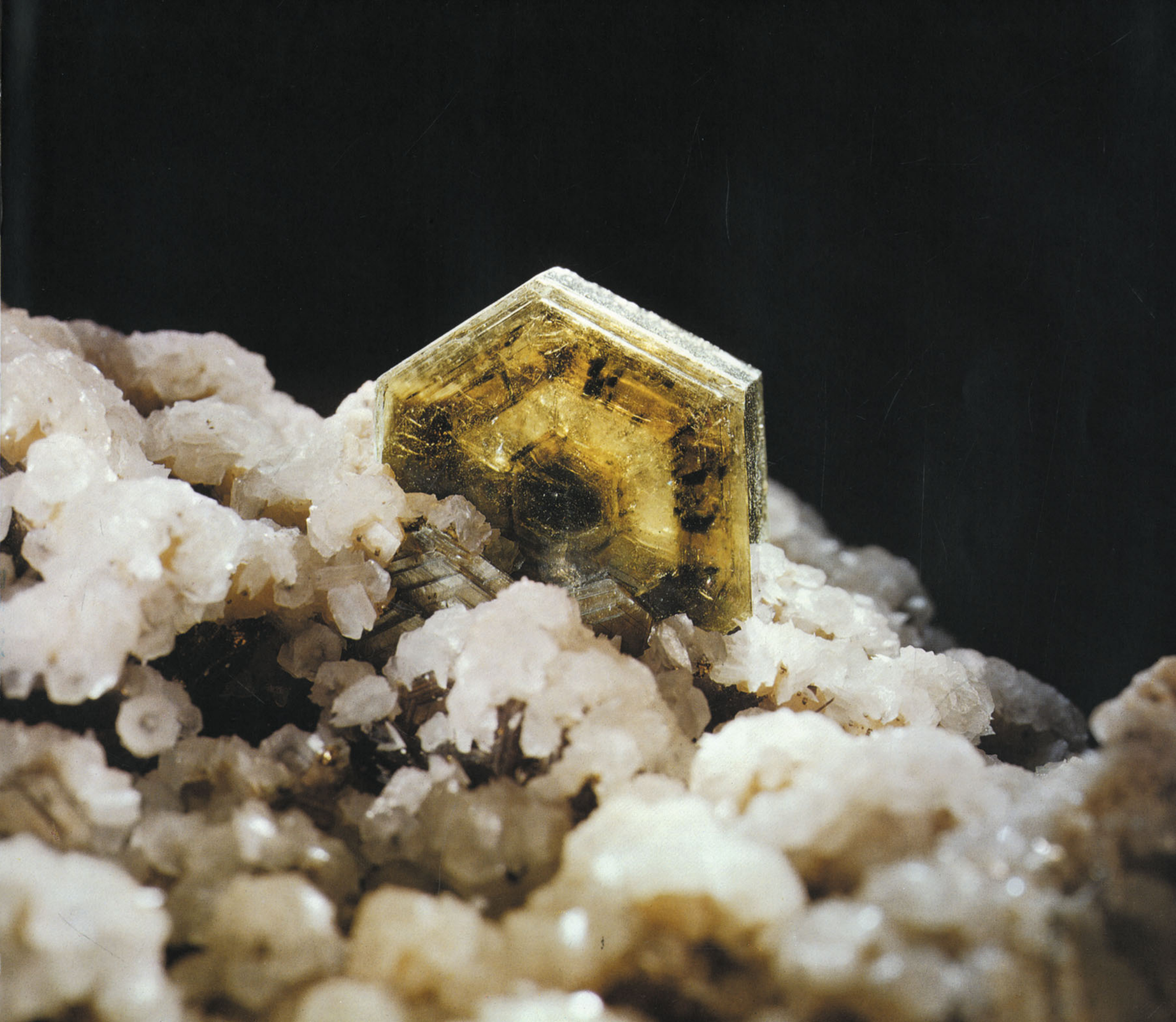
Through chemical decomposition of magmatic rocks and the apatite contained therein, phosphoric acid circulates in the biosphere. A part of the dissolved phosphate is transported away but much of it remains behind. That which remains in the earth is important in plant growth and is also incorporated into the bodies of animals when they eat plants. In the form of hydroxyl- or carbonate-apatite (with OH replacing F, or additional carbonate) it is an important constituent of the hard part of bones and teeth, as well as the skeletons of many lower animals. When these remains accumulate in sedimentary basins they often form large organic sedimentary phosphate deposits of great economic importance. This type of sediment is known as phosphorite. Phosphorites consist of

highly impure, microcrystalline apatite in the form of earthy, reniform, crusts or nodular concretions. The largest deposits of this type, big enough to be mined, are found in Morocco and Tunisia, as well as in Algeria and Florida. Extensive phosphorite deposits have also been formed from the accumulation of sea bird excrements. The phosphoric acid derived in this way from the animals' *guano* (an old Peruvian Indian term for dung) reacted with limestones and formed apatite. Very important guano deposits are found, mostly in the form of crusts and cavity fillings in the underlying stratified limestones, on the island republic of Nauru (main export; phosphorite), in the Pacific. Also on the islands of the West Indies, the Seychelles, and on the Namibian coast. Formed in a similar manner to apatite is the deposit of iron oolites known as the Lothringer Minette. In the process of smelting this important iron ore, the phosphor content is recovered in the form of artificial fertilizer, called Thomasmehl. Apatite and phosphorite are used almost exclusively for the manufacture of superphosphate, an important fertilizer. The guano, because of its additional nitrogen content, is especially valuable as a fertilizer. In small quantities apatite serves the chemical industry in the manufacture of phosphoric acid and also elemental phosphorus which is used in the fabrication of matches and phosphorus bronze. The annual world production of apatite and natural phosphates (excepting guano) is about 98 million tons, and the main exporters are the U.S.A., the U.S.S.R., and Morocco.

74 Apatite

Panasqueira/Portugal

Original size 37 × 43 mm





75 **Apatite**
Cerro de Mercado, Durango/Mexico
Original size 19 x 14 mm

76 **Adamine** - $\text{Zn}_2[\text{OH}|\text{AsO}_4]$
Orthorhombic
Laurion/Greece
Original size 8 x 9 mm



Systematic Classification of Minerals

In comparison to the immense variety and number of species in each of the plant and animal worlds, the number of well-defined, distinct minerals stands at about 3000 and is conspicuously small. The number of insects alone with over 800,000 species, the fishes with 25,000, and the seeded plants with about 170,000 species many times outnumber the mineral species. In 1735 the famous Swedish naturalist Carl von Linné, with his work *Systema Naturae*, introduced a binary nomenclature in which every animal and plant species is identified by a double name – family and species – and thereby classified, providing a foundation for a systematic classification in zoology and botany. His attempt to apply the same classification to the mineral kingdom was not successful and the effort was abandoned about 100 years later.

The systematic classification for minerals is based on crystallographic and chemical characteristics. A system based on mineral chemistry alone was introduced in 1824 by the Swede Joh. Jacob von Berzelius and subsequently refined through mineralogical observations. The discovery of X-ray diffraction in 1912 by Max von Laue and its use in determining crystal structures led to the development of a classification according to the crystallochemical na-

ture of the minerals. In this system all minerals are grouped in various categories:

1. Elements
2. Sulfides
3. Halides
4. Oxides and hydroxides
5. Nitrates, carbonates, borates
6. Sulfates, chromates, molybdates, tungstates
7. Phosphates, arsenates, vanadates
8. Silicates
9. Organic compounds

1. Elements

The elements found in their “native” state in the earth’s crust are subdivided into metals, semi-metals, and non-metals. Examples of native **metals** in nature are the elements copper Cu, silver Ag, gold Au, platinum Pt, and mercury Hg. The latter metal is the only element that is in liquid form at ordinary temperatures. Iron, one of the most common elements in the crust in combination with other elements, is only rarely found in its native state. Only under unusual circumstances, as when iron-rich magmas intrude coal beds, is the iron reduced to the metallic form and protected from oxidation by being sealed in the rock which formed

Wavellite – $\text{Al}_3[(\text{OH})_3(\text{PO}_4)_2] \cdot 5\text{H}_2\text{O}$

Orthorhombic. The mineral was named in 1805 by the English doctor, chemist, and mineralogist William Babington, after its discoverer William Wavell, a physician in Devonshire.

Wavellite is found almost exclusively in radial tufts or hemispheres that form continuous crusts. It may also rarely appear in single acicular crystals. The crystal groups have a glassy luster and are mostly gray, yellow, or green in color. Cross-sections of the spherical aggregates may exhibit various colors in different sectors or in bands concentric to the rounded surface. Hardness $3\frac{1}{2}$ –4, specific gravity 2.3.

Wavellite is hydrothermal in origin, but may be found in clefts and fissures in a wide variety of types of rocks. At Dünsberg, near Giessen, and Langenstriefis, near Freiberg in Saxony, it is in siliceous slates (Fig. 77); at Barnstaple, Devonshire, and St. Austell, Cornwall, England, on decomposed granite; and especially nice specimens occur in slates at the São-Miguel mine, near Ouro Preto, Minas Gerais, Brazil. Also famous are the blue-green radial spheres on quartzite from Montgomery, Arkansas, U.S.A.

77 Wavellite

Langenstriefis, Sachsen/GDR
Original size 15 x 17 mm



when the magma cooled. Metals also occur in natural alloys, for example electrum, which is an alloy of gold and silver. Most metals are characterized by being good conductors of electricity and heat, having high density, a strong reflectivity, and metallic luster. They are also ductile, so that they lend themselves to forging.

Semi-metals, also known as brittle metals, are similar to metals in their metallic luster and high density, but differ in that they have good cleavage and are brittle. Among them are arsenic As, antimony Sb, bismuth Bi, selenium Se, and tellurium Te.

Non-metals, which have essentially no metallic properties, include the polymorphs of carbon, graphite, and diamond, as well as sulfur.

2. Sulfides

These compounds are oxygen-free and are composed of sulfur with one or more metals such as iron Fe, cobalt Co, nickel Ni, copper Cu, silver Ag, zinc Zn, mercury Hg, and lead Pb, or with the semi-metals arsenic, antimony, bismuth, selenium, and tellurium. Included in this group are minerals which are simple metal sulfides combined with sulfides of semi-met-

als. Examples are the antimonides:

stephanite $5\text{Ag}_2\text{S} \cdot \text{Sb}_2\text{S}_3$

Boulangerite $5\text{PbS} \cdot 2\text{Sb}_2\text{S}_3$.

These are similar in their properties to the sulfides, as are the arsenides, selenides, and tellurides, and therefore are included with the sulfides in this classification. Except for a few metals such as iron, manganese, chrome, aluminum, tin, and uranium, that occur primarily as oxides, the sulfides comprise most of the economically important ores:

Sphalerite ZnS (zinc)

Chalcopyrite CuFeS_2 (copper)

Galena PbS (lead)

Stibnite Sb_2S_3 (antimony)

Pyrite (FeS_2) and pyrrhotite (FeS) are mined mostly for conversion to sulfuric acid.

Referring to luster and related optical characteristics, in former times old German text used a subclassification of sulfides into Kiese, Glanze, Fahle, and Blenden (plural forms). These terms in conjunction with a metal's name result from old mining terminology as the German names of are minerals (e.g. Kupferkies, Bleiglanz, Zinkblende = Chalkopyrite, galena, sphalerite). Occasionally we can find these old mineral names still in today's German linguistic usage.

Erythrite - $\text{Co}_3[\text{AsO}_4]_2 \cdot 8\text{H}_2\text{O}$

Monoclinic. The name describes the outward appearance of the mineral. As early as 1754 it was mentioned by J.F. Henkel in his book *Kieshistorie*. The mining engineer A.F. Cronstedt (1770) of Stockholm described it as thin earthy coatings on cobalt ores, and as radially grouped sprays of dark red crystals. The term "cobalt bloom" was equally used to describe the efflorescence on the ores as well as the flowery arrangements of the crystal groups. Erythrite is derived from the Greek *erythrós* = red, or reddish, which alludes to the characteristic red color of the mineral. In 1832 the name was formalized by the mineralogist F.S. Beudant. The crystals are always small in size and form acicular, or star-shaped and radially leafy aggregates, also earthy coatings or thin films. The color is dark red with a violet tint (peach blossom red). The luster is pearly on the cleavage surfaces, otherwise it is glassy. Hardness 2, specific gravity 3.07. Erythrite forms in the oxidation zones of hydrothermal cobalt-nickel deposits through replacement of the primary cobalt nickel minerals such as skutterudite (CoAs_3) and cobaltite (CoAsS). The most famous localities for the mineral are Schneeberg in Saxony, Richelsdorf in Hessen (Fig. 78), and Bou Azzer, Morocco, where it is found in particularly beautiful crystal groupings.

78 Erythrite

Richelsdorf, Hessen/FRG

Original size 13 × 15 mm



Vivianite - $\text{Fe}_3^{2+}[\text{PO}_4]_2 \cdot 8\text{H}_2\text{O}$

Monoclinic. This mineral was originally called *Blau-eisenerde*, but was later named vivianite by A.G. Werner (1817) after the English mineralogist J.G. Vivian, its discoverer. The crystals are elongated prismatic or they are in radial to fibrous rosettes and spheres. The mineral often occurs in earthy form, hence the German name “blue iron earth”. Very fresh crystals are colorless or white, but they rapidly turn blue, darkblue, or black when exposed to air due to oxidation of divalent iron. They are transparent to opaque with various lusters, as they are sometimes tarnished. When fresh they are glassy. They have a pearly luster on cleavage surfaces. Hardness 2, specific gravity 2.6.

Vivianite originates in zones near the earth's surface, however largely in the absence of oxygen. It is the product of the interaction of phosphoric acid-carrying solutions upon iron minerals, such as pyrrhotite, pyrite, or siderite. It is also formed in pegmatites through the hydration of primary iron phosphates. The mineral is extensively found in finely divided form in argillaceous sediments. Vivianite has also been found associated with fossil bones and teeth. The phosphate came from the apatite of the bone materials and the iron from circulating groundwaters. These types of substance, mostly teeth from mammoths, mastodons, or dinosaurs, were once called bone turquoise or odontolite due to their similarity to the mineral turquoise.

Well-crystallized vivianite comes from St. Agnes, Cornwall, England; Trepča, Yugoslavia; Waldsassen, in east Bavaria; and from Cerro de Pasco, Peru (Fig. 79). Especially large crystals, reaching a length of 1.5 m were found in the clay deposits of Anloua, near Ngaundere, Cameroons.

79 **Vivianite** Cerro de Pasco/Peru
Original size 21 x 40 mm





Kiese possess a prominent metallic luster, are pale yellow, reddish, or white to light grey and have a hardness of about 5 to 6.

Glanze have less of a metallic luster, are darker grey in color and have a hardness of only 2 to 3. Some oxides are also termed *glanz* (hematite, Fe_2O_3 , in German is Eisenglanz).

Fahle possess even less of a metallic luster, are dark grey to black, are relatively soft and brittle [Fahlerz is tennantite, $\text{Cu}_3\text{AsS}_{3.25}$].

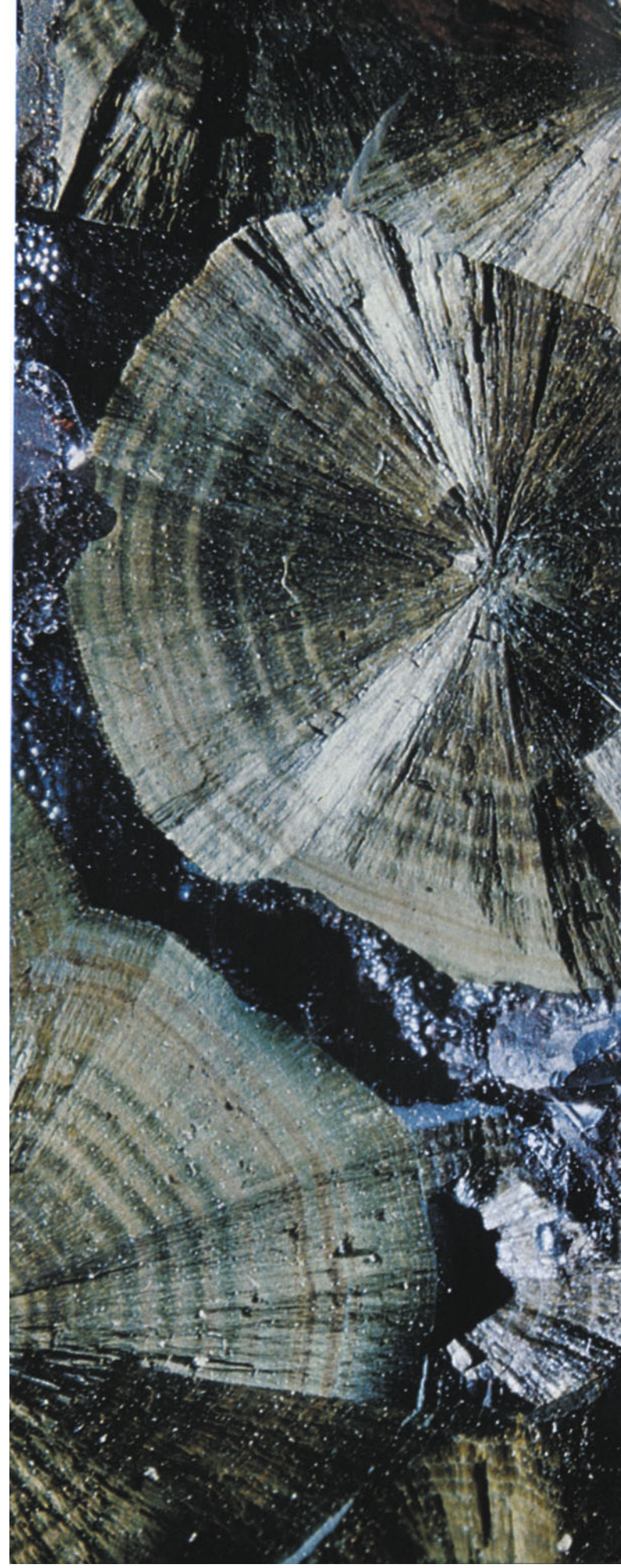
Blenden are minerals with a semi-metallic to non-metallic appearance, transparent to translucent, of various colors, excellent cleavage, and even less hardness (sphalerite is zinkblende, ZnS).

All sulfides have relatively high densities. They are most often found in ore veins, precipitated from hydrothermal solutions, but may also be sedimentary in origin (as are the copper-rich shales of Mansfeld, Germany), or even metamorphic.

3. Halides

The minerals of this group are chemical compounds with either fluorine, chlorine, bromine, or iodine. Their appearance is nonme-

80 **Dufrenite** – $\text{Fe}_3^{2+}\text{Fe}_6^{3+}[(\text{OH})_3|\text{PO}_4]_4$
Monoclinic
Phoenix/USA
Original size 15 × 23 mm





tallic and glassy in luster. Most are colorless, but they may also be brightly colored when they contain trace elements or are exposed to certain types of radiation. They tend to be soft. For the most part halides are of marine sedimentary origin. These are readily soluble and have a salty taste:

Halite	NaCl
Sylvite	KCl
Carnallite	KMgCl ₃ ·6H ₂ O
Others are not very soluble and are the products of hydrothermal or pegmatitic processes:	
Fluorite	CaF ₂
Cryolite	Na ₃ AlF ₆

4. Oxides and Hydroxides

Simple compounds of metals, more rarely semi-metals and non-metals, with oxygen are known as oxides. In the case of hydroxides one finds the hydroxyl ion (OH⁻) instead of oxygen. There are few similarities which characterize the minerals of this class. Only some of the oxides, especially those of iron, manganese, and chrome, are dark to black and metallic to semi-metallic in luster. Since oxygen comprises 46.6% by weight of the crust, oxides

are predictably widespread. Quartz is the most common oxide and makes up as much as 12.6% of the main components of many rocks. Another oxide is water, which forms hexagonal crystals of ice (H₂O) below its freezing point of 0°C. The oxide class contains a large number of economically important minerals and ores:

Oxides	
Cuprite	Cu ₂ O
Magnetite	Fe ₃ O ₄
Chromite	(Fe,Mg)Cr ₂ O ₄
Corundum (ruby and sapphire)	Al ₂ O ₃
Hematite	Fe ₂ O ₃
Quartz (and varieties)	SiO ₂
Rutile	TiO ₂
Cassiterite	SnO ₂
Uraninite (pitchblende)	UO ₂

Hydroxides	
Gibbsite	Al(OH) ₃
Goethite	FeOOH
Manganite	MnOOH

5. Nitrates, Carbonates, Borates

Of the various compounds in this class, the carbonates are the most significant in nature.

81 **Picropharmacolite** – Ca₄MgH₂[AsO₄]₄·11 H₂O
 Triclinic
 Anton Mine near Schiltach, Schwarzwald/FRG
 Original size 20 × 23 mm



All three groups, the nitrates, carbonates, and borates, have similar anion complexes, $[\text{NO}_3]^-$, $[\text{CO}_3]^{2-}$, and $[\text{BO}_3]^{3-}$, in which nitrogen N, carbon C, and boron B bond to three oxygens forming basic structural units of threefold symmetry. The negative charges of these complexes are balanced by combination with positive cations like Na^+ and Ca^{2+} . $[\text{NO}_3]^-$ and $[\text{CO}_3]^{2-}$ are components of crystal lattices of nitrates and carbonates, respectively, as independent units, while $[\text{BO}_3]^{3-}$, in much the same way as in silicates, may link together to form groups (double triangles), rings, and chains, resulting in complexly structured borates.

Nitrates are relatively soluble salts that are found in sedimentary environments in hot arid climates:

Nitratite	NaNO_3
Nitre	KNO_3

Carbonates form in all environments, especially under sedimentary and hydrothermal conditions. They do not dissolve in water but do so readily in acids with the release of CO_2 . The hardnesses of carbonate minerals lie between 3 and 5.

Important members of this group include:

Calcite	CaCO_3
Aragonite	CaCO_3
Magnesite	MgCO_3
Smithsonite	ZnCO_3
Siderite	FeCO_3
Rhodochrosite	MnCO_3
Dolomite	$\text{CaMg}[\text{CO}_3]_2$
Cerussite	PbCO_3
Azurite	$\text{Cu}_3[\text{OH} \text{CO}_3]_2$
Malachite	$\text{Cu}_2[(\text{OH})_2 \text{CO}_3]$

Borates may form in small quantities from volcanic exhalations but most are found in boron-rich sediments from seas known as salt deposits:

Borax	$\text{Na}_2[\text{B}_4\text{O}_5(\text{OH})_4] \cdot 8\text{H}_2\text{O}$
Boracite	$\text{Mg}_3[\text{Cl} \text{B}_7\text{O}_{13}]$
Colemanite	$\text{Ca}[\text{B}_3\text{O}_4(\text{OH})_3] \cdot \text{H}_2\text{O}$

82 **Pharmacolite** – $\text{CaH}[\text{AsO}_4] \cdot 2\text{H}_2\text{O}$
 Monoclinic
 Richelsdorf, Hessen/FRG
 Original size 17 × 26 mm





6. Sulfates, Chromates, Molybdates, Tungstates

The minerals of this class have anion complexes in which four tetrahedrally arranged oxygen atoms enclose the elements sulfur, chrome, molybdenum, and tungsten: $[\text{SO}_4]^{2-}$, $[\text{CrO}_4]^{2-}$, $[\text{MoO}_4]^{2-}$, $[\text{WO}_4]^{2-}$. These minerals are always non-metallic, translucent to transparent, and glassy in appearance. There are sulfates with or without crystal water in their composition and others which also contain the univalent anions OH^- , F^- , and Cl^- . Sulfates with large H_2O or OH^- contents are usually soft and have low densities. Some, such as alunite and chalcantite, are very soluble in water and are not very stable. Barium, strontium, and lead sulfates are among the most insoluble. Sulfates are mostly sedimentary in origin or they are produced from the oxidation of sulfides, but barium sulfate (barite) is also common in hydrothermal deposits.

Important sulfates are:

Anhydrite	CaSO_4
Celestite	SrSO_4
Barite	BaSO_4
Anglesite	PbSO_4
Brochantite	$\text{Cu}_4[\text{OH}]_6[\text{SO}_4]$
Chalcantite	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$
Potassium alum	$\text{KAl}[\text{SO}_4]_2 \cdot 12\text{H}_2\text{O}$
Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$

Chromates

Crocoite	PbCrO_4
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Molybdates

Wulfenite	PbMoO_4
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Tungstates

Scheelite	CaWO_4
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83 **Tsumcorite** $\text{Pb}(\text{ZnFe})_2(\text{OH}, \text{H}_2\text{O})[\text{AsO}_4]_2$
With Aragonite Monoclinic
Tsumeb/Namibia
Original size 20 x 31 mm





7. Phosphates, Arsenates, Vanadates

The phosphates are grouped with the arsenates and vanadates because of their closely related crystallochemical character. Their anion complexes $[\text{PO}_4]^{3-}$, $[\text{AsO}_4]^{3-}$, and $[\text{VO}_4]^{3-}$ are similar to those of the sulfate group in that they are composed of oxygen tetrahedra but they have a different valence. For this reason the phosphates and sulfates are classified separately. In addition to water-free (anhydrous) phosphates and arsenates, there are a large number of minerals in this group that contain water (H_2O), hydroxyl, or a halide element, mostly chlorine (Cl) or fluorine (F). The anhydrous phosphates are often the product of primary magmatic or pegmatitic origin, more rarely sedimentary. The number of phosphate minerals is very large. They are mostly secondary in origin, having formed through alteration and hydration of primary phosphates. As with the sulfates, all the minerals of this class have a non-metallic appearance. Most occur in colorful crystals.

Torbernite - $\text{Cu}[\text{UO}_2|\text{PO}_4]_2 \cdot 8 - 12\text{H}_2\text{O}$

Tetragonal. Torbernite is a member of the “Uranglimmer” (uranium mica) group. The crystal lattice of this mineral consists of two-dimensional stable layers of the uranium phosphate complex that are relatively loosely interconnected, and for this reason they exhibit a micaceous cleavage. A closer chemical or crystallographic relationship with the mica minerals does not, however, exist.

The uranium micas were recognized even before the discovery of uranium, which is credited to the pharmacist and chemist Martin Heinrich Klaproth in 1781. Prior to this, torbernite was known only as green mica. After the Swedish chemist Torbern Olaf Bergmann in 1780 found that the mineral contains copper, it was called chalkolite (Greek *chalkos*=copper, *lithos*=stone). In 1786 A. G. Werner named the mineral torbernite in honor of Bergmann, electing to use his first name.

The crystals usually are flat tabular to short prismatic singles, or scaly bundles. They are bright blue-green to yellowish green in color, have a glassy luster except on the cleavage surface where they are pearly. Hardness 2–2½, specific gravity 3.3. In contrast to most secondary uranium minerals, torbernite does not fluoresce under the ultraviolet light.

Torbernite is found exclusively as an oxidation product of primary uranium minerals such as uraninite (UO_2), and is often associated with these minerals, as in the Saxon-Bohemian Erzgebirge; Redruth, in Cornwall, England; and Shinkolobwe, Shaba, Zaïre.

84 **Torbernite**

Shaba Province (formerly Katanga)/Zaïre
Original size 11 × 17 mm





Some of the more important and interesting members of this group are:

Monazite	$\text{Ce}[\text{PO}_4]$
Amblygonite	$(\text{Li}, \text{Na})\text{Al}[(\text{F}, \text{OH}) \text{PO}_4]$
Apatite	$\text{Ca}_5[\text{F}, \text{OH}](\text{PO}_4)_3$
Pyromorphite	$\text{Pb}_5[\text{Cl}](\text{PO}_4)_3$
Mimetite	$\text{Pb}_5[\text{Cl}](\text{AsO}_4)_3$
Vanadinite	$\text{Pb}_5[\text{Cl}](\text{VO}_4)_3$
Vivianite	$\text{Fe}_3[\text{PO}_4]_2 \cdot 8\text{H}_2\text{O}$
Erythrite	$\text{Co}_3[\text{AsO}_4]_2 \cdot 8\text{H}_2\text{O}$
Turquoise	$\text{CuAl}_6[(\text{OH})_2 \text{PO}_4]_4 \cdot 4\text{H}_2\text{O}$
Autunite	$\text{Ca}[\text{UO}_2 \text{PO}_4]_2 \cdot 8-12\text{H}_2\text{O}$

8. Silicates

The silicates constitute the largest and most complex group of minerals. They comprise about 80% of the volume of the earth's crust and are the most important components of nearly all rocks. They tend to have a stony non-metallic appearance and, with few exceptions, are relatively hard, ranging from about 6 to 8. All silicates contain, as their basic structural unit, anion complexes $[\text{SiO}_4]^{4-}$. In this respect they are analogous to the sulfates and phosphates. Silicon is in the center of these anionic complexes surrounded in tetrahedral arrangement by four oxygens. These $[\text{SiO}_4]^{4-}$

groups can combine with a great number of positively charged metal ions and this leads to the occurrence of a great number of silicate minerals. A characteristic of the silica tetrahedra is their ability to share one, two, three, or all four oxygen atoms with other tetrahedra. The various linkings that are possible result in six distinctly different types of silica groupings upon which a precise classification is based.

1. Nesosilicates combine independent $[\text{SiO}_4]^{4-}$ tetrahedra with metals, as well as with other anions such as O, OH, and F that are foreign to the tetrahedra.

Examples:

Olivine	$(\text{Mg}, \text{Fe})_2[\text{SiO}_4]$
Garnet (spessartine)	$\text{Mn}_3\text{Al}_2[\text{SiO}_4]_3$
Zircon	$\text{Zr}[\text{SiO}_4]$
Topaz	$\text{Al}_2[\text{F}_2 \text{SiO}_4]$

2. Sorosilicates are those in which two SiO_4 tetrahedra are linked to a common oxygen atom, forming the complex $[\text{Si}_2\text{O}_7]^{6-}$.

Example:

Thortveitite	$(\text{Sc}, \text{Y})_2[\text{Si}_2\text{O}_7]$
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3. Cyclosilicates (ring silicates) consist of rings formed by SiO_4 tetrahedra each sharing two of their oxygen atoms.

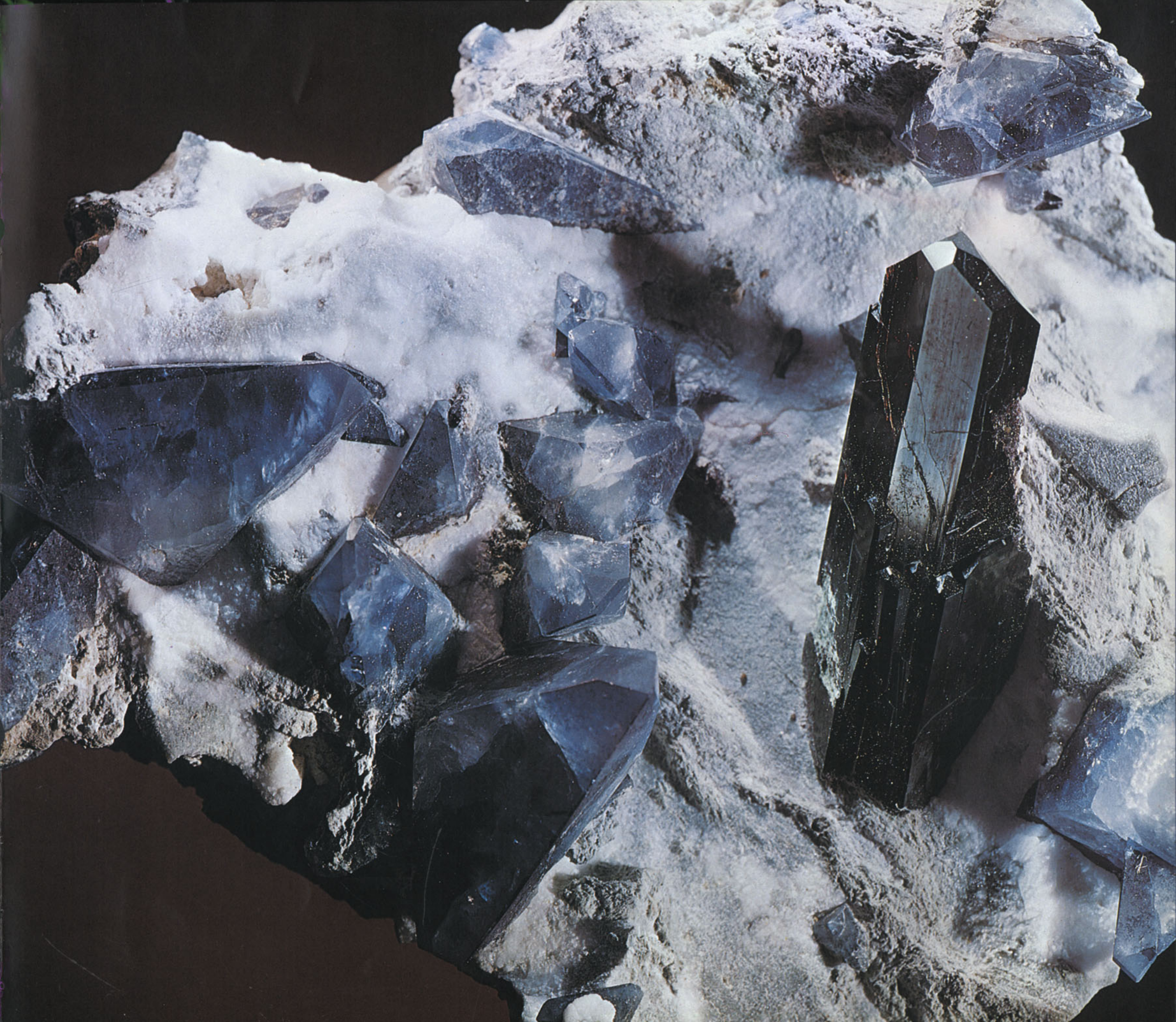
Benitoite - $\text{BaTi}[\text{Si}_3\text{O}_9]$

Trigonal. Benitoite was named after the only locality where it has ever been found, on the San Benito River, in San Benito County, California. The mineral was first discovered in 1907. Due to its blue color it was originally thought to be sapphire. The lower hardness, however, soon led its discoverers to think that it might be a new mineral. Benitoite is one of the few examples of the class of silicate minerals whose structure is based upon three SiO_4 groups linked together to form a ring.

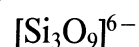
The crystals are found in the form of trigonal bipyramids and may reach the size of 3 cm. They are normally pale to sapphire blue, and almost always cloudy and unclear. Only rarely are they perfectly transparent, but when they are they may be cut into beautiful gems. The size of the faceted stones is small, seldom exceeding 6 carats. Hardness $6\frac{1}{2}$, specific gravity 3.65–3.68.

Benitoite occurs growing in snow-white, dense natrolite $(\text{Na}_2[\text{Al}_2\text{Si}_3\text{O}_{10}] \cdot 2\text{H}_2\text{O})$ in solution cavities and fissures within a chloritized former slate at the Dallas Gem mine, on Mount Diablo, San Benito County, California. It is usually in association with long prismatic, blackish brown crystals of neptunite $(\text{KNa}_2\text{Li}(\text{Fe}^{+2}, \text{Mn})\text{Ti}_2[\text{O}|\text{Si}_4\text{O}_{11}]_2)$.

85 **Benitoite** and Neptunite on Natrolite
San Benito County, California/USA
Original size 50 × 58 mm



a) Three tetrahedra may comprise the ring



Benitoite



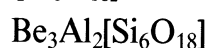
b) Four tetrahedra rings $[\text{Si}_4\text{O}_{12}]^{8-}$

Baotite

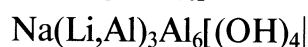


c) Six tetrahedra rings $[\text{Si}_6\text{O}_{18}]^{12-}$

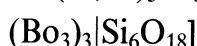
Beryl



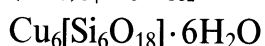
Tourmaline



(elbaite)



Diopase



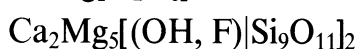
4. Inosilicates (or chain silicates) are those in which SiO_4 tetrahedra form continuous chains through sharing of two of each of their four oxygen atoms and the complexes are in the form of $[\text{Si}_2\text{O}_6]^{4-}$. Pairs of chains in opposite or mirror image orientations can join to form infinite double chains, shown as $[\text{Si}_4\text{O}_{11}]^{6-}$ complexes.

Examples:

Diopside



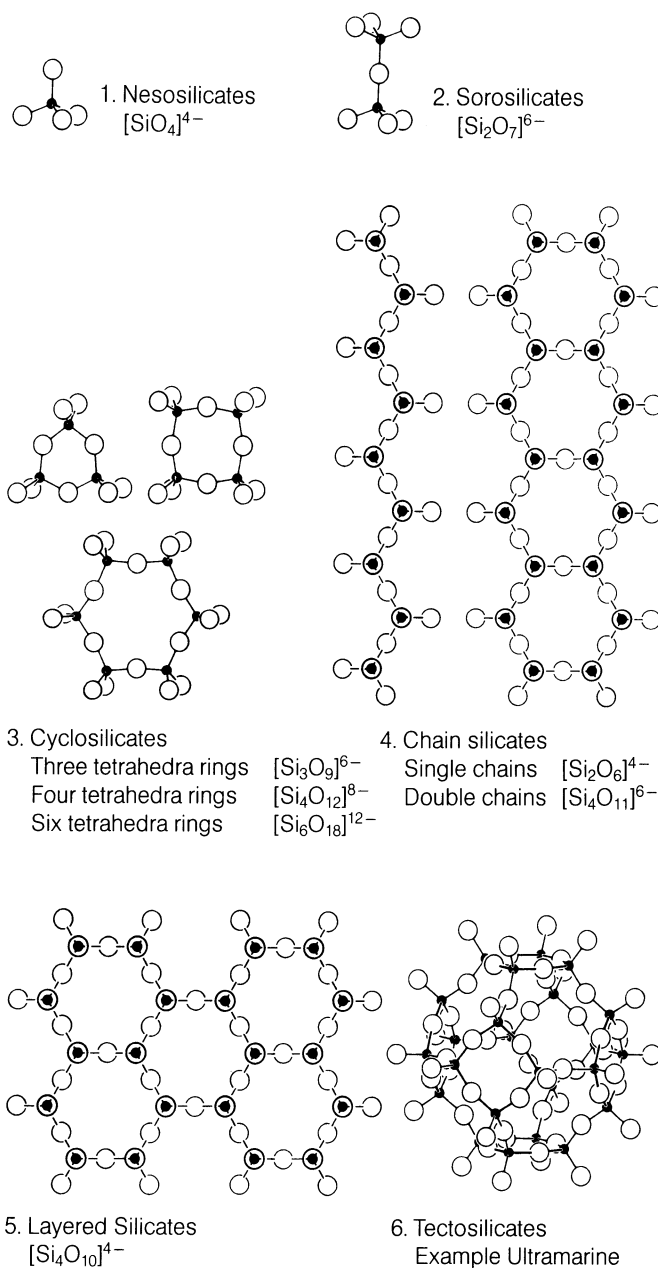
Aktinolite



5. Phyllosilicates (or layered silicates) consist of infinite sheets of SiO_4 tetrahedra, each of which shares three of its oxygen atoms with the three neighboring tetrahedra, forming a continuous sheet of $[\text{Si}_4\text{O}_{10}]^{4-}$ complexes. A notable char-

Silicate structures

Black spheres: Silicium atoms Si
White spheres: Oxygen atoms O



86 **Kämmererite**

Kop Dağları near Erzurum, East Anatolia/Turkey
Original size 23 x 26 mm



acteristic of layered or sheet silicates is a prominent platy cleavage parallel to the sheets of linked silica tetrahedra. The mica group of minerals are the most familiar members of this structure type.

Examples:

Apophyllite	$\text{KCa}_4[\text{F}(\text{Si}_4\text{O}_{10})_2] \cdot 8\text{H}_2\text{O}$
Muscovite	$\text{KAl}_2[(\text{OH}, \text{F})_2\text{AlSi}_3\text{O}_{10}]$

6. Tectosilicates or Framework Silicates (or tectosilicates) are three-dimensionally linked tetrahedra. All of the oxygen atoms of a SiO_4 tetrahedron are shared by four neighboring tetrahedra. Without other elements present the framework would be just SiO_2 , or quartz. However, up to half of the silicon atoms (Si^{4+}) can be replaced by aluminum (Al^{3+}). The resulting compounds are called aluminosilicates. For every aluminum atom that replaces an oxygen atom, a single negative charge is imparted to the tetrahedron which must be neutralized by univalent positive charged atoms (sodium, potassium, rubidium etc.). With two aluminum atoms the charge balance is accomplished by the addition of bivalent metals such as calcium, strontium, barium, etc.

Examples:

Nepheline	$\text{KNa}_3[\text{AlSiO}_4]_4$
Leucite	$\text{K}[\text{AlSi}_2\text{O}_6]$
Sanidine	$\text{K}[\text{AlSi}_3\text{O}_8]$
Anorthite	$\text{Ca}[\text{Al}_2\text{Si}_2\text{O}_8]$

9. Organic Compounds

Many of the earlier mentioned organic compounds are poorly defined mixtures that probably do not qualify as minerals. Today this class includes the salts of some organic acids, various hydrocarbons, and resins. The number of these compounds is so small, however, that they are usually not found in many mineral texts. Those most often included are a few compounds of oxalic acid ($\text{H}_2\text{C}_2\text{O}_4$) or mellitic acid $\text{C}_6(\text{CO}_2\text{H})_6$, for example:

Whewellite	$\text{Ca}[\text{C}_2\text{O}_4] \cdot \text{H}_2\text{O}$
Mellite	$\text{Al}_2[\text{C}_6(\text{COO})_6] \cdot 18\text{H}_2\text{O}$

The hydrocarbons are mostly paraffin and carbocyclic acid compounds. The best known resin is amber.

Apophyllite – $\text{KCa}_4[\text{F}(\text{Si}_4\text{O}_{10})_2] \cdot 8\text{H}_2\text{O}$

Tetragonal. Because this mineral has the property of exfoliating when heated, the Frenchman René Just Haüy, in 1806, gave it the name apophyllite, from the Greek *apophyllein*, which means leafy. Apophyllite crystals are almost always on matrix and are dipyr-ramidal (see p.44, Fig. 17), prismatic, pseudocubic, or tabular in form. The transparent or translucent crystals show a pronounced pearly luster on cleavage surfaces. In reference to this peculiar luster the mineral was also called ichthyophthalm, which means fish-eye stone. Apophyllite may be colorless, white, yellowish white, pink to rose red, brown, or light bluish green. Hardness $4\frac{1}{2}$ –5, specific gravity 2.3–2.4. Apophyllite is hydrothermal in origin and forms in gas cavities in basalts and related rocks. Large greenish-white, pseudocubic or prismatic crystals (Fig.87) come from Poona, India, often associated with scolecite $\text{Ca}[\text{Al}_2\text{Si}_3\text{O}_{10}] \cdot 3\text{H}_2\text{O}$ and stilbite $\text{Ca}[\text{Al}_2\text{Si}_7\text{O}_{18}] \cdot 7\text{H}_2\text{O}$. Other localities include the Antas Tunnel, Rio Grande do Sul, Brazil; Sasbach, on the Kaiserstuhl; Haslach, in Baden; and transparent colorless, white, or pinkish crystals are found in the fissures and clefts in the Seiseralm, near Bozen, Italy. Pink crystals were once common in the ore veins of St. Andreasberg, in the Harz, and yellow crystals occurring with harmotome $(\text{Ba}, \text{K}_2)[\text{Al}_2\text{Si}_6\text{O}_{16}] \cdot 6\text{H}_2\text{O}$ from Finland.

87 **Apophyllite**
Poona/India
Original size 30 × 35 mm



Garnet - $A_3^{2+}B_2^{3+}[\text{SiO}_4]_3$

Isometric. The term garnet includes a group of silicate minerals that all crystallize in the isometric system and have the same general formula, and therefore belong to the group of nesosilicates. In the A and B positions in the formula a variety of elements may be found. The A position accommodates two-valence metals, such as magnesium (Mg), iron (Fe), manganese (Mn), and calcium (Ca). The B position is occupied by three-valence metals, such as aluminum (Al), iron (Fe), and chromium (Cr). Iron can occur in both two- and three-valence states. The individual members of the garnet family have their own names and these can be ordered into three groups:

Aluminum garnets

Pyrope	Magnesium-aluminum	$\text{Mg}_3\text{Al}_2[\text{SiO}_4]_3$
Almandine	Iron-aluminum	$\text{Fe}_3\text{Al}_2[\text{SiO}_4]_3$
Spessartine	Manganese-aluminum	$\text{Mn}_3\text{Al}_2[\text{SiO}_4]_3$
Grossular	Calcium-aluminum	$\text{Ca}_3\text{Al}_2[\text{SiO}_4]_3$

Iron garnets

Andradite	Calcium-iron	$\text{Ca}_3\text{Fe}_2[\text{SiO}_4]_3$
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Chrome garnets

Uvarovite	Calcium-chrome	$\text{Ca}_3\text{Cr}_2[\text{SiO}_4]_3$
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By mutual substitution of the metal ions with one another mixed crystals occur that lie somewhere between the pure end-members for each formula type.

In the Middle Ages garnet was often placed in the "carbuncle" species group, even though this was primarily a term for ruby. Carbuncle, the carbuncle stone of poetry, is derived from the Latin *carbunculus* (= small coal), since the stone ostensibly glowed like a coal in the darkness. Pliny, however, considered carbuncle a general term for a series of various red stones. Albertus Magnus (ca. 1250) named three different carbuncles in his work *De Mineralibus*: the ba-

lagius (balas = red spinel, also balas ruby), the rubinus (ruby), and the granatus, and is thus credited with first bringing into use the term garnet.

The word is derived from the Latin *granum* (= grain), no doubt because the mineral so often occurs as granules in rock. It may, however, allude to the color of the fruit of the granat tree (pomegranate). Garnet was one of a group of 29 stones thought to possess magical and healing powers in early times and in the Middle Ages. It was said to make the heart happy and to drive away sorrows (Albertus Magnus), and also to help the circulatory system. In 1778 Johann Friedrich Gmelin wrote: "The heart-strengthening powers, that were described by the older physicians, are fully fictitious."

The typical crystal form of the garnet is the rhombic dodecahedron (granatohedron, see p.44, Fig.3), often in combination with the icositetrahedron and the hexoctahedron. The crystals, of a glassy-greasy luster, are found in many color variations, with the exception of blue. Most are red, but white, green, and black are common. Hardness and specific gravity vary with the different species but lie within the range of hardness $6\frac{1}{2}$ – $7\frac{1}{2}$ and specific gravity 3.4–4.2.

Because of the diversity of compositions in the garnet group, the members of the group are found in a broad variety of occurrences. Garnet is found as a common rock-forming mineral in metamorphic rocks such as gneisses, mica schists, and eclogites, as well as in the contact metamorphic zones next to crystalline limestones and dolomites. It is also found isolated in magmatic rocks such as granites. Due to its high re-

88 Grossular

Quebec/Canada

Original size 22 x 34 mm





sistance to chemical and mechanical weathering it is usually concentrated after the decomposition of the host rock. Its high specific gravity causes it to settle in sands and heavy mineral placers. Crystals whose quality permits cutting are used as gemstones.

Pyrope is a deep-red magnesium-aluminum garnet, the color is produced by traces of iron and chromium. It has been used as a gemstone from the earliest times and is one of the most common garnet gems today. The name comes from the Greek *pyropós*, which means fiery or fire-like. Throughout history pyrope has been known to occur on the south side of the Bohemian central mountains in the serpentines of Měrunice (Meronitz) or in the related placers near Trüblitz (Triblitz) and Podsedice (Podseditz). In early times it was known as Bohemian garnet. Bohemian garnet was in great fashion in the middle of the last century and for a time it was almost as valuable as ruby. Pyrope is a typical associated mineral of diamond, found both in the primary kimberlite matrix as well as in the secondary placer deposits. The pyropes readily available from the diamond mining operations of South Africa have reduced the importance of the Bohemian garnet deposits.

Almandine, named by Pliny *carbunculus alabandicus*, after the city of Alabanda in Asia Minor, is an iron-aluminum garnet which owes its bluish red to red-brown color to the iron that is always present in its chemistry. Almandine commonly forms beautiful and sometimes very large crystals in chlorite and mica schists as well as in gneisses and amphibolites, as in the Zillertaler and Ötztaler Alps. Fine cutting quality almandine comes from the gem placers of Sri Lanka.

Rhodolite possesses a rose red to red-violet color and bright luster, being intermediate in composition between pyrope and almandine. Beautifully colored

specimens come from Georgia and North Carolina, U.S.A., and from newer finds in Tanzania.

Spessartine is a manganese-aluminum garnet and is named for the locality where it was first found, Rauhensteingipfel, near Aschaffenburg, in the Spessart, F.R.G. The brilliant fire red to orange-yellow color, caused by the content of manganese, makes it one of the loveliest members of the garnet group. It is found almost exclusively in manganese-rich granites, pegmatites, or metamorphic rocks. Crystals, sometimes as large as 7 cm in diameter, come from the tourmaline pegmatites of San Diego County, California, U.S.A. (Fig. 89), and spessartine of cutting quality comes from Sri Lanka, upper Burma, Tanzania, and Madagascar.

Grossular, the calcium-aluminum garnet, was named from the Latin *grossularia* (= gooseberry) because of its typical green color. It is a widespread mineral of contact metamorphic origin. In addition to green, it is also found colorless, pink, and orange-red. It is rarely found in gem-quality crystals, but some comes from Pakistan and it is found in light green shades in the Lelatema Mountains of Tanzania. An emerald-green grossular, first found in Tanzania in 1968 and later in Kenya in 1971, has been given the commercial name tsavorite after the famous Tsavo animal reservation. Grossular with a very low iron content and a red-brown color is called hessonite (Greek *hesson*=lesser, alluding to the lower hardness it has when compared to the similar appearing zircon). Hessonite is found mainly in the gem placers of Sri Lanka; other localities include Minas Gerais, Brazil; Quebec, Canada (Fig. 88); and near Auerbach on the Bergstrasse, F.R.G. Cryptocrystalline compact masses of grossular in green and pink colors have been found since 1925 in the Transvaal, South Africa. The pink color is caused by manganese and the

green by chromium. This material is often misleadingly referred to as Transvaal jade.

Andradite, a calcium-iron garnet, was named after the Portuguese mineralogist I. B. d'Andrada. As with grossular, andradite is formed by contact metamorphism. Its colors are mostly brown, green, black, and even colorless. Andradite in brilliant green crystals sometimes forms in clefts in serpentine and chlorite-rich rocks and is then known as **topazolite**. Well-known topazolite localities include Wurlitz in the Fichtelgebirge, F.R.G., and Val d'Ala in Piedmont, Italy. The most unusual and also most valuable variety of andradite is **demantoid**, which means diamond-like. Its brilliant colors, from the finest emerald green to a yellowish green, are due to traces of chromium. It is extremely lustrous because of its high refractive index, and its dispersion exceeds that of diamond. Demantoid was first discovered in 1868 by gold miners working the gold placers of Nishni-Tagil, in the Urals, and it was first thought to be emerald. Its lesser hardness, however, between 6½–7, made it easy to differentiate from emerald. Titanium-bearing andradite, such as that at the Kaiserstuhl, F.R.G. is known as **melanite** (Greek *melas*=black).

Uvarovite, the calcium-chromium garnet, is yet another emerald-green garnet. It was named after the Russian statesman Sergei Semenovitch Uvarov. The few localities of this rare mineral are associated with the chrome deposits of Sysertsk, in the Urals; in the Bushveld, Transvaal, South Africa; and in Turkey. Especially fine specimens of well-formed crystals come from Outukumpu, Finland.

89 **Spessartine** in Albite
Ingle's Mine, Ramona, San Diego County,
California/USA
Original size 22 × 25 mm



Dioptase - $\text{Cu}_6[\text{Si}_6\text{O}_{18}] \cdot 6\text{H}_2\text{O}$

Trigonal. When diopase was first discovered in 1785 on Altyn-Tübe Mountain in the Kirgiz Steppes, its color caused it to be confused with the very similar-appearing emerald. In 1797 Haüy recognized the mineral for what it was and named it diopase, after the Greek *diopteia*, which means to see through. The name was chosen in reference to the fact that one can see into the crystal and view minute internal cleavage fractures.

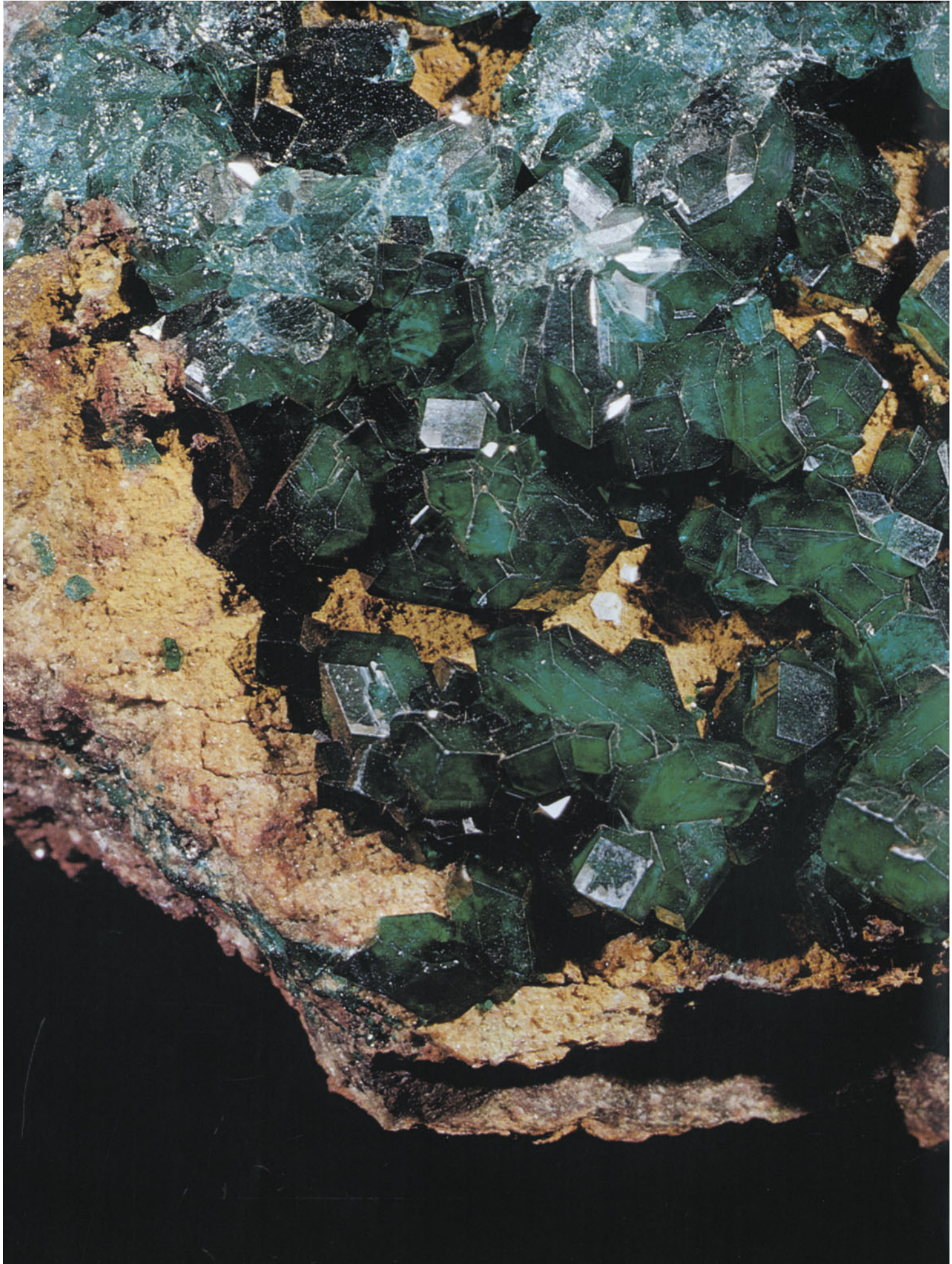
Dioptase crystals are almost always formed in vugs and cavities, seldom reaching a size in excess of 1.5 cm. They usually occur as short columnar prisms terminated with rhombohedral faces (Fig. 90). The color is a strikingly brilliant dark emerald green. Single crystals are mostly translucent, but sometimes transparent, in which case they may be cut into gems. Hardness 5, specific gravity 3.3.

Dioptase is typically found close to the earth's surface, having crystallized from aqueous solutions, or in the oxidation zones of copper deposits. Superb crystals were found in the clefts in a dolomite near Guchab, and more recently exceptional crystals came from Tsumeb, in the Otavi region of Namibia; near Renéville, Mindouli, and in the Shaba province, Zaïre. Other famous localities include the Altyn-Tübe Mountain, east from Tashkent, in the Kirgiz Republic, U.S.S.R.; Copiapo, Chile; Peru; and Pinal County, Arizona, U.S.A.

90 Dioptase

Tsumeb/Namibia

Original size 58 × 110 mm





Tourmaline - $\text{Na}(\text{Li,Al})_3\text{Al}_6[(\text{OH})_4](\text{BO}_3)_3\text{Si}_6\text{O}_{18}]$

Trigonal. The Singhalese used the term *turamali* as an inclusive name for all brown or red gemstones. When Dutch travelers to the Indies brought back the first stones to Europe in 1703, they brought the name with them. The Dutch knew of the extraordinary property of tourmaline, its tendency to become electrically charged when rubbed or heated. With its help they were able to remove the ashes from their meerschaum pipes and therefore also called the mineral "aschen-trekker" (ash carrier, or remover), a term that never found use as a mineral name. Later Benjamin Franklin, researcher, writer, and statesman, did extensive research on the electrical properties of tourmaline. Due to its rich and varied colors, tourmaline was already a popular stone in Victorian times (1820–48), and has remained popular to the present. Its colors sometimes gave rise to confusion. The large "ruby" that King Gustav III of Sweden gave to Catherine the Great of Russia in 1786, to illustrate the true color of a genuine ruby, was in fact a rubellite, the red variety of tourmaline. Beliefs of mystical and magical powers so commonly attributed to many of the ancient gemstones were not associated with tourmaline because of its late discovery. It was, however, often said to bring about valued friendships and, as a stone of the Muses, was thought to inspire artists, to increase knowledge and enrich the mind.

Tourmaline is a boron-aluminum silicate of a varied and complex composition. It comprises a variety of compositional types which occur in mixed crystals, one member of which is named **elbaite**. This variety can be found in virtually every color. Other members of the tourmaline family are **dravite**, **uvite**, **buergerite**, and **schorl**, the latter being found in many granites as black radially clustered sprays called "tourmaline suns." All have a structure of planar BO_3 groups and

Si_6O_{18} rings in common. Unlike the Si_6O_{18} rings in beryl, the unit rings in tourmaline are all oriented with the tetrahedral points in one direction, thereby causing the polarity which is evidenced in the crystal form and its electrical properties. The BO_3 groups are responsible for the trigonal symmetry of the mineral.

Tourmaline crystals are found as fine acicular crystals in rocks or as large individual crystals grown upon matrix where they may reach a weight of several kilograms. Most form elongated and striated trigonal prisms and these are terminated with trigonal pyramidal faces. Tourmaline crystals show a polar morphological development, which means that in complete crystals (doubly terminated) the upper and lower pyramidal forms are different (see p.44, Fig.13). The mineral is transparent to opaque and exhibits a glassy or pitchy luster. Crystals containing iron are black, crystals with little or no iron come in every other color. Hardness $7\frac{1}{2}$, specific gravity 3.02–3.26.

A distinctive physical property of tourmaline, as already mentioned, is pyroelectricity (Greek *pyr*=fire). Through warming or rubbing the crystal an electric charge is produced, one end positive and the other negative. When dusted with a mixture of powdered yellow sulfur and red lead powder, the sulfur is attracted to the positive end and the red lead to the other. As with quartz, tourmaline also exhibits piezoelectric properties so that it has important application as a frequency stabilizer.

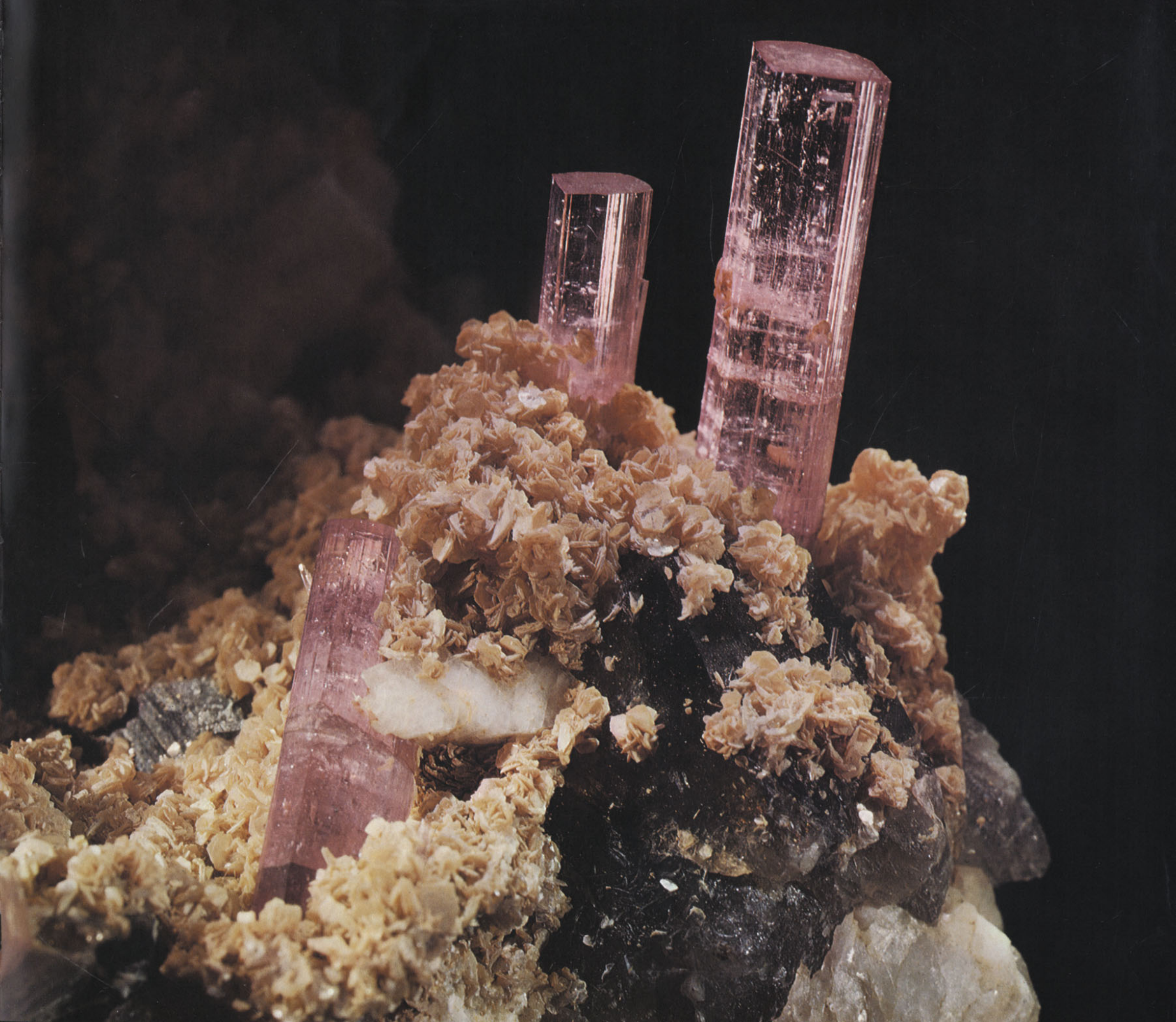
The variation of the range of colors of tourmaline is unequaled by any other gemstone. There are tourmalines in all possible colors and tints and in every conceivable mixture of shades.

91 Tourmaline

Elba/Italy

Original size 33 x 52 mm





Achroite is colorless tourmaline, **sieberite** is rose to violet, named for the locality in the Urals. Especially valued is the red variety, which is called **rubellite**, and the emerald-green variety, **verdelite**. Blue tourmaline is called **indigolite**, and the brown variety **dravite**, from the locality on the Drave, near Unterdraubing, Carinthia. The common tourmaline found in many granites and pegmatites is black. The abundant colors are caused by the elements iron (Fe^{3+} for yellow and brown colors, Fe^{2+} for blue to green hues), manganese for pink and red, and chromium and vanadium for the greens. The range of green colors includes brownish green, yellow-green, blue-green, and extends from colorless pale green to the deepest emerald green. Many of the dark green crystals contain chromium and are known as chrome tourmalines. Some that have a dark green or blue-green color become a brilliant emerald green upon heating to about 650°C and these are highly prized. Polychrome tourmalines are those that show zones of different colors in the same crystals. This type of tourmaline from the Island of Elba may be colorless to pale greenish in the body but has a dark brown to black cap and is known as Moor's head. Turk's heads are those crystals, mostly from Brazil, that are green within and red on the top. These two varieties often have a colorless zone between and a sharp separation of colors. In some cases these colors can be reversed. Finally, a tourmaline is also found that, when cut parallel to the base, exhibits a rose red center, a very thin colorless band parallel to the surface of the crystal, and a brown or green outer layer. This type of crystal, usually found in Mozambique and Madagascar, is called watermelon tourmaline.

Another characteristic of tourmaline is its extreme pleochroism (dichroism). In transmitted light the color of the mineral is different when viewed in different orientations, due to its ability to absorb light differently in

these directions. Many crystals show virtually no absorption in one direction and almost total absorption in the other. Such crystals were used to produce polarization of light in the early days of polarization optics. This property must be taken into consideration by the gem cutter in order to produce an optimally colored gemstone.

Tourmaline is a mineral of pneumatolytic origin, and is often a constituent of pegmatitic veins, found in clefts, vugs, and miarolytic cavities in granite. Typical associated minerals are quartz, alkali micas, topaz, and cassiterite, among others. It can occur in granites as a contact mineral and can occasionally "tourmalinize" the neighboring rocks or the granite itself. The light colored crystals formed by late crystallization in pegmatites have been recrystallized by hydrothermal action to form the gem quality crystals.

The most important localities for tourmalines of all colors are found in the highly decomposed pegmatites in the state of Minas Gerais, Brazil (Fig. 92). Other important localities are Usakos and Karibib, Namibia; Zimbabwe; Alto Ligonha, Mozambique (in very large crystals); near Antsirabe, Madagascar (where crystals 1 m long and up to 30 cm thick have been found, which when sliced in thin sections show a zonal development with up to 30 different color zones); Tanzania (beautiful green chromium-vanadium types); Pala, and in San Diego County, California, U.S.A. (partly as handsome large rubellites, Fig. 93). Older localities include the pegmatites of Mursinka, Sarapulka, in the Urals, or the Nertschinsk, Transbaikalia, U.S.S.R.; and San Piero, in Campo, on the Island of Elba, as the famous Moor's heads and beautiful red or pink crystals (Fig. 91).

92 Tourmaline

Minas Gerais/Brazil

Original size 50 × 50 mm





93 **Rubellite** with Albite and Quartz
Tourmaline King Mine, Pala, San Diego County,
California/USA
Original size 190 x 140 mm

94 **Cuprosklodowskite** – $\text{CuH}_2[\text{UO}_2(\text{SiO}_4)_2 \cdot 5 \text{H}_2\text{O}]$
Monoclinic
Shaba Province (formerly Katanga)/Zaire
Original size 13 x 15 mm



Microcline - $K[AlSi_3O_8]$

Triclinic. Microcline is a silicate and a member of the feldspar group of minerals. The feldspars are major constituents of the rocks of the earth's crust and comprise some of the most important rock-forming minerals. As in quartz, the crystal structure consists of three-dimensional SiO_4 tetrahedral frameworks in which, however part of the four-valence silicon (Si^{4+}) is replaced by three-valence aluminum (Al^{3+}). The resulting charge imbalance is compensated by the addition of single-valence sodium (Na^+) or potassium (K^+), or two-valence calcium (Ca^{2+}). The most common members of the feldspar group are:

Potassium feldspar (orthoclase)	$K[AlSi_3O_8]$
Sodium feldspar (albite)	$Na[AlSi_3O_8]$
Calcium feldspar (anorthite)	$Ca[Al_2Si_2O_8]$

Albite and anorthite are completely miscible at any temperature and form a continuous series from one to the other known as the **plagioclase feldspars**. Intermediate members have been given the names oligoclase, andesine, labradorite, and bytownite. In contrast, albite and potassium feldspars are miscible only at high formation temperatures. With slow cooling the two immiscible feldspars separate to form perthitic intergrowths.

The triclinic members of the potassium feldspar family are called microcline. In terms of morphology and twinning there is practically no difference between the monoclinic orthoclase and sanidine (see p.44, Fig.24). The optical properties and X-ray patterns of the two, however, clearly serve to differentiate between them.

The crystals of microcline are either embedded in or growing upon matrix. They are tabular to prismatic with various directions of elongation, and sometimes of a pseudo-hexagonal development. Their color can

range through all variations from brilliant green or blue-green to faded and pale. The green variety is called **amazonite** (amazonstone) because of its early confusion with another green stone once found in the gravel of the Amazon River in Brazil. Because of the blue-green color it is widely used in the manufacture of jewelry and decorative objects. Hardness 6, specific gravity 2.56–2.58.

Microcline crystallizes in pegmatites and may reach sizes of awesome proportions. Beautiful crystal groups have formed in vugs and clefts inmiarolytic cavities in granites. Known localities include the pegmatites of Iveland, near Kristiansund, Kragerö and Larvik, in Norway; Miask in the Urals; Brazil; and Madagascar. Especially beautiful crystals and crystal groups come from Pikes Peak and Crystal Peak, Colorado, U.S.A. (Fig.95).

95 **Microcline** (Amazonite)
Crystal Peak, Colorado/USA
Original size 63 × 98 mm





Muscovite - $\text{KAl}_2[(\text{OH}, \text{F})_2|\text{AlSi}_3\text{O}_{10}]$

Monoclinic. The name of this mineral is relatively new. It was first used in 1850 by the American mineralogist James Dwight Dana, and refers to the large plates of the mineral that were found in Russia in the 18th and 19th centuries, known then as *vitrum muscoviticum*, or Moscow glass. In antiquity the mineral was used in place of glass because it was easily split into thin transparent sheets. Muscovite was also known earlier as *lapis specularis*, which means mirror stone; later, in the Middle Ages as *Spat* (spar), *Katzengold* (cat gold), or *Katzensilber* (cat silver). Muscovite is a member of the mica group of minerals and is the most important of the layered silicates, that is silicates having layered structures. A common characteristic of these structures is planar-linked lattices of SiO_4 tetrahedra, so members of this group are referred to as phyllosilicates. In muscovite the respective double layers of SiO_4 tetrahedra are loosely bonded together due to the presence of potassium in between them. The low cohesion between the layers produces an easy and perfect cleavage parallel to the basal plane. In place of aluminum other elements can occur, such as magnesium, iron, manganese, and lithium.

Another common mica group mineral, colored black by iron, is **biotite** $\text{K}(\text{Mg}, \text{Fe}^{2+})_3[(\text{OH})_2(\text{Al}, \text{Fe}^{3+})\text{Si}_3\text{O}_{10}]$, also a common rock-forming mineral. Other minerals in the mica group include the sodium mica **paragonite** (similar to muscovite), the industrially important **phlogopite**, and **lepidolite**, which is an important source of lithium. Muscovite, like all minerals of the mica group, is found in tabular, pseudohexagonal crystals. It often forms irregularly bounded plates or rosette-like growths. Compact aggregates of fine scaly and silky material are called **sericite** (Greek *serikos*, = silky). Crystals are ordinarily nearly colorless, but also yellowish, brownish, or greenish with a

pearly luster. Even some rather thick cleavage plates are clear and transparent, and they are elastic. Hardness 2–2½, specific gravity 2.78–2.88.

Muscovite occurs in rocks such as granites, gneisses, mica schists, and similar rocks as either a major or accessory constituent. Large plates of the mineral are found in pegmatites and are often mined from them for technical utilization. Mined mica pegmatites are known from the Uluguru Mountains, Tanzania; Bengal and Madras, India; Quebec and Ontario, Canada; North Carolina and Maryland, U.S.A.; and Alice Springs, Australia. Well-crystallized groups on matrix come from Minas Gerais, Brazil (Fig. 96). An emerald-green, chromian muscovite, a metamorphic mineral in chromium-bearing olivine rocks, is known as **fuchsite**.

Of the mica minerals only muscovite and phlogopite are economically important. They are used in the electronic industry as insulators, while inferior quality material is pulverized and used as a constituent in plaster and as a filler for paper, plastics, rubber, pigments, and wall paper.

Minerals with properties similar to the micas make up another group, the **chlorites**. However, the cleavage of chlorites is less perfect and the individual plates are not elastic. Chlorites are magnesium- and often iron-bearing aluminum and aluminosilicates which, in contrast to the micas, contain no alkali metals. The crystal structure is closely related to that of the micas. A common chlorite is **penninite** (named after the Pennine Mountains). Its color is bluish green. With a proportionate replacement of the aluminum by chromium, the mineral has a red color and is then known as **kämmererite**. Kämmererite was first described in 1841 and named after Kämmerer, a mine director in Petersburg. Due to twinning the monoclinic crystals often appear as a rhombohedron. Kämmererite is the product of metamorphism of chromium-bearing

rocks and is found, along with uvarovite, in the chrome deposits of Bissersk, near Sverdlovsk, U.S.S.R.; and from Guleman and Kop Dağlari, near Askale in the Erzurum Province, Anatolia, Turkey (Fig. 86).

96 **Muscovite** on Feldspar
Minas Gerais/Brazil
Original size 48 x 55 mm



Beryl - $\text{Al}_2\text{Be}_3[\text{Si}_6\text{O}_{18}]$

Hexagonal. This is a mineral that occurs in a great variety of color types, ranging from translucent common beryl to some of our most highly prized gemstones, most of which have their own independent varietal names, such as emerald and aquamarine. The etymology of the name beryl is unknown. It is possibly found in the middle Indian Prakrit word *verulliyam*, which is repeated in the Latin *berullus*, or *beryllus*, and the Greek *beryllos*. From *beryllus* is derived the middle high German *Berille*, *Barille*, or also *Brille*. In Pliny's time it was known that eyeglasses could be made from the mineral. Emperor Nero wore such a pair. The present German word for eyeglasses, *Brille*, apparently has its origin in this old name for beryl. In the Middle Ages beryl was seen as a symbol of purity. It was used as a decoration for monstrosities and reliquaries, and was believed to help luminaries see into the future. The Benedictine monk Marbod of Rennes (deceased 1123) thought beryl was the protective stone for conjugal love.

In earlier times beryl played an important role in the healing arts. Greek physicians treated kidney and bladder stones with water in which beryl had been placed for a few days. Konrad von Megenberg (1309–1378) used the same therapy “with success” in the treatment of asthma. According to Saint Hildegard beryl protected against poisoning.

The structure of the silicate mineral beryl, with horizontally stacked hexagonal rings $[\text{Si}_6\text{O}_{18}]^{12-}$ mirrors itself in the morphological development of the crystals. The often large crystals are found imbedded in or grown upon matrix and these are usually in the form of simple hexagonal prisms with a flat basal termination, less commonly as hexagonal bipyramids (see p.44, Fig.9). Transparent crystals have a glassy luster, translucent ones are usually more dull. The color of

beryl encompasses a widely varied palette: colorless, emerald green, yellow-green, blue-green, blue, yellow, golden yellow, pink, and red. Most are greenish white and cloudy. Hardness $7\frac{1}{2}$ –8, specific gravity 2.63–2.80.

Common beryl, of no value to the gemstone industry because of its poor color and lack of transparency, is of technical importance as an essential ore of beryllium. This type of beryl is commonly found in giant crystals as, for example, one of 200 tons from Picui, in Brazil. The annual world production of beryl is about 10,000 tons, which represents 360 tons of beryllium metal. Beryllium is used in the hardening of steel, the manufacture of rockets and jet airplanes, as a retardant in reactors, in acid-resistant chrome-nickel-molybdenum alloys, and as an important component of faster-than-sound projectiles. Beryl is a typical mineral of pegmatite veins in granitic rocks. Some pegmatites are so rich in beryl that they are referred to as beryl pegmatites. Crystals in this type of occurrence are usually elongated and columnar. At times beryl may form in a later stage of hydrothermal recrystallization in which case transparent “precious” beryl, often in tabular shapes, is produced. The Colombian emeralds are also of hydrothermal origin.

Emerald is one of the most desired and valuable gemstones known. Its superb dark green color results from the presence of minor amounts of chromium. Only those green beryls colored by chromium are described as emeralds. Small amounts of iron can also cause beryl to be dark green, but the characteristic color nuance of emerald is never produced. Traces of the elements iron and vanadium together,

97 **Emerald**
Muzo/Colombia
Original size 23 x 35 mm





on the other hand, produce a yellow-green or grass-green color. The original meaning of the Greek word *smaragdos*, from which the German name *Smaragd* is derived, is unknown. It is thought to be a word borrowed from the Sanskrit *samâraka* or the Persian *zamarrad*. Emerald was prized even in antiquity. Pliny placed the importance of the gem just below diamond and pearl and he praised it in his *Historia Naturalis*: "We enjoy the green color of herbs and other plants, but that of the emerald is generally regarded as the most beautiful of all. Moreover it is perhaps the only precious gemstone that satisfies the eye without satiating, and when the eye becomes weakened by other observations, it is strengthened again by the viewing of emeralds." The wonderful effects ascribed to emerald are numerous. It was considered to be the stone of peace, harmony, and friendship. It was said to bring constancy and fidelity in love.

The oldest emerald localities known to us were probably the mines of Kosseir on Djebel Sikait and Djebel Sebara, on the Red Sea, Egypt. These were famed as the mines of Cleopatra, but were already supplying the Pharaohs with emeralds 2000 years before. The mines were later lost and only found again in 1818 by the Frenchman Frédéric Cailliaud. Because of their low production and poor quality, it was, however, then not worth reopening the mines.

Emeralds were extremely rare in Europe until the end of the Middle Ages. When the Aztec Empire in Mexico was conquered by Cortez, and the Inca Empire in Peru by Pizarro in the 16th century, huge treasures fell into the hands of the conquerors, above all emeralds, which then found their way to Europe. Long before these conquests the emerald mines of Colombia, which still today produce the best gem emeralds, were worked by the Indians. The Indians regarded the emerald as holy. Legends relate that the ancient Peruvians in the Mantu Valley worshipped an emerald

the size of an ostrich egg as the goddess of chastity. Many of the large emeralds date from the time of the Spanish conquests and came from both Central and South America. A famous large rough crystal, belonging to the Duchess of Devonshire, which weighs 1385 carats, can be seen in the British Museum of Natural History in London, and an urn 12 cm high, cut from a single crystal, can be admired at the Viennese Treasure House. This urn, which was acquired by the Habsburgs in the 17th century, weighs 2205 carats. By far the largest collection of choice old emerald pieces is displayed in the treasure house of the Topkapi-Serail Museum in Istanbul, with countless emeralds cut into vessels and decorative objects, set with gold, and even adorned with other precious gems and pearls. The symbol of the Serail is the famous Topkapi dagger set with dazzling emeralds, which is preserved here along with what are probably the largest rough emerald pieces in the world, weighing 3260 and 1310 g.

The finest and best-colored emeralds come from Colombia. Of the approximately 150 localities, the most important are the Muzo and Chivor mines, about 100 km north and 200 km northeast of Bogota, respectively. The Chivor locality was abandoned by the Spaniards and was only rediscovered in 1896, following a long search, near the village of Somondoco (god of the green stones). The Colombian emerald mines are worked partly by terracing and partly by underground mining. The emerald-bearing matrix at Muzo consists of dark sedimentary shales which are transected by calcite veins. The hydrothermally formed emerald crystals are found in vugs in the calcite veins or as doubly terminated crystals nested in a granular white earthy material.

All other emerald occurrences are in mica schists which have been intruded by pegmatitic veins. In this mode of formation the pegmatitic fluids supplied the

elements essential for the formation of beryl, and the schist necessary for the color chromium. Well-known emerald localities of this type were found in 1831 on the River Takowaja in the Urals, a locality which for nearly 100 years, together with those in Colombia, was the most important. Large crystals up to 20 cm in length were found here. They were, however, mostly of a poor color and badly flawed. The only gemstones cut from this material were small, about one carat. After a long history of very good production the locality today is insignificant. Numerous other emerald localities formed under conditions similar to those of the Russian occurrences. One of the oldest, probably worked as early as in Roman times, lies in the Habachtal, in Pinzgau, Austria. At an altitude of 2000 m specimens are still found by collectors in the Legbach fissure area. The locality of Gravelote, in the Leydsdorp District, South Africa, by contrast, is economically important and is equipped with the most advanced equipment for mining. Other well-known localities are found in Zimbabwe, in the Sandawana Valley (discovered 1956–1957); the Belingwe District; the Novello Claims, near Fort Victoria (found in 1960); and in the Bikita District. Other deposits worth mining are found in India, Pakistan, Brazil, and Australia. One emerald deposit, discovered only recently, is on the south side of Lake Manyara, near the well-known Manyara animal reservation. The locality, near the village of Maji Moto about 200 km southwest of Kilimanjaro, is very rich and contains some very fine emeralds.

Emerald is a gemstone with an exceptional appearance. It is greatly coveted and highly prized, especial-

98 Morganite with Tourmaline
Minas Gerais/Brazil
Original size 92 x 106 mm



ly in rich, full green-colored stones. Cut gems are very rarely free of inclusions. These imperfections, or flaws, give the illusion of an ever-changing view into a magic garden, and one could not more appropriately characterize the fascinating play of light upon the inclusions than with the word used in the gem trade, “jardin”.

Beryls of a sea green to deep blue color are called **aquamarine**. According to legend, the blue beryl originates from the treasure chests of mermaids, and its secret powers are intensified when the stone is placed in water. In Latin **aquamarine** means “sea water.” The name has been used in Europe since the Renaissance to describe blue green beryls. The bluish aquamarine color is caused by trace amounts of iron (Fe^{2+}). Large crystals, free of imperfections, are not rare, in contrast to emerald. The largest gem quality aquamarine found to date was discovered in 1910 in Marambaya, Minas Gerais, Brazil, and weighed 110.5 kg. After cutting, it produced more than 100,000 carats of the highest quality stones.

Aquamarine, as a mineral of pegmatitic formation, is found in numerous occurrences, often in decomposed pegmatites and associated with other gem minerals such as topaz and tourmaline. Occasionally it is also found in vugs and clefts in granites. The most important deposits of aquamarine are in the state of Minas Gerais, Bahia, and Espirito Santo, Brazil. As with most gems, those crystals with the deepest color are most highly prized.

Aquamarines from certain localities often have a distinctive color. Those from Brazil have sometimes been given the names of their place of origin because of their colors. One may therefore speak of Santa Maria aquamarine when describing the finest color, and there are also Espirito Santo stones, etc. There are numerous aquamarine occurrences in Madagascar as well; also the Miami mica field, Zambia; Mo-

zambique; Namibia; and in the U.S.S.R., especially Mursinsk in the Urals, or Adun Tschilon, near Nertschinsk, where it is associated with topaz.

Morganite is a pink to salmon-colored beryl named after the New York financier and precious stone collector John Pierpont Morgan. It occurs, associated with tourmaline and albite, in the form of short prismatic or tabular crystals terminated by basal planes and striated pyramidal forms (Fig. 98) in precious gem pegmatites. The pink color is caused by trace quantities of the element manganese. Also characteristic of morganite is the presence of small quantities of caesium and lithium, which, in contrast with aquamarine, give the mineral a higher specific gravity. Most morganites come from Minas Gerais, in Brazil; from Antsirabe, Madagascar; Ramona and Pala, San Diego County, California; and Namibia.

Other color variations of beryl include **gold beryl**, a lemon to golden-yellow variety, mostly found in association with aquamarine, as at Minas Gerais, Brazil, and Zambia, as well as the yellow-green beryl, first found in Namibia in 1910, and named **heliodor** (after the Greek *helios*, which means sun, and *doron*, for gift). The colors of golden beryl and heliodor are caused by natural radiation. They display blue luminescence under ultraviolet light.

One of the most interesting and rare color variations of beryl has only been known since 1974 and it comes from the Wha Wha Mountains, in Utah, U.S.A. (Fig. 99). The crystals found at this locality have an intense red color. They were, at first, mistakenly thought to be red tourmaline (rubellite). A colorless beryl, of no importance as a gemstone, is named **goshenite**, after its place of discovery, Goshen, Massachusetts, U.S.A.

99 Beryl

Wha-Wha Mountains, Utah/USA
Original size 24 × 28 mm



Topaz - $\text{Al}_2[\text{F}_2(\text{SiO}_4)]$

Orthorhombic. The name topaz was first used to describe many different gems, all of which possessed a golden yellow color. False names such as gold topaz, Madiera topaz, etc., are still in use today. These are most often used to describe cut citrines as well as amethyst quartz that has been heat-treated to change its color to yellow. To differentiate the genuine topaz from these stones the name precious topaz is often used. The Greeks and Romans called the mineral *topazos*, or *topazion*. The origin of the name is subject to various interpretations. According to Archelaos (about 400 B.C.), a student of Anaxagoras in Athens, the stone was first found by shipwrecked pirates on the Arabian Island of Cytis, in the Red Sea, as they were digging for roots and other edibles. At that time islands and stones were named *topazos* in Arabic, which means "sought after and found." Pliny relates the same story. However, he referred to topaz as a mineral of a green color, so that the stones in question were most likely not topaz but peridot, the locality for which lies on the Island of St. John, or Seberget, in the Red Sea. Another derivation can probably be traced back to the Sanskrit word *tapas*, meaning ember or fire, alluding to the brilliant luster and golden yellow color.

Even though topaz is found in many colors it has been described as a yellow-colored stone since ancient times. In his *Kräuterbuch* *Siebender Theil* (Herb Book, Seventh Part), 1679, Adamus Lonicerus wrote about topaz: "It is like gold. If one throws it into boiling water, and then puts one's hand in the water, one can recover it without harm." The cooling property was also supposed to bring other miraculous results. "It extinguishes the carnal desire of lechery," and also "the stone, when layed on a wound, stops the bleeding immediately." Saint Hildegard knew that

topaz warned of poisoning and bestowed those who wore it beauty and intelligence. The often complex crystals – more than 140 crystal forms are known – are usually short prisms terminated by rhombic pyramids (see p.44, Fig.21). Single crystals, commonly attached to matrix on one end, usually show perfect facial development and can attain a great size, more than 30 kg. In compact form topaz is found in larger pieces that are similar in appearance to feldspar, or stalky aggregates called pyknite.

Topaz is found in many color variations. Very common are transparent colorless crystals known as silver topaz or, in Brazil, *pingos d'ago* (= waterdrops). Colorless topaz can sometimes be mistaken for other stones. When cut after the fashion of diamonds, they once served as a diamond imitation. Even the large 1680-carat Braganza diamond in the Portuguese state treasury is in reality a colorless topaz. Otherwise yellow colors dominate, exhibiting a range from light yellow, golden yellow, to brown-yellow, most with reddish tints. In addition topazes are found in blue, green, pink, and even red. The origin of the allochromatic coloring in yellow and blue crystals is probably due to traces of iron, and in pink topaz to traces of chromium. The color is often characteristic for a given locality. Long exposures to sunlight sometimes cause fading of the color. On careful heating (burning) golden yellow topazes from certain mines in Brazil can be made to change their color. They first become colorless, but upon cooling assume a permanent salmon to deep pink color. Many of the pink topazes in commerce have been enhanced in this manner. The higher refractive index gives topaz a strikingly bright glassy luster so that it can usually be distinguished in appearance from quartz (citrine).

100 **Topaz** on Smoky Quartz and Albite
Alabaschka, Ural/USSR
Original size 75 x 103 mm







Hardness 8, specific gravity 3.53–3.56. These properties also serve to distinguish it from quartz. Topaz has a perfect cleavage so that many crystals have a sharp cleavage face on the base.

As a mineral of typical pneumatolytic formation, topaz occurs in the granitic plutonic rocks and is a major component of many tin ore deposits. It is paragenetically associated with fluorite, cassiterite, tourmaline, beryl, smoky quartz, and feldspar. Exceptional crystals of idiomorphic form come from miarolytic cavities in the margins of granite. With the decomposition of primary deposits topaz remains almost unchanged. Its crystals therefore are usually found in good condition among decomposition products in gem deposits. The most important topaz localities lie in the state of Minas Gerais, Brazil, chiefly in the region of Ouro Preto, near Dom Bosco and Rodrigo Silva, but also from Marambaia and Teophilo Otoni. Topaz occurs here with beryl, tourmaline, and chrysoberyl (Al_2BeO_4) in primary and secondary deposits. Well-known Russian localities in the Urals include Alabashka, Mursinsk, near Sverdlovsk (Fig. 100).

Water-clear crystals of superb development have been found on the Kleinen Spitzkopje, near Usakos, Namibia; beautiful light blue crystals come from the decomposed pegmatite of the St. Anne's Mine, in Zambia. One of the few German localities for gems are the topaz occurrences at Schneckenstein in the Vogtland, G.D.R., a high rocky ridge of approximately 24 m on the west side of the Eibenstocker granite massif. This locality produced an abundant supply of fine wine yellow topaz crystals between 1739 and 1741, of which 485 of the best were cut and set in the British Crown Jewels. The locality has long been of historical significance only, and is now a protected monument.

101 **Topaz**

Pakistan Original size 94 × 70 mm

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Dr. Olaf Medenbach, born in 1949 in Giessen/FRG. Studied mineralogy at the Justus-Liebig University in Giessen; subsequent specialized study at the Rupprecht-Karl University in Heidelberg. Doctorate in 1976.

Since 1976 employed as scientific worker at the Institute for Mineralogy at the Ruhr University, Bochum. Inspired by the beauty of rare minerals, he became interested in photography already at the beginning of his studies, and soon became an internationally known photographer in the special field of mineralogy.

In 1976 he became associate editor for photography with the American Mineralogical Record, one of the most important mineralogical journals in the world.



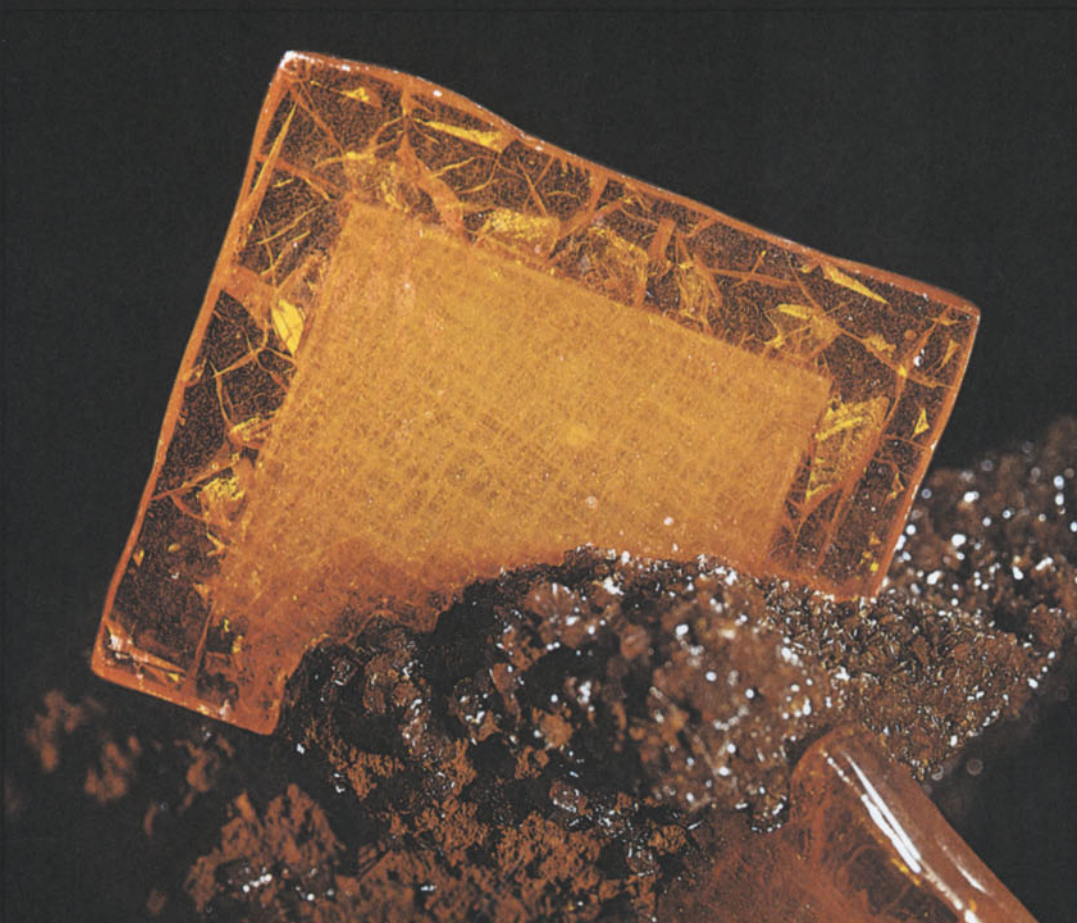
Professor Dr. rer. nat. Harry Wilk, born in 1930 in Berlin/FRG. Studied mineralogy and chemistry at the Free University and the Technical University in Berlin.

On completion of his studies, scientific work at the Institute for Mineralogy and Crystallography, at the same time custodian, head and advisor of the mineralogical collection of the TU, Berlin.

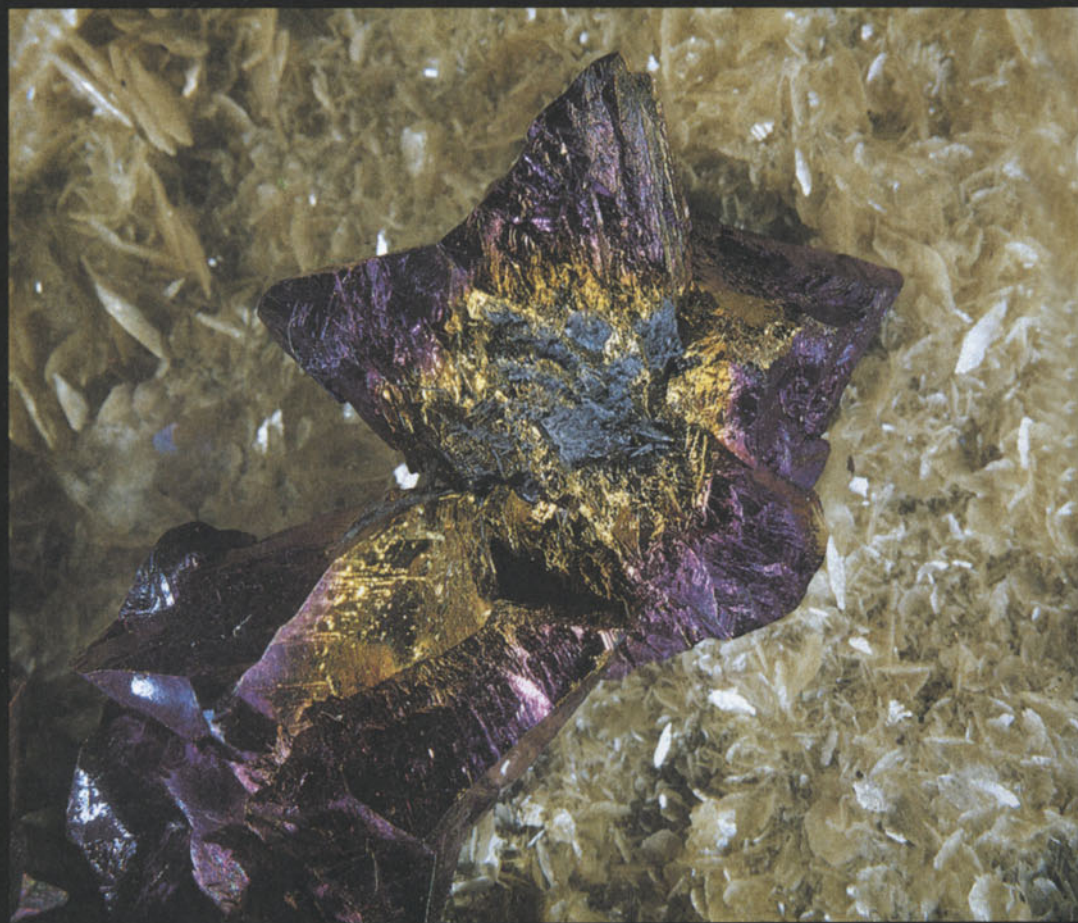
Research work and lectures chiefly in the field of gems-minerals.

Numerous research expeditions have taken him to Asia, Africa, and South America to study occurrences of minerals and gems.

Has lived since 1976 in the Taunus mountains near Wiesbaden, worked as an independent scientist, fulfilling various functions in counseling.



Wulfenite, Mexico – 15 × 18 mm



Chalcopyrite, Westerwald – 21 × 25 mm



Cuprite, Tsumeb – 10 × 12 mm



Azurite, Peru – 14 × 16 mm