

MINERALOGY

AND SOME OF ITS APPLICATIONS



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mineralogy as a career. Mineralogy is a natural science and, although some mineralogists confine themselves to laboratory work, many enjoy their profession because of the opportunity of being out-of-doors part of the time. It offers the dual challenge of making accurate observations in the field and interpreting the results after a careful laboratory study of collected specimens. Furthermore, mineralogy is the common focus of certain phases of geology, chemistry, physics, and mathematics and in it one can integrate these related sciences.

Mineralogy is not a crowded field. In 1955 there were 321 Fellows of the Mineralogical Society of America. This number included practically all the professional mineralogists in the United States and Canada and some in foreign countries. Also included are many who use mineralogy in their special fields of geology, petrology, and crystallography. Although the number of openings in mineralogy is not large, it is increasing each year as more and more industries employ men with specialized mineralogical training.

As mentioned above, mineralogy draws heavily on geology, chemistry, physics, and mathematics and specialized work in it cannot be carried on effectively without a good grounding in these related sciences. For a successful career in mineralogy, one must have not only a love of minerals but also a love of science in general. Since these other sciences are prerequisite to mineralogy, it is impossible to go deeply into the subject in a normal four year college course. Many practicing mineralogists feel that it is better for the undergraduate college student to concentrate on the related sciences and wait until he becomes a graduate student for the serious study of mineralogy. Only a few people become well qualified mineralogists without a M.S. degree, and most find it necessary to have a Ph.D. degree.

WHAT IS A MINERAL?

The practice of mineralogy is as old as human civilization. Tomb paintings in the Nile Valley executed nearly

5,000 years ago show busy artificers weighing malachite and precious metals, smelting mineral ores, and contriving delicate gems of lapis and emerald. Minerals and products derived from minerals have figured largely in the growth of our present technologic culture, from the prized flints of Stone Age man to the uranium ores of the present-day atomic scientist. Mineral substances and products are indispensable to the welfare, health, and standard of living of modern man. They are the most valued and jealously guarded of the natural resources of a nation.

In view of the age-old dependence of man on minerals for his weapons, his comforts, his adornments, and often for his pressing needs, it is surprising that many persons have only a vague idea about the nature of a mineral and are unaware of the existence of a systematic science concerning them. Yet anyone who has climbed a mountain, walked on a sea beach, or worked in a garden has seen minerals in their natural occurrence. The rocks of the mountain, the sand on the beach, and the soil in the garden are completely or in large part made up of minerals. Even more familiar in everyday experience are the products made from minerals, for all articles of commerce that are inorganic, if not minerals themselves, are mineral in origin. All the common materials used in a modern building such as steel, cement, brick, glass, and plaster had their origin in minerals.

In general, we may think of minerals as the materials of which the rocks of the earth's crust are made, and, as such, minerals constitute the most important physical and tangible link with the earth's history. The mineralogist regards the minerals he finds in rocks and veins as the stable end products of a series of natural processes which it is his task to unravel.

Although the great bulk of minerals occur as essential and integral constituents of rocks, others, frequently of greater significance to the studies of the mineralogist, are in veins and cavities. The primary goal of the mineralogist is the study of the physical, chemical, and historical aspects of these materials. Therefore, the term mineral and the study of mineralogy are limited to materials of natural occurrence.

Thus steel, cement, plaster, and glass, although all are derived from naturally occurring mineral raw materials, are not regarded as minerals themselves, since they have been processed by man.

The mineralogist, who must be to some extent a practicing physicist, chemist, crystallographer, and geologist, declines to be a biologist as well. Hence, he excludes from the study of mineralogy all substances resulting directly from the processes of plant and animal life. Thus coal, oil, amber, and bones of animals are excluded, even though they occur naturally in the earth's crust. The economist, however, does not observe this restricted definition of the mineralogist. When he speaks of the mineral resources of a country, he includes petroleum and coal, both of which are of organic origin.

Perhaps the most important and significant limitation placed by the mineralogist upon his definition of a mineral is that it must be a chemical element or compound that can be expressed by a chemical formula. If an element is found as a mineral uncombined with other elements, its formula is merely the symbol of the element, as Au for gold. To express the compositions of other minerals by formulas, the elements that make them up must always combine with one another in rational ratios. For the common mineral quartz, the ratio is one atom of silicon to two atoms of oxygen, with the formula SiO_2 and for the important iron ore, hematite, the formula Fe_2O_3 indicates a ratio of two atoms of iron to three of oxygen. Analyses of the common rock-forming mineral olivine lead to a formula $(\text{Mg,Fe})\text{SiO}_4$. This indicates that both magnesium and iron are found in almost all olivine in proportions that vary from locality to locality. The ratio of the total number of atoms of magnesium and iron to the number of atoms of silicon and oxygen, however, is constant. Thus, magnesium and iron are free to substitute for one another in similar positions in the geometrical framework of atoms characterizing the mineral olivine.

Now that we have determined what shall be included and what excluded, we may frame a definition of a mineral as a naturally occurring chemical element or compound formed

as a product of inorganic processes. This definition sets logical limits for the sphere of activity of the mineralogist and permits the construction of a consistent classification of minerals.

HOW ARE MINERALS STUDIED?

The science of mineralogy is an integrated field of study intimately related to geology on the one hand and to physics and chemistry on the other. The mineralogist may in the field map rock formations, mineral deposits, and structural features of the earth's crust. He may then subject the specimens he collects to scrutiny in the laboratory, using the techniques of the chemist and the physicist. It is neither necessary nor desirable to view mineralogy as compartmented into definite divisions, but for the sake of ease of treatment in many books the following arbitrary divisions are used: crystallography, physical mineralogy, chemical mineralogy.

Crystallography

Although crystallography is a little-known science, all of us have seen crystals and most of us have observed them in the process of growing. Anyone who has stood by a misted window on a chilly evening and watched the frost feathers spread their delicate fronds over the pane has seen crystals of a mineral growing in their natural environment; for ice is, by the most rigorous definition, a mineral, and the frost feathers are truly crystals. The water droplets, free a moment before to pursue with perfect mobility a winding course across the pane, are locked in an instant into the geometrical rigidity of the spreading crystalline pattern. It is as though each tiny particle of water knew instinctively where to attach itself to preserve the symmetry of the growing crystal. If now a small fragment of the frost crystal is detached and placed in front of a photographic plate in the path of a beam of x-raye, a symmetrical pattern of spots characteristic of crystalline solids **will** appear on the plate. A drop of the liquid water from the same window pane so exposed will show no such pattern, indicating the absence in

it of the orderly arrangement of the component particles.

Examination of a frost feather detached from the window pane is rather disappointing, because we find that the restriction imposed by the flat surface and the mutual interference of the numerous rapidly growing crystals have so malformed the individual crystals that we can make out little about their symmetry. However, if this process of the crystallization of water vapor takes place high in the atmosphere where individual crystals are free to grow without mutual interference, there result the delicately beautiful and perfectly symmetrical snow crystals familiar to all. (See cover). Study of these snow crystals, which generally take the form of six-rayed stars, often elaborately ornamented, or thin six-sided plates, reveals that among other elements of symmetry all possess 6-fold symmetry about an axis perpendicular to their flattening. Furthermore, some, particularly the thin, six-sided plates, display perfectly smooth, shining faces in constant geometric relation to each other. Thus, the flattened faces are rigorously parallel to each other, and the angles between the narrow faces making the six edges of the plates are exactly 120° on all crystals on which they appear.

When it was discovered that the arrangement of the faces on a crystallized mineral and the angles between them were characteristic of a given mineral, their study became an important part of mineralogy. The study of crystals, which had its beginning in the study of well-crystallized minerals (see Figs. 1..4), has itself today developed into a major science. Thus crystallography has become a tool of physicists, chemists, metallurgists, ceramists, and biologists, and each year finds additional applications in other fields. It should be made clear that crystals are not necessarily a product of nature but can be grown in the laboratory by many different means. Such crystals, however, are not minerals.

Physical Mineralogy

The mineralogist is being constantly called upon to identify minerals, and to this end he must bring to bear all the various means that he has at his disposal. If a mineral is well crystallized, the skilled mineralogist may be able to identify it by



*Smoky quartz (black) and microcline feldspar (green)
Pikes Peak, Colorado*



*Fluorite coated with quartz
Northumberland, England*



*Calcite coated with hematite
Cumberland, England*



*Rhodochrosite (pink) with quartz
Alma, Colorado*

inspection or by the careful measurement of the crystal angles. However, such specimens are the exception, and most minerals are found in imperfect crystals or irregular grains or aggregates.

To determine such minerals one must necessarily rely on other characters. The most important of these are the physical properties. The color and luster can be observed at a glance. By a closer inspection one can tell whether the mineral is transparent or opaque and whether it has the smooth, easy fracture, called cleavage, or a rough, irregular fracture. The touch is characteristic of such soft minerals as talc and graphite, which feel greasy, and the taste is diagnostic for a few of the water-soluble minerals. By lifting a mineral specimen one may recognize at once that it is light or heavy as compared with familiar substances of similar appearance and thus gain a rough idea of its specific gravity. And, finally, one can determine the hardness by touching the smooth surface of a mineral with the knife blade. These are all physical properties, and frequently they so uniquely characterize a mineral that they suffice for its identification.

Color. For a few minerals the color is so characteristic that it alone serves for identification, and the beginning student is quick to recognize the green of malachite, the azure blue of azurite, the pink of rhodochrosite (Fig. 4), and the brass yellow of pyrite. In other minerals, however, the color varies from specimen to specimen, and the student must learn those minerals for which color is a distinguishing criterion. For example, the black quartz and greenfeldspar in Fig. 1 are not characteristic colors except at certain localities. On the other hand, the pink color is always characteristic of rhodochrosite (Fig. 4). In Fig. 3 colorless calcite is coated with fine-grained hematite. The red color is diagnostic of hematite but the calcite could be any color. The mineral in Fig. 2 is fluorite which, like calcite, can be any color.

Cleavage. Although the exterior of a mineral may be rough and irregular, the interior will have the regular, ordered arrangement of atoms characteristic of its crystal structure. The atomic arrangement may permit some miner-

als to break easily along one or more smooth plane surfaces. The presence or absence of this property known as cleavage is frequently an important aid in mineral identification.

Hardness. The forces acting to hold the atoms of minerals together vary greatly from mineral to mineral. If these forces are strong, only with difficulty can one force the atoms apart by pressing on the surface with a needle point or knife blade, and the mineral is said to be hard. If the bonding forces are weak, the knife blade can easily be pressed into the mineral to scratch the surface. The difference in hardness exhibited by different minerals is easily determined in a qualitative way and can frequently be used as a determining criterion in mineral identification. For example, the minerals apatite and beryl, both found in similar-appearing six-sided crystals, can easily be distinguished on the basis of hardness. Apatite can be readily scratched by the knife blade, whereas beryl is much harder and cannot be scratched.

Specific Gravity. The specific gravity of a mineral is its weight per unit volume referred to water as 1. It is particularly helpful in identification of fine crystals or gem stones that one does not wish to mar in any way, for the determination involves merely weighing the specimen in air and again in water.

In general, specific gravity is dependent upon two factors, (1) the kind of atoms present, and (2) the packing of the atoms. Lead is a heavy element, and, consequently, those minerals that contain lead will have a high specific gravity. On the other hand, aluminum is comparatively light, and we can expect aluminum minerals in general to have a relatively low specific gravity. However, two minerals made up of the same elements in the same proportions may have different specific gravities, for in some minerals the atoms are packed tightly together, in others they are more loosely packed and a given number occupy a greater volume.

Chemical Mineralogy

It has been pointed out that minerals are chemical elements or compounds that have ordered internal atomic arrangements which give rise to certain crystallographic and

physical properties. However, these properties may not be sufficient to determine the mineral. For such specimens it is necessary to make chemical tests to identify the constituent elements of the mineral. Ordinary chemical procedure is often laborious, and the mineralogists have developed short cuts with the use of the blowpipe. Consequently, much of the chemical work of the beginning student is carried on with this useful tool. However, it is impossible to obtain satisfactory tests for all the elements with the blowpipe, and recourse must often be made to the chemist's test tube.

The chemical tests made by the beginning student are qualitative; that is, he merely determines the presence of an element without regard to the amount. If all other tests fail, or if a new mineral is being described, it is necessary to have a quantitative chemical analysis in which the percentages of the constituent elements are determined. Such analyses are extremely important in mineralogy, for by means of them formulas can be written expressing the chemical composition, and it is largely upon chemical composition that the classification of minerals rests.

APPLICATIONS OF MINERALOGY

There are several branches of mineralogy. We can think of the petrographer as a mineralogist specializing in the rock-forming minerals, and it is through him that the major contributions in this group of minerals has been made. The economic geologist is likewise a specialized mineralogist concentrating in the ore minerals. His techniques in polishing and studying the opaque ore minerals not only have given mineralogists a valuable tool for mineral study but also have contributed to our knowledge of the occurrence, association, and origin of minerals. Although crystallography is becoming a science in its own right, most of the present-day crystallographers had the introduction to their science as part of a mineralogical training. In their specialized crystallographic studies, they are contributing valuable information about minerals.

The mineralogist per se cuts across the boundaries

limiting the petrographer, the economic geologist, and the crystallographer, and has the whole field of mineralogy for his domain. He studies all minerals with whatever tools he has at his disposal and thus may make frequent excursions into petrography, economic geology, and crystallography.

What does a professional mineralogist do? What are the various properties that he determines in studying minerals that the elementary student does not learn in his beginning course? In working out the mineralogy of a new deposit, the mineralogist should first have an understanding of the geologic setting in which the minerals were found, for without this knowledge it is impossible to speculate intelligently regarding the origin.

Each mineral must be identified by whatever means lends itself best. Some may be determined by inspection, through recognition of crystal form, color, cleavage, etc.; others may require a hardness test or a specific gravity determination; whereas still others yield their identity only through chemical tests or through the measurement of the optical constants by means of the polarizing microscope. If the optical properties fail to identify a mineral, the next step is to take an x-ray powder picture. Since the intensity and positions of the lines on the film are characteristic for each crystalline substance, the mineral may be identified by comparing its x-ray photograph with known standards. X-ray photographs are as characteristic of crystalline substances as finger prints are of human beings.

Occasionally a mineral is encountered that defies identification, for it has never been described before; it is a new mineral. Such minerals require a complete mineralogical study and description. A quantitative chemical analysis must be made, from which a formula can be written expressing the composition.

If the new mineral is in crystals, a morphological study should be made; that is, the angles between the crystal faces should be measured on a goniometer, axial ratios calculated, and crystal drawings made. X-ray pictures of single crystals should be taken, from which can be calculated the dimensions of the unit cell and the space group.

The optical constants must be determined as well as the other physical properties of hardness, specific gravity, color and luster. When all these data have been carefully measured and presented in a unified mineral description, they characterize the species so completely that another worker encountering the same substance cannot fail to recognize it. In the past, incomplete mineral descriptions have many times caused confusion. New names have frequently been given to minerals previously described and named but so poorly characterized that the new worker failed to recognize the earlier description as referring to his presumably new mineral.

The methods of the mineralogist are used every day to solve practical problems, and a person with mineralogical training finds many outlets for his talents outside of the field of pure mineralogy. The methods are applied successfully in many industries where the materials studied are not minerals but synthetic products. For example, in the manufacture of abrasives, ceramics, refractories, synthetic crystals, and steel, mineralogical techniques have contributed much, and many of the manufacturers of these products employ full time mineralogists on their staffs.

Mineralogy in mining has already been mentioned, and it is an everyday tool with the mining geologist. Likewise the prospector should be a student of mineralogy, for otherwise he can be led sadly astray. This is illustrated in the early history of Climax, Colorado.

Since 1913 the mines at Climax have produced a high percentage of the world's supply of molybdenum mined as the sulfide, molybdenite. Molybdenum is used chiefly as an alloy to give greater strength and toughness to steel. Molybdenite is a black, soft, platy mineral and for 2000 years has been confused with galena (the sulfide of lead) and graphite; both of which are soft, black minerals. In 1890 mineral claims were staked on Bartlett Mountain at Climax, because of the presence of a black mineral which was thought to be galena. Galena frequently carries silver, so the prospectors thought their ore might yield both silver and lead. Some of the "galena" was sent to an assayer for analysis, but was deter-

mined to be a poor grade of graphite! As a result the prospectors dropped the claims. It was not until five years later that the mineral was correctly identified as molybdenite. Had the mineral been identified correctly at first, the ownership of the great mines at Climax would be different today.

The tests necessary to differentiate these minerals are simple, and the elementary student should perform them unerringly. Because of more general mineralogical training, it is safe to say the mistake would not be made today. Galena can be told by its high specific gravity and three cleavages at right angles to each other. Molybdenite and graphite are both platy minerals but can be easily distinguished by specific gravity and "streak". There are also several good blowpipe tests for molybdenite, whereas graphite is quite inert before the blowpipe.

In addition to learning the various properties of the different minerals, the student should also become familiar with certain mineral associations which are so characteristic that they may be as important in identification as color, cleavage, or hardness. For example, the most common minerals at Franklin, New Jersey, are black franklinite, greenish willemitite, and red zincite in white calcite. This combination is so characteristic of Franklin that one can recognize all four minerals immediately. In a similar manner specimens from the tri-state district of Missouri, Kansas, and Oklahoma can be recognized by the association of galena, sphalerite, calcite, dolomite, and chalcopyrite. Certain combinations of minerals are found at many localities, and the presence of one leads the mineralogist to suspect the presence of the other, as galena and sphalerite, realgar and orpiment, cinnabar and opal, pyrite and chalcopyrite, platinum and chromite, and pyrrhotite and pentlandite.

It has been through the association of minerals that the true nature of many important mineral deposits has been recognized. An excellent example is given by the deposit of emery at Chester, Massachusetts.

Emery, a mixture of two minerals, corundum and magnetite, has for centuries been used as an abrasive. It was early mined on islands in the Grecian archipelago and on the

mainland of Turkey. In 1846 the Turkish government employed J. Lawrence Smith to study their deposits, and his report, including the mineralogy, was published in 1850 in the American Journal of Science.

In 1860 Dr. H. S. Lucas discovered at Chester, Massachusetts a vein of black magnetic material which he believed to be magnetite. Magnetite, magnetic iron ore, was a well-known mineral and at that time was being mined at several places in eastern United States. Attempts to smelt the Chester material as an iron ore met with failure; it did not react in the furnace as iron ore should. Accordingly, Charles T. Jackson, the State Geologist of Massachusetts, was consulted. His examination of the property showed that the "iron ore" was associated with chlorite, margarite, diaspore, and chloritoid. These minerals in themselves meant little to him until he recalled that the exact association had been reported by J. Lawrence Smith in his paper on the Turkish emery. Thus, by association, Jackson identified the "iron ore" as emery, and, as a result, an abrasive industry sprang up in the small town of Chester, Massachusetts. Although the Chester emery was mined out long ago, the manufacture of abrasive materials persists there to the present day. In 1860 emery was considered a distinct mineral species, and not until some time later was it discovered to be a mixture of magnetite and corundum.

The mineralogist is frequently consulted on unusual problems where his special knowledge is useful. An interesting problem was presented during World War II to Dr. Clarence S. Ross of the United States Geological Survey.

Beginning on November 1, 1944, and continuing for a period of six months the Japanese set loose 9000 balloons destined for the shores of Canada and the United States. They were designed to travel in the upper atmosphere where the high velocity of the air currents would drive them rapidly eastward. The incendiaries that they carried would be a serious menace to the forests of the northwest during the dry summer months. It was, therefore, highly important that steps be taken to locate the launching sites so that continued release of the balloons could be prevented.

Each balloon carried about thirty 6-pound sand bags which were dropped successively when the balloons fell below an altitude of 30,000 feet. It was the sand recovered from one of the balloons that was given to Dr. Ross for analysis. By means of optical and physical properties, he was able to identify each of the constituent minerals, and with heavy liquids and other techniques each mineral was separated from the others and its percentage determined as shown in the accompanying table.

Composition of Ballast Sands of Japanese Balloons"

<u>Mineral</u>	<u>Per Cent</u>	<u>Mineral</u>	<u>Per Cent</u>
Hypersthene	52	Magnetite	10
Augite	7	Quartz	16
Hornblende	8	Plagioclase	
		feldspar	6
Garnet	1	Zircon	1

Sphene, biotite, and volcanic glass were also present in small amount.

By knowing the geology of Japan, it was determined that there were only five possible places from which sand of this mineral composition could have come. To quote General Wilbur.**

"The Air Force was asked to check activity at those places. Shortly we had a report, with pictures, of one of the sites. The photos showed a manufacturing plant and outside it several pearlgray spheres, apparently gas bags being inflated for the flight to America!" Truly, mineralogy has served in a direct military way.

* Clarence S. Ross, "The Dark-Field Stereoscopic Microscope for Mineralogic Studies," Am. Mineral., 35, 1950.

**W. H. Wilber, Reader's Digest, August 1950.