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MINERALOGY'S CONTRIBUTION TO OTHER SCIENCES AND TO INDUSTRY*

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If, as Wentworth suggests, the position of geology among the sciences is an anomalous one, that of mineralogy is much more so. If geology is "a sort of peripatetic relative of the fundamental sciences, going the rounds of more respectable abodes," mineralogy may be looked upon as a more dependent relative characterized by a very little individuality. Geology may indeed be regarded as a daughter of physics and chemistry and a stepdaughter of zoology, inheriting many of its habits and methods of thought from its nearest relatives, but it possesses marked individual traits due to its travels abroad—away from the abodes of its family group.

Mineralogy, on the other hand, is mainly a laboratory science, and though perhaps more dependent upon chemistry and physics for its methods of action than is geology, it nevertheless possesses some individuality, which although less noticeable than that of geology, has led to results that have earned for itself an honored place in the family of sciences, in that it has contributed to the family points of view and methods of thought that have well repaid its relatives for the aid received from them.

Mineralogy can claim no methods of work or even conceptions that are distinctly its own, but neither can physics, chemistry nor zoology, except in small measure. The border lines between these sciences are very shadowy and are becoming less and less sharp as our knowledge of their fundamental conceptions becomes better known. Chemistry and zoology have borrowed from physics in order to explain some of their phenomena, and physics in turn has borrowed largely from chemistry, especially in the field of molecular philosophy. There are, however, certain fields of thought that are characteristically physical and others that are characteristically chemical, that are enough different from one another to be individualistic. Mineralogy, perhaps, depends more upon physics and chemistry for the tools with which it solves its problems, than do these

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sciences upon each other or upon mineralogy, but mineralogy has developed one phase of thought that is as distinctive for it, as have both physics and chemistry. For instance, crystallography was developed as the result of the study of minerals. It has shared this field with physics and chemistry to such an extent that one is apt to forget that mineralogy was responsible for its development.

Mineralogy is often considered as a branch of geology because it deals with the materials that make up such a large portion of the Earth's crust. But zoology and botany also contribute largely to the mass of materials composing the crust and have been active in producing a great part of the rocks of which it is made.

Of the two sciences geology and mineralogy, the latter is to be regarded, perhaps as the older. At any rate minerals were recognized as objects to be studied, earlier than was the crust of the Earth, and the name was certainly used before the name "geology," although F. D. Adams¹ has discovered that the word "geologia" was used by D. Aldrovandus in the title of one of his unpublished manuscripts listed in his will, written in 1605.

Because of their use as the sources of metals and as decorative materials, minerals have attracted the attention of mankind from the earliest time. Their early study, however, consisted merely of their description in general terms, so that other specimens might be identified in turn, and all classifications were based on superficial appearances. Later they were studied as chemical compounds, and it was not until attention was directed toward their forms that mineralogy became differentiated from the other sciences. So far as known, the first description of minerals was given by Theophrastus in about the year 315 B.C. The first known systematic treatment of them was by Albertus Magnus in his "De Mineralibus," written in the year 1262. In the 16th century Georgius Agricola published his book on the minerals of importance in mining; K. Gesner, in 1565, his systematic treatise on minerals; and Boethius de Boodt, in 1609, his volume on precious stones. The beginning of the study of crystal optics is marked by the researches of Erasmus Bartholinus on Iceland spar in 1669. The relation of chemistry to mineralogy was recognized by Wallerious in 1747 and by Cronstedt in 1758, but this relationship was not fully appreciated until some time later.

It was, however, not until after the publication of Rome de l'Isle's "Essai de Cristallographie" in 1772, in which he showed that the forms of crystals are characteristic of the substances that exhibit them, and the appearance in 1784 of Abbé Haüy's essay on the structure of crys-

¹ Adams, F. D., Further note in the earliest use of the word geology: *Bull. Geol. Soc. Am.*, vol. 44, pp. 821-826.

tals, which laid the groundwork for the development of the important laws of crystallography, that crystallized minerals became of great interest to chemists and geometers. It was then that modern mineralogy may be said to have been established as a distinct branch of study. With the invention of the reflecting goniometer by Wollaston in 1809, and his discovery of the laws of isomorphism and dimorphism, in 1819–21, and the discovery by Brewster, in 1818, of the close relation between the forms and the optical properties of crystals, the foundations of the science were stabilized. But as Browne² has well said "the boundaries of one science encroach upon the territories of others and it is in that fertile borderland where chemistry, physics, biology and other fields of knowledge overlap that the greatest discoveries are now being made." The worker in a given science, who, in his quest for truth, strays over into the field of another science is not stigmatized as an intruder, but is greeted rather as a welcome visitor.

Today I purpose to adventure into the provinces of scientists in other fields and with the help of a few illustrations call attention to the fact that mineralogy is largely a service science, contributing to other sciences and to industry, in return for some of the contributions received by it from them.

From the earliest days, as has been said, minerals have been gathered for their decorative value. Later they were sought as sources of metals and for other industrial purposes, and this search has been continued to the present day. Obviously it is unnecessary to dwell on the contributions made to the sciences and industry by the discovery of new minerals and by the study of the distribution of those of economic value, since the importance of these is generally recognized. It may be remarked, however, that in the course of this type of work, chemistry has been enriched by the discovery of tantalum by Hatchell in 1801, of palladium and rhodium in platinum by Wollaston in 1803 and 1804, of lithium in spodumene, petalite and other minerals by Arfvedson in 1817, and of thorium in thorite by Berzelius in 1825. Moreover, the attention of physicists has been called to the electrical and optical properties of tourmaline, Iceland spar and other minerals, and of geologists to the microscopic study of the mineral components of rocks and their alterations.

The discovery of the double refraction of Iceland spar was made by Bartholinus in 1669, of the electrification of tourmaline upon heating by Aepinus in 1762, and of the production of phosphorescence in flourspar and certain other minerals by Pott in 1755, and before him by Wall in

² Browne, C. A., *Science*, vol. 84, p. 4, 1936.

1708 and by Du Fay in 1735. Wilson, in 1762, knew that tourmaline became electrified by rubbing, with a positive and a negative pole, like glass and certain gems, and Aepinus, in 1776, together with Bergman had learned that the pole which was positively electrified with rising temperature became negatively electrified as the temperature fell. Huygens, in 1678, described the two rays transmitted by Iceland spar as being unlike and as possessing properties different from those of ordinary light, but it was not until 1808 that Malus recognized the light as being like that reflected from window glass, which he called polarized, and directed the attention of scientists to the peculiar properties of this kind of light by constructing an instrument consisting of plates of reflecting glass for producing it, and using a crystal of calcite, or a second reflecting glass surface, to detect it. This gave a new tool to mineralogists, but it was not used by them until a more convenient method of producing polarization than was afforded by Malus's reflecting surfaces was discovered.

Seebeck and Biot, in 1813 and 1814, discovered that tourmaline also is doubly refracting, after Cordier in 1809 had observed that one of its refracted rays is absorbed. This knowledge was taken advantage of by Seebeck and Biot in the construction of their tourmaline polariscope—the familiar tourmaline tongs. This instrument, however, gives a polarized ray that is strongly colored and, consequently, is unsatisfactory for many of the purposes for which a polariscope might be used. Nevertheless, it was employed to study the polarizing properties exhibited by other minerals, but because of the color and weakness of the transmitted light its use was limited, and among mineralogists in general it found little favor. Even after Nicol, in 1828, invented his calcite prism, no attention was paid to the possibility of using the completely polarized colorless ray it produced in the study of minerals for thirty years. It was not until Sorby, in 1858, published his paper "On the microscopic structure of crystals" that mineralogists became impressed with the idea that polarized light offered them a new and convenient means of investigating crystallized minerals.

Soon after the means of producing polarized light became available, Brewster discovered that fluorspar and halite, which are normally non-polarizing, become doubly refracting under pressure, after Seebeck, in 1813–1814, had learned that glass, after being heated and then cooled rapidly, also showed double refraction. This observation of Seebeck's led to the process of annealing glass by slow cooling.

About this time also Biot, in 1815, Herschel, in 1820, and Brewster, in the same year, studied the rotation produced in a ray of light passing through quartz in the direction of its vertical axis—a phenomenon which

Fresnel had already, in 1817, denominated circular polarization—and found that the rotation was to the right, or to the left, in accordance with the presence of right- or left-handed forms on the crystals. The phenomenon, when studied in more detail, suggested the construction of instruments for measuring the amount of rotation produced by other substances, the most familiar instrument being the saccharimeter used to determine the strength of sugar solutions for the purpose of fixing the tariff rate that should be charged on imported cargoes of raw sugar.

The Nicol prism soon supplanted all other instruments for producing polarized light, since it yielded a colorless ray, but it could cover only a small area because of the impossibility of securing large crystals of Iceland spar, except at an enormous price.

The demand for a means of diminishing the glare from the headlights of automobiles approaching each other, suggested to Mr. E. H. Land a few years ago that the result desired might be accomplished by polarizing the light leaving the headlights and cutting it out by an analyzer in the windshield of the approaching car, or by analyzing goggles worn by its driver. The Nicol prism was not suitable for this purpose because of its small size, its expense, and its clumsy shape. In order that the method might be practical it was necessary that the polarizing medium should be capable of covering large areas and that it be comparatively cheap. These requirements were met by the invention of the film, known as "polaroid." This consists of a sheet of cellulose acetate in which are imbedded millions of tiny, doubly refracting dichroic crystals of hercynite, or sulphate of iodoquinine. The compound forms orthorhombic plates flattened parallel to the brachypinacoid. Of its two refracted rays produced when light is incident on this plane, the ray that vibrates parallel to the orthopinacoid (100) is almost completely absorbed, while that vibrating parallel to the base (001) is transmitted with a very faint olive-green tinge, which in very small crystals is not noticeable, and which, of course, is polarized. When the polarizing axes of the small crystals are uniformly oriented, as they are in polaroid, they produce the effect of a single large crystal. This polarizing film possesses great advantages over other polarizers in that it is flexible, mechanically stable, and is resistant to moderately high temperatures. Moreover, it can be made of a size to polarize over a large area. Because of these characteristics, besides destroying the glare of automobile lamps, the film may become a valuable aid in industry by reducing the glare from the surfaces of materials being inspected for imperfections, by making it possible to detect strains in models made up of transparent substances, and by offering a means of presenting three dimensional motion pictures in color. The use of polar-

ized light has been employed for some of these purposes in scientific laboratories, but its use has heretofore been employed as a working tool in industrial establishments to only a slight extent.

Recently the use of polarized light has also been called into service in the study of the moon. For the past 300 years astronomers have busied themselves mapping the surface features of the moon until now no part of that portion of its surface visible to us has been unexplored. They have attempted to explain the origin of these features but have been unable to do so because ignorant of the exact nature of their materials. The problem of ascertaining their nature has been assigned to a committee of which Dr. F. E. Wright³ of the Geophysical Laboratory is chairman, in the expectation that if the composition of the moon's surface materials is discovered it may be possible to explain the origin of its physiographic features. Advantage is taken of the fact that the moon's face is made visible to us by reflected sunlight, and that the reflected light differs from direct sunlight in that it is partially polarized. By measuring the intensity of the light reflected from different areas, and its degree of polarization, it has been learned that, in general, the mountains and lighter areas of the moon reflect more light than is reflected from the smooth portions of its surface (the seas) and other dark areas, and that only about half as much is polarized. By measuring the amounts of plane polarization in light reflected by terrestrial materials and comparing the result with the polarization in the moon's reflected light, it is inferred with a strong degree of probability that the moon's material is like that of the light colored and porous substances occurring on the Earth, and that the probability is that it consists of acid volcanic ash and pumice. It is expected that with further detailed measurements of the nature of the light reflected from the moon it will be possible to ascertain with fair certainty what the lunar surface materials are, and how they are distributed on that part of the moon visible to us, and we then "shall be in a position to attack the problem of its physiography and the mode of formation of its surface features."

After Nicol's invention of the polarizing prism a means was at hand for obtaining polarized light by an instrument that could be applied to a microscope, and as a result the polarizing, or petrographic, microscope became available to students of minerals, though advantage was not taken of the aid that this instrument offered them until many years later. It is true that Ehrenberg in 1839 made use of the microscope in the study of chalk and tripolite, and in the examination of many other sedimentary rocks, and Brewster in 1824, and Nicol in 1828, had studied the fluid

³ Wright, F. E., The surface features of the moon: *Scientific Monthly*, vol. 40, pp. 101-115, Feb. 1935.

cavities in the quartz of rocks, but none of these students felt any necessity in their work for the aid of polarized light. Zirkel, in 1862, began to teach the new methods of studying rocks by the optical investigation of their component minerals, and petrography was founded as a daughter of mineralogy. The close relationship of petrography and mineralogy is recognized by our Society in the description of the contents of its official publication, so I need not hesitate to consider petrography merely as a phase of mineralogy, and give credit to the latter for any contributions to science that have been made through the former—in other words, to consider petrography as one subsidiary of the holding company, mineralogy, the others perhaps being crystallography and mineralography.

It is hardly necessary to refer to the very intimate relationship existing between petrography and petrology. The latter is undeniably a phase of geology, whereas the former is as definite a branch of mineralogy. Petrography is a descriptive science, dealing with the composition of the solid crust of the earth, petrology is a philosophical science dealing with the origin and relationships of the components of the solid crust. A thorough knowledge of the petrography of rock masses is necessary before a study of their petrology is possible. For instance as, Barth⁴ has remarked "without a knowledge of the mineral phases of metamorphic rocks it is impossible to discuss properly any theory of their origin or evolution." This is as true today as it has been in the past, and so far as we can see in the future it will always be necessary for petrography to help petrology in working out the laws governing the origin of rocks, and thus will always be intimately linked with geology through a gradation so uniform as to be with difficulty recognizable as a linkage.

The methods of petrography are based on the study of light transmitted through transparent crystallized bodies. But there are other bodies in rocks, and especially in those portions of rocks that function as ore deposits, which are opaque. These cannot be studied by transmitted light. They can, however, be viewed by reflected light, which as we have learned is always more or less polarized. Although engineers had been viewing through the microscope sections of steel and other metallic substances, in the study of their structure, especially with reference to the aggregation of their crystallized components, it was apparently Sorby who originated the method in his study of the structure of meteoric irons and described it to the British Association in 1864. Later mineralogists developed the methods and described the behavior of the ore-minerals when polished, etched and illuminated by reflected polarized light and thus laid the foundation for the study of the opaque minerals constitut-

⁴ Barth, T. F. W., Petrology and metamorphism of the Paleozoic rocks: *Bull. Geol. Soc. Am.*, vol. 47, p. 779, 1936.

ing the greater portion of ore bodies, which now must be recognized and the relations between which must be known before the most efficient methods of ore-dressing may be planned. Thus mineralogy has been an aid to the smelting and refining industry and indirectly to the miner. In "Mineral Trade Notes"⁵ we find the statement that "In ore-dressing the petrographical microscope is assuming an increasing important role because it furnishes the mineralogical composition of a given ore, the size, range, the structural characteristics and the degree of alteration of its components, and furnishes the technician with the information he needs to enable him to treat the ore with the maximum efficiency."

It is quite apparent to him who has followed the development of mineralography during the past 15 years, that economic geology could not have reached its present advanced stage had it not been for the enthusiastic work of mineralogically trained men on polished sections of ore-masses.

In the ceramic industry, also, the use of petrographic methods has been of great value in the examination of its products to discover imperfections with the purpose of remedying them, in the examination of raw materials with the view of selecting those substances of sufficient purity for the purposes desired, and in the study of reactions occurring between solids at high temperatures.

On the theoretical sides, the contributions of the workers in mineralogy, more particularly those of the Geophysical Laboratory in Washington, have been of inestimable importance in the understanding of the equilibrium conditions of the silica minerals, especially with reference to the manufacture of siliceous refractories, in the study of the effect of impurities in the raw materials upon the properties of the products made from them, and in the study of the action of clays and glasses on refractories. Among other contributions may be mentioned the recognition of mullite as a synthetic product, distinct from sillimanite, from which it had not hitherto been distinguished, a knowledge of the reactions of kyanite and andalusite at high temperatures which made possible their use in the manufacture of refractories and spark-plugs, and the suggestion that a mixture of forsterite and magnesite might be used for the making of basic brick for furnace linings.

Moreover, the study of the clay minerals by the aid of the microscope and *x*-rays, and the changes occurring in clays during firing, have done much to increase the understanding of those materials and to replace some of the old rule-of-thumb methods in the industry by scientific ones. It has been shown that clays composed of montmorillonite or beidellite

⁵ *Mineral Trade Notes*, May 20, 1936, p. 34.

possess the best bonding properties for making synthetic molding sand, and that muscovite and talc are far superior to quartz and calcite for the coating of asphalt fillers, and thus have pointed the way to improve the quality of these products. It has been shown also that clays composed essentially of montmorillonite and beidellite exhibit to a high degree the ability to decolorize oils, and thus make it no longer necessary to use Fuller's earth for this purpose.

It has also been proven recently that the influence of acids and alkalis on the properties of clays is an effect due to base-exchange, the capacity for which rests in the clay mineral constituents and that different constituents have different base-exchange capacities. Heretofore it has been recognized that acids and alkalis influenced the properties of clays in different ways and to different extents, but the reasons therefore were not known.

Perhaps the greatest contribution to ceramics has been presented in the studies made by mineralogists and petrographers on the mineral composition of ceramic clays, and on the relation of mineral composition to ceramic properties, thus leading to a better understanding than formerly, of the factors controlling these properties. This understanding is helpful in processing clays to higher quality products, in the search for new supplies of raw material, and in providing a rapid method of predicting the ceramic properties of a clay before actual ceramic tests are made upon it.

The work of the members of the Geophysical Laboratory have also contributed greatly to the understanding of the reactions that take place in the manufacture of cement clinker, and in the production of refractories and of the slags in metallurgical processes. The results obtained by Rankin⁶ and others in the study of the stability relations in the ternary system $\text{CaO}-\text{Al}_2\text{O}_3-\text{SiO}_2$ have done much to clarify our knowledge of the nature of cement clinker. It has been shown that the chief constituents of a satisfactory clinker are $2\text{CaO} \cdot \text{SiO}_2$, $3\text{CaO} \cdot \text{SiO}_2$ and $3\text{CaO} \cdot \text{Al}_2\text{O}_3$, and that any minor components (unless excessive in amount) that may be present in raw materials have little or no influence on the properties of the finished cement, except perhaps as diluters. With this knowledge at hand the manufacturer may select the material for the making of a cement that will meet the demands of the cement users with much more confidence than had hitherto been the case.

The inspection and comparison of the two ternary diagrams of calcium-iron and magnesium-iron silicates will show that when CaO is forced into ferrous iron silicates the melting temperature of the mixture

⁶ Rankin, G. A. and Wright, F. E., *Am. Jour. Sci.*, second series, vol. 39, Jan. 1915.

is reduced, and therefore iron furnace slags containing lime are liquid, whereas, if MgO is added an opposite effect is produced, resulting in a raising of the melting temperature and a more viscous slag. Thus, also, since magnesium-rich materials are resistant to the fluxing action of ferrous silicates, it follows that linings of magnesite, or periclase, in an open hearth steel furnace absorb a large quantity of iron from the metal bath and form with it a solid solution that resists high temperatures. Likewise, olivine can be used as refractory blocks in steel cupolas because it can absorb 25% of Fe_2SiO_4 and maintain a high melting point.

Some of the facts just related have been known to cement makers and metallurgists for a long while, but only as the result of experience. The reasons for them were not appreciated. It is no longer necessary to have the identical raw materials as were formerly used to produce a given product, since the engineer, knowing what happens in his oven or his furnace, is now able, within recognized limits, to adapt his processes to the nature of the raw materials he is able to secure and reach as good results, or even better, than did his predecessors with their traditional methods.

The consideration of base exchange referred to a moment ago, and so familiar to us in the operation of domestic water softeners, suggests that it may be the key to the explanation of the response of the soil to treatments for the purpose of making it more adaptable to plant growth, either by causing a change in its physical condition or by furnishing it plant food in which it may be deficient. For more than 50 years soil chemists have been studying the soil and have discovered many facts of interest concerning it. But in order to explain its character they have been compelled to make certain assumptions as to the nature of its components which latterly mineralogists working with the petrographic microscope and x -rays have shown to be untenable. Among these were the assumptions that kaolinite is the dominant component of its clayey portion, that zeolites are abundant in it, and that it contains colloidal material which was thought to be a mixture of amorphous aluminous and other hydroxides, and silica. It is now known through the work of several investigators, notably Ross, Hendricks, Fry, Grim, Kerr and others in this country, that the colloidal materials that are most effectual in base exchange are the micaceous-like minerals of the montmorillonite and beidellite series, and not zeolites, kaolinite, or the indefinite colloidal complex which had been regarded as one of the most active components of soils. These minerals (montmorillonite and beidellite) adsorb the plant foods and retain them in forms which can be utilized by plants, and by the exchange of calcium and magnesium for sodium in sticky soils render these more amenable to cultivation. Base exchange has now been

established on a mineralogical basis and the process cannot be studied except in relation to mineralogy, and in order to understand the cause of soil variations it becomes necessary to understand the mineral composition of soil colloids.

It may seem a far cry from petrography to archaeology but during the past decade, the methods employed in the study of rocks have been used to help archaeological students solve some of their special problems. For instance, they had assumed that since the material of the jade ornaments so widely distributed over the central portions of North America resembles so closely that from which were made the abundant ornaments so valued in China, Burma and other central Asiatic countries, that it must have originated in Asia, and that its existence in large quantity in Central America must be evidence that commercial connections existed between the Eastern Continent and this portion of the Western Continent, and that there was probably migration of peoples between them. Washington,⁷ however, after a careful study of a series of jade ornaments from Mexico concluded that the jade from which they are made "differs from the usual jadeite of Burma and other sources of Chinese jade in two important particulars: the constant presence of large or considerable amounts of diopside with the jadeite in the pyroxene; and the presence of much albite in most of the series, either wholly in solid solution in the pyroxene, or partly so and in part separately crystallized." He suggests that the American jade shows such well marked general and serial characters as to be deserving of a special name and proposes "mayaite" to distinguish it from the more widely known Burman jade, the jades which contain little or no diopside or feldspar. "Purely jadeite jade," he states, "seems to be unknown from, or at least is of very rare occurrence in Middle America," and the conclusion is warranted that "the material of the Central American and Mexican 'jade' objects is of American and not Asian provenance." Although no American locality is yet known where mayaite occurs in situ he believes that it came "from either Mexico or Central America and that there are probably two centers of supply, both near the west (Pacific) coast, one probably in Oaxaca or Guerrero, and the other in Guatemala."

If this conclusion is correct there is no evidence that there was necessarily any commercial intercourse between Middle America and Asia at the time the jade ornaments were made.

Moreover, there is now being studied by petrographic methods the nature of the materials employed in the manufacture of ancient pottery, especially in the southwestern part of the United States, under the super-

⁷ Washington, H. S., The jades of Middle America: *Proc. Nat. Acad. of Sciences*, vol. 8, No. 11, pp. 319-326, Nov. 1922.

vision of Dr. A. V. Kidder and Miss A. O. Shepard⁸ in the Laboratory of Anthropology at Sante Fé, New Mexico, which promises to throw important light on the intercourse between pre-historic peoples in this district. Pottery is recognized as one of the most important sources of evidence for cultures antedating written records. It has been used to trace not only the migration of ancient peoples, but also to chart the paths followed by commercial intercourse. Heretofore, archeologists have depended mainly upon stylistic features to guide them to their conclusions. Recently, however, it has been suspected that further information might be gained by a study of the method of manufacture of the pottery found at different sites, which would lead to more definite results than could be obtained by stylistic studies alone. It was realized that if the nature of the raw materials used by the primitive potter could be discovered they might furnish better clues to the origin of the finished product than its shape, color, design, etc., because these features are known, in some cases, to be constant over widely spread areas. Examination by petrographic methods of thin sections and the powder of Pueblo and Mayan pottery fragments, and of the glazes used on them, has brought out the importance of the method as a means of determining the volume of trade between villages and centers of manufacture, where there is a diversity of geological formations within the areas concerned, and by comparing the results of the examination of pottery fragments from successive stratigraphic horizons within a given area or in a rubbish heap, has led to the dating of the relative time at which a given type of ware may have been introduced into a region, and to a knowledge of the development of pottery making as an industry.

Perhaps the most valuable contribution made to chemistry and physics in large part by mineralogists, aided however by chemists, mathematicians and physicists, has to do with the structure of crystals. Haüy, as the result of his early work, was led to suggest that crystals may consist of minute particles, having the form of the cleavage fragments of the minerals concerned, packed together in a regular manner to make up their crystal shapes. Later, when the conception of atoms and molecules had been established by the chemists, the molecule was substituted for Haüy's cleavage particles, and the crystal was imagined as made up of molecules equidistantly distributed along parallel lines in a net-like structure—or a space lattice—which may be pictured as consisting of three sets of parallel planes enclosing parallelepipeds, at the corners of which are placed the constituent molecules of the crystal. In

⁸ Kidder, A. V., and Shephard, A. O., *Pottery of Pecos*, Vol. II, pp. 21-24, Yale Univ. Press, New Haven, Conn., 1936.

1850 Bravais showed that if this conception is accepted space can be partitioned into 14 space lattices—and Sohncke, in 1879, substituted “points,” or the centers of gravity of the molecules for the molecules themselves, and proved that all of the 65 point systems developed by him might be derived from the 14 space lattices of Bravais, by interpenetrating any one space lattice with one or more identical lattices, and proposed a definition of a crystal which is still acceptable to all crystallographers. After the discovery of the Röntgen rays, v. Laue in 1912, found, as was to have been expected, that crystals of rock salt acted as gratings reflecting the rays from atoms, rather than from molecules in such a way as to interfere and give rise to the now well known Laue diffraction patterns of space lattices. Then followed the x -ray spectra developed by the methods of W. L. Bragg—a discovery which, according to Klockman, resulted in the greatest advance made in physics and mineralogy since the beginning of the present century.

The experiments of Laue and Bragg furnished a means for the examination of a solid substance, the structure of which, hitherto, could be inferred only from certain facts of crystallography and certain phenomena that are dependent upon its surface skin reactions. It was soon learned that the structure of the solid (crystalline) body is due to the arrangement of its atoms relative to one another, and only indirectly to the arrangement of the atoms in molecules, or of the molecules with respect to each other. The results of the study indicated that the structural unit in most crystalline (solid) bodies is the cell, and not the molecule, as conceived from the study of gases and liquids, although it is possible that in some crystals, as in diamond according to Sir Wm. Bragg, the cell and the molecule may be coextensive, and in some others the cell may contain groups of molecules, comparable with those in gases and liquids, but which are much less strongly held together than are the atoms in the molecules.

The chemist has long recognized that the molecule possesses structure and that substances which consist of the same number of the same kinds of atoms but differ in their properties do so because of the different arrangement of these atoms in the molecule, and he has expressed their difference in his structural formulas. But the molecule is three-dimensional and the formulas have indicated the atomic arrangement in two dimensions only. The study of molecules in solutions can give no hint as to the arrangement of their atoms in the third dimension. It is necessary to get aid for the settlement of this problem from the study of the crystal cell.

The results of the study of crystals by x -ray methods has caused the abandonment of the old conception of the molecule as a particular group-

ing of atoms that is fixed for any one substance under all conditions, and the adoption of the new conception of the cell as the architectural unit of solid bodies. The molecule in the crystal is not always the same as when in a gas or liquid. "We even find some cases," says Sir William Bragg, "in which there is such a regrouping of the atoms that a new molecule may be said to have formed. There is always regularity in the arrangement within the crystal; but it is not strictly correct to say that it is an arrangement of the molecules unless the chemist will allow that his molecules can be altered." The conception of the cell in the architecture of solid bodies is an addition to the chemist's tools, which enables him to understand the way in which solids are constructed much more clearly than had hitherto been possible.

Another contribution of importance to chemistry is due directly to the discovery by N. Fuchs in 1815 that in the mineral gehlenite, which is essentially a calcium aluminum silicate ($3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$), there is always more or less ferrous oxide, and that the greater the amount of iron in the compound the less is the amount of calcium in it, but that always the sum of the two is equivalent to the amount of either alone that would balance the silica and alumina present. In other words, he declared that the ferrous iron and the calcium, in this instance, constitute compounds with silica and alumina that crystallize essentially in the same forms, analogous to the potassium and ammonium phosphates and arsenates investigated by Mitscherlich in 1819 and called by him "isomorphous," and it was deduced from these observations that isomorphous compounds are capable of mixing in various proportions to form homogeneous crystals. In referring to the alums, later, Fuchs remarks that "sulphate of alumina forms, with ammonium, an alum just as well as with potash or with both these alkalies" and that "the potash can here be completely or partially replaced by ammonium or vice versa," and again in another statement he generalized to the effect that certain elements or groups of elements are capable of replacing partially, or entirely, other elements or groups of elements in compounds without introducing any considerable change in their crystalline forms. Constituents possessing this property were called "vicarious."

Not only did this discovery revolutionize the classification of minerals, but it also introduced the conception of the possibility of the replacement of one atom or group of atoms by an analogous atom or atomic group in crystalline mineral compounds without changing the plan of their atomic structure, and inferentially also in many other chemical compounds, a conception which is now universally recognized in the term "isomorphous mixtures."

Among the minor contributions of mineralogists to the chemists was the introduction to them by Cronstedt, in 1765, of the blowpipe and the establishment by Bořický, in 1877, of the microscope as analytical instruments. Although the blowpipe had been used in industry since very early days and its value in the detection of the more important components of mineral compounds had been recognized for some time in Sweden, it was not until Cronstedt's treatise had been translated into English by von Engeström, in 1770, that its importance to the analytical chemists was realized.

Similarly, before Bořický's time the microscope had been employed, in a minor way, in the testing of substances by the observation of the shapes of the grains of precipitates produced by their treatment with known reagents, but it was not until this worker systematized the methods used and applied them to the detection of the constituents of minerals that the practice was appreciated as a valuable means of recognizing the components in small quantities of substances. Behrens broadened the use of the process in 1894 and 1921, and in 1930-31 Chamot and Mason, in their great treatise, the "Handbook of Chemical Microscopy," refined it and secured for it the serious attention of chemists. It may be true that the chemists pay more attention to the color reactions of the substances being tested than do the mineralogists who depend more upon crystallized precipitates produced; nevertheless, the process must be regarded as having been developed originally by students of minerals.

In addition to the aid furnished to physics in the understanding of the structure of crystallized bodies it has been the good fortune of mineralogy, also through crystallography, to help, in some measure, in the perfection of electrical devices.

Haüy, in 1801, discovered that some minerals will conduct electricity and that others will not, and so divided them into two groups, conductors and insulators, and Ritter, in 1802, and Wartman, in 1853, found upon experimentation that monoclinic crystals in general are non-conductors. Muscovite was indicated as one of the non-conductors. Because of its ready cleavage into thin plates, its resistance to heat and the ease with which its sheets can be cut and punched, muscovite and to a less extent the amber mica, phlogopite, were found to be well adapted to serve as insulators. Great quantities of the two minerals are now required for the production of electric lamps and for the construction of electrical appliances that have become necessary to modern industry.

Further, when a non-conducting crystal with polar axes of symmetry (and a few others) is subjected to changes of temperature a charge of electricity will be developed on its surface, which, with rising tempera-

ture will be positive at one end of the polar axis and negative at the other, and with falling temperature will be reversed. Such crystals are said to be pyroelectric. The property was first discovered in tourmaline by Aepinus and Wilson independently in 1762, and was more precisely investigated by Bergman in 1766, though the phenomenon of electrification exhibited by minerals had been recognized 50 years earlier by other observers. Since, when a pyroelectric crystal changes its temperature it expands or contracts, it was natural to infer that the reverse might be true—that if compressed in the direction of a polar axis it might become charged with electricity in the same way as though it were being subjected to a falling temperature, and if, on the other hand, it were subjected to an electric charge it might change its shape. These inferences were found to be correct by P. and J. Curie and the facts were announced by them in 1880 and 1881.

The type of electric charge produced by compression is known as piezoelectric. It is exhibited by the same kinds of crystals that exhibit pyroelectricity, and the two phenomena are regarded as very closely related. Lippman, in 1881, indicated that we should expect electrification to alter the size and shape of such a crystal, and the Curies found this to be the case. By subjecting a thin plate of a pyroelectric crystal to a rapidly alternating electric field it is made to vibrate, i.e. to alternately expand and contract, and if the frequency of vibration of the current agrees with the natural frequency of vibration of the crystal plate the amplitude of the oscillation of the plate becomes relatively large. If, therefore, thin plates of quartz crystal are cut so that their broad faces are perpendicular to one of its polar axes, and these plates are subjected to alternate pulsating currents, they contract and expand alternately and so assume a rhythmic vibration which controls and forces into audio frequency the current transmitted to the radio receiving set.

Another characteristic of certain crystallized minerals, such, for instance, as galena and pyrite, is that when introduced into an electric current in contact with a metal they influence the current to flow much more easily in one direction between the surface of the crystal and the metallic contact than in the opposite direction. Thus when such a couplet of crystal and metallic contact is built into a wireless receiving set it causes "rectification" or the conversion of the type of alternating current in the radio receiving antenna into a pulsating unidirectional form that will cause a diaphragm to vibrate with a frequency which results in the production of sound waves. This property was made use of in wireless telegraphy and telephony and in the construction of early radio sets (crystal sets).

At present, however, the piezoelectric property of quartz plates is employed to control radio reception and force it into audio frequency, as has already been indicated.

In medicine the mineralogist has contributed very little in recent times. In the Middle Ages he offered a number of minerals to practitioners to cure various maladies, but with the exception of a very few they were of little value.

It will be recalled that the forerunners of modern chemists, the alchemists, up to the beginning of the 18th century, published accounts of the medicinal properties of metals and minerals. In the "Pharmacopeia Medico-Chymica" of Johann Schröder, for instance (1641), some minerals were listed as being dominated by the sun and, therefore, as having a good influence on humanity, others as being related to the moon and, therefore, being neutral in their influence, and others as being controlled by Saturn and, therefore, being inimical to mankind. Others were declared to be dominated by Mars or by Venus. To produce an effect on a patient a selected mineral was dissolved, distilled, decomposed or otherwise treated to produce a draught that was supposed to acquire the virtue of the mineral treated, which upon being swallowed it imparted to the patient. The hyacinth decoction for instance strengthened the heart, was a specific against convulsions, and when worn as an amulet it protected against the plague. The attempt to change the difficultly decomposable minerals into forms in which they could be prescribed to men led to experimentation and observation, and these processes to philosophizing, giving rise to the invention of theories, some of which influenced chemistry profoundly and initiated discussions which, when they were settled, had helped the science materially on its way to the construction of a firm foundation. Thus the remarkable J. J. Beeher, economist, adventurer in finance, alchemist, physician, etc., in 1669 issued his famous "Physica Subterranea" in which he discussed mineral bodies, classified them, investigated their properties and as a result declaimed against the Aristotelian philosophy, and gave an explanation of their constitution which was adopted later by G. E. Stahl (1660-1734) as a foundation for his phlogiston theory, which kept chemists busy discussing for a hundred years or more until it was disposed of by Lavoisier in 1783, thus clarifying chemical theory and giving a new and inspiring trend to the science.

Recently, however, in the study of the cause of silicosis the mineralogist has, by the study of the dust in certain manufacturing and mining industries, discovered that this dread disease is occasioned when the dust contains a considerable proportion of tiny quartz particles and in

this way has indicated the possibility of the prevention of the disease.

In another way medical practice has been indirectly helped through the study of the phosphorescence and fluorescence of minerals by mineralogists and physicists.

The property of phosphorescence in minerals had been detected by Pliny and later by Albertus Magnus, but the phenomenon attracted little attention until Cascariola, a cobbler and amateur alchemist, in 1602, discovered that barium sulphide became self luminous for a short time after exposure to light. Shortly thereafter, it was found that a number of other substances possessed this same property, and they were classed together as "phosphori", or light bringers, and the phenomenon became known as phosphorescence.

Fluorescence, which is closely allied to phosphorescence, differing from it principally in that the bodies exhibiting it emit their characteristic light only while under the influence of the exciting impulse, which may be light or some other form of radiant energy, was not observed until 1833 when Sir David Brewster described a phenomenon, which he called internal dispersion, in a solution of chlorophyl through which a ray of light was passed, and a little later announced that the same phenomenon had been observed also in flourspar and in certain other minerals. About 20 years later Sir G. G. Stokes named it fluorescence.

In recent years the list of minerals exhibiting fluorescence under various kinds of light has been greatly extended and the nature of the light emitted from them has become their most important diagnostic property. Thus, natural gems are easily distinguished from artificial gem substitutes.

Moreover, since fluorescence is excited by *x*-rays and by some of the rays emitted by radioactive substances, screens coated with fluorescing mineral powder are in common use for detecting these rays. The most familiar of these screens is the fluoroscope employed by physicians in the examination of the bones and the internal organs of their patients.

Reference has already been made to the use of polarized light in the study of the composition of the Moon's surface material. Another astronomical field in which petrographers have been active has to do with meteors, which have generally been regarded as "remnants of cosmic materials employed in the formation of worlds"—a conception that is seriously considered in Lockyer's well known volume "Meteoritic Hypothesis," though it was based on little authentic knowledge of these bodies. During the past quarter century meteorites have been studied more critically than hitherto with the aid of the petrographic microscope by Sorby, Daubrée, Tschermak, Cohen, Meunier, Doelter and others

abroad, and by Farrington and Merrill in this country. Merrill⁹ particularly examined many falls and as the result of his examination expressed views as to the origin of their structures and of their material, as we now find it. He concluded that their composition is not such as to indicate that the meteorites which have been described, consist of world-making materials like those of the earth, since the rocks of the earth are of a much more highly siliceous type than those of meteorites, unless the material of these represent an extreme phase of magmatic differentiation from a more acid magma, no trace of which has yet been found in any of our celestial visitors. He believed, however, that the structure of meteorites, and particularly the spacial relations existing between their metallic constituent and their siliceous ones, is such as to indicate that the former is not an original component but is later in origin than its siliceous neighbors, and that it was formed by the reduction of the ferrous chloride, lawrenceite, which occurs in varying, though small, proportions in nearly all meteorites, and which originally must have been present in many of them in large quantity. Their structure and the existence in them of ferrous chloride, which is common among volcanic products on the Earth, and the numerous rounded bodies known as chondrules led him to believe that meteorites are unmistakably volcanic products and can not represent an exploded planet or the residuals in the process of world-building.

While, perhaps, no satisfactory conclusion has been arrived at with respect to the origin of meteorites, the field has been cleared for a further attack on the problem and we have a better idea now than was formerly the case, as to the phenomenon to be explained.

Mention has already been made of the help given to geology through the use of the petrographic microscope in the study of the nature of rocks and their origin, and by the metallographic microscope in the study of ores. There are other ways also in which the cooperation of the mineralogist has been of benefit in the solution of the geologist's problems. For instance, through the identification of the heavy mineral series in different beds of sedimentary rocks, it has been possible in some cases to work out their relative stratigraphic positions, and in others to discover the sources of their components.

Moreover, there are certain minerals, especially those containing uranium and thorium, and other elements of large atomic weights that are constantly and continuously emitting radiations as a result of the spontaneous disintegration of their heavy elements into other elements

⁹ Merrill, Geo. P., Composition and structure of meteorites: *U. S. Nat. Museum, Bull.* 149, 1930.

of lower atomic weights, with the separation of helium, which is emitted as α rays. The resulting newly formed elements are themselves in turn radioactive, and successively undergo further disintegration with the ultimate formation in all cases of stable forms of lead that differ from ordinary lead in their atomic weights.

The study of the pleochroic halos surrounding radioactive particles embedded in biotite and other minerals indicates that the rate of disintegration of the most important radioactive minerals has been uniform since the earliest geologic time, and, consequently, that a determination of the quantity of the lead and helium accumulated in the disintegrating compounds will give us a measure of their age and of the time that has elapsed since the rocks in which they occur were formed.

It is true that the discovery of radioactivity was first announced by Becquerel, in 1896, and that its significance was developed later as the result of the investigation of numerous other physicists, nevertheless the application of the knowledge thus acquired to the determination of the ages of rocks has been made mainly by mineralogists and geologists with a mineralogical training, and thus may be justly regarded as aid given by mineralogy to the solution of the problem of determining not only the relative ages of rock formations, but as well in many cases their actual ages.¹⁰

Since, we are all familiar with the many ways in which mineralogy has come to the help of geology, especially through crystallography and petrography, it is unnecessary to follow this phase of our subject any farther. The two sciences are so closely interwoven along portions of their borders that it is almost impossible to delimit their fields.

In international politics mineralogy is also beginning to play a part. Since the World War it has been evident that the most fertile cause of strife between nations is the necessity of those nations that are over populated to seek either more land to which their surplus population may be sent to relieve the pressure on their resources, or to increase their resources and become more industrialized so that that portion of their surplus population which declines to emigrate may be kept busy and contented. The development of industries, however, depends very largely upon mineral resources. If these are not present in sufficient quantity to furnish a country the raw materials upon which a large portion of its industry must depend, it is thought necessary, in order that it may live, to seek these resources outside of its own boundaries. Germany, Italy and Japan furnish illustrations of countries which are restless because of their great lack of mineral resources within their own boundaries. In the

¹⁰ The age of the Earth: *Bull. Nat. Research Council*, No. 80. Washington, D. C. 1931.

past, so long as there were potential sources of minerals in districts that were not already controlled by powerful influences it was necessary only to send out expeditions and take possession of them. At present, however, this procedure is not so easy as there are few areas of potential mineral resources that are not under the watch of the great powers, since there is no country, as the World is now organized, self-sufficient in its mineral resources. According to Sampson¹¹ the United States controls 34.1% of the World's mineral resources and the British Empire 21.3%, and yet neither of these areas contains all the minerals necessary to satisfy its demands if it were completely blockaded.

In recent years economic geologists, whose training is largely mineralogical, have been studying closely the distribution of the present and the potential mineral resources of the World in the hope that such a study may result in economic readjustments that will remove the pressure which in the past has been an excuse for engaging in war.

Finally, mineralogists have suggested a new concept in philosophy through the proposal by Goldschmidt,¹² Palache and Peacock of a modification of the laws of crystallography which they call the law of complication, based on the two hypotheses, (1) that a crystal is a rigid system of like and similarly oriented particles, and (2) that every crystal face is a plane normal to a force of attraction exerted from the crystal's center. As a result of these forces, and in consequence of their different magnitudes a certain face predominates on each crystalized substance, its position being determined in accordance with the parallelogram of forces, and its node (the projection point of its face-normal in the gnomonic projection) is regarded, likewise, as the principal one for the crystal and is given the symbol 1, which serves as the unit from which other nodes are measured. It is assumed, however, that the entire magnitudes of the forces are not exerted to produce this resultant, but that these principal forces divide into aliquot parts, normally in halves, one half of each principal force acting to produce the resultant which determines the face with the node 1, and the remaining halves combining to give the resultant forces determining faces with nodes $\frac{1}{2}$ and 2. "Similarly the successive combinations of halves of the remainders of the principal forces with halves of the newly formed resultants give further resultants determining the positions of faces with the nodes $\frac{1}{3}$, $\frac{2}{3}$, $\frac{3}{2}$, and 3, besides the two limiting nodes 0 and ∞ . Thus the node symbols as given on opposite sides of the symbol 1 are reciprocals of one another. It is

¹¹ Sampson, E., Mineral commerce and international relations: *Jour. Franklin Inst.*, vol. 221, No. 1, January 1936.

¹² Peacock, M. A., *Am. Mineral.*, vol. 17, 1932, p. 317, and a criticism by Buerger, M. J., *Ibid.*, vol. 21, 1936, p. 702.

impracticable to discuss at this time the reasoning employed in establishing the law. It is enough to state that Goldschmidt has applied the conception to the relative vibration periods of the notes of a major scale in music, and on it is said to have built up an elaborate system of harmonic analysis. He has also applied it to the relative wave lengths of the most prominent Fraunhofer lines of the solar spectrum. The relative distances of the planets from the Sun also complies with the Law of Complication, provided the major and the minor planets are considered separately, as do also the distances of the satellites of Jupiter and of Uranus, measured from their mother planets. This relation led Goldschmidt to the theory that groups of cosmic bodies forming complication series were each generated in distinct epochs. He believed that the Law of Complication underlies other groups of natural appearances, and that that development of the manifold from the simple, by complication, is a universal process.