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PROSPECT OF MINERALOGY*

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On this occasion I might follow the usual course and devote most of this address to a review of recent developments in mineralogy, with emphasis on that part of the subject in which I have taken some part, and conclude with the hope that the good work may continue on similar lines. Such a course is suitable in the evolutionary periods of the development of a science when the extent of the field of study and its relations to adjoining fields appear to be well-defined and generally accepted; when the underlying theories of the subject have been consolidated into definite doctrine which no longer requires defense; when important discoveries are rare and observations lead mainly toward the refinement of existing knowledge; when methods of observation, description, classification, and interpretation are established and further effort results chiefly in the improvement of numerical detail, systems of notation, and style of presentation; when comprehensive treatises can be compiled with deliberation and prospect of completeness; and when, as a consequence, scientific output can be fairly predicted as the product of trained men and working hours.

But these lengthy periods of relatively placid scientific industry are occasionally interrupted by rude disturbances when the proper territory of a science and its boundaries with adjacent fields are subject to revision and dispute; when established theories are shaken by bold new hypotheses and speculations which are advanced on the one hand and rejected on the other; when every day brings new discoveries and there is no time for refined observations; when new instruments are devised, new notations are improvised, and good form and polished style give way to rougher and readier modes of presentation; when the author of a comprehensive work is bedevilled by current changes of viewpoint and notation and an unceasing flood of new results which tend to make the first part of such a work out-of-date before the last has been prepared; and when steady satisfaction with accumulating scientific achievement on established

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lines gives place to the occasional exhilaration of notable discoveries in the course of arduous efforts in new directions. In mineralogy we are at present in the midst of such a period of revolution, and at such a time the usual contented view of the past and cheerful look to the future will be of no great value. It will be more useful, I think, to attempt to survey the situation more widely, to try to assess the trend of the rapid new developments, and to endeavor to coordinate the new activities and results with the old in a logical sequence.

Before looking more closely at the present situation let us recall a former revolution in mineralogy which sprang from a single discovery in crystal physics, namely the double refraction of Iceland Spar and the use of this effect in the Nicol prism to make a polarizing microscope. At first, physicists developed the beautiful theory of crystal optics on the basis of the optical behaviour of natural crystals and crystal plates, providing for the first time a way of looking through a mineral and seeing, as it were "through a glass darkly," not the actual crystal structure but certainly effects which are intimately related to the architecture of the crystal. Soon the mineralogists adopted the theory and methods of optical crystallography as their own; the optical properties of all the non-opaque minerals were eventually determined and with the noteworthy development of the immersion method for the approximate determination of optical properties on microscopic fragments, the fruits of this important development were incorporated in a serviceable method for the identification of minerals. At the same time the polarizing microscope gave rise to the study of rocks in thin sections and ores in polished surfaces, leading to the development of petrography and ore microscopy.

When minerals are studied mainly in thin sections, or polished surfaces, or crushed fragments there is some danger of never learning to know them in their proper crystal forms; he who has seen feldspar, pyroxene, epidote, pyrite, pyrrhotite or magnetite only in sections or grains, is like one who has seen a salmon only in the can. In the end, of course, mineralogy was greatly enriched by the methods and results of crystal optics, and optical mineralogy and mineralography have become smoothly incorporated in regular mineralogical doctrine.

The latest revolution in mineralogical history, and I think without question the most profound, likewise originated with the discovery of a new physical effect obtained with a mineral crystal, namely the production of a regular diffraction pattern by the passage of a beam of x-rays through a crystal of zincblende on to a photographic plate. This time the new radiation fully illuminated the internal structure of the crystal. When suitable apparatus was devised and appropriate methods of measurement and mathematical treatment were worked out it was clear that the result was no less than the determination of the actual atomic arrangement within the crystal. In the development of this subject the late Sir William Bragg and his son, now Sir Lawrence Bragg, our distinguished Roebling Medallist, played the leading part; and for about two decades after the initial experiment in 1912 the analysis of structures of ever increasing complexity was carried out, mainly on minerals, by the Braggs, their students, and their followers. Some details of this work have just been given by Dr. Tunell and Sir Lawrence at the luncheon table.

Mineralogists as a body were slow to appreciate the full meaning of the new work; the symmetry notation used by the physicists was unfamiliar, their lists of lattice planes seemed strange, and the complex arrangements of spheres in space appeared to have little relation to the familiar properties of minerals. So strong was the classical conception of an axial cross within a crystal, rather than a crystal lattice, that it took years before it was generally recognized that a properly chosen axial cross is nothing but the edges of the properly chosen unit cell of the structural lattice. Similarly it took time to realize that a crystal face is but the limiting plane of a set of equidistant planes traversing the entire crystal and that the indices of a crystal face are most conveniently defined as the numbers of parts into which the corresponding set of planes cuts the edges of the lattice cell. Mineralogists have been slow, too, to admit that the lattice type and even the space-group can often be recognized and reliably predicted from the development of the crystal forms.

In the same way the belief in chemical composition in simple rational proportions has resulted in some reluctance to accept the often irrational numbers of atoms found in the unit cell by calculation from the chemical analysis, the cell volume, and the density. Isomorphous mutual substitution between atoms of equal valence had already been recognized, but such substitution between atoms of unequal valence, notably silicon and aluminium, irrational cell contents by defect or vacant equipoints, and the distinct leaning away from simple rational proportions in many metallic minerals, are only now gaining wide acceptance.

It is not surprising, therefore, that mineralogists have tended to treat the results of *x*-ray analysis as an appendix to classical mineralogy, rather as the treatment of space-lattices and space-groups used to be given as an appendix to classical crystallography. I think if we were to set out today to arrange the contents of a specific mineral description in the most logical way we would commence with the crystal structure, recognizing that the kinds and number of the atoms in the unit cell, the symmetry of their arrangement, and their particular positions and bonding must underlie and be capable of explaining all the remaining properties of the mineral crystal. Such an arrangement would I believe soon come to be accepted by mineralogists and it would also appeal to physicists, chemists, metallurgists, and others interested in natural crystalline materials.

In considering the progress of science we cannot overlook the fact that the research of today is being done by the university graduates of yesterday, and that much of this research is usually accomplished in the period of special energy and enthusiasm and relative freedom from burdensome duties that rarely extends more than a decade after graduation. In mineralogy the question therefore is: Who shall teach our selected students the art of x-ray analysis with its formidable recent development of vector and electron density maps and computing devices, and where shall they apply the art to the analysis of mineral structures?

In some mineralogical laboratories the determination of the symmetry, dimensions, and atomic content of the unit cell is already taught at the undergraduate level, and these first steps in x-ray analysis are regular procedure in mineralogical research. The preparation of standard x-ray powder patterns and the identification of minerals by means of such patterns, often on minute samples picked out of ore or rock sections, is also becoming standard practice. However, few teachers of mineralogy would be prepared to give a rigorous course on the physics of x-rays and x-ray diffraction by crystals, and the modern methods of x-ray analysis. The necessary basic instruction in these matters might be offered in a Physics Department or, in larger institutions, in a Department of Crystallography which would serve the needs of students of Physics, Chemistry, Mineralogy, Metallurgy, and Biochemistry, all of whom have direct interest in the subject.

The application of the art of x-ray analysis must clearly be done in mineralogical laboratories. Like the spectrograph and the microscope, x-ray diffraction equipment of the various useful kinds has its proper place in a mineralogical laboratory, and it is to be hoped that convenient devices for the measurement and calculation of the intensities of x-ray reflections may soon become more generally available. With these means the extension of x-ray analysis to such large groups of minerals as the sulfo-salts, the phosphates, and the arsenates offers a promising program of research for suitably prepared graduate students in years to come.

In emphasizing the fundamental nature of crystal structure in mineralogy and the propriety of applying structural methods to the whole field of mineralogy I would guard against using mineral crystals merely as grist for the roentgenographic mill. Rather would I urge the conservation of the classical methods of mineralogical study and the preservation of the great body of accurate information which has been obtained by the older methods. Today, already, the art of chemical analysis of minerals is almost forgotten. How many competent chemical analysts are there today who for love or money will expend the skill and care that is needed to obtain the chemical composition of a mineral of average complexity, using perhaps a tenth of a gram of material? Very few indeed. There is great need for example and guidance in this matter, and this would be better provided in the university than in a commercial laboratory. Again, the art of crystal measurement on the reflecting goniometer, projection, calculation, and drawing is still cultivated in only a few institutions, and the latest books on crystallography give but the meagrest sketch of this important aspect of mineralogical study. Today, I think, a morphological study should accompany every study of structure to throw further light on the absorbing problem of the relation of crystal form to crystal structure. And yet again, with the wide use of the immersion method in optical mineralogy giving results that are good to 1 or 2 units in the third decimal of refractive indices and 5 or 10 degrees in optic axial angle, the more exact methods of optical mineralogy using cut plates and wedges are almost forgotten. Typical exercises in these methods can be effectively introduced in undergraduate work. The preservation of the results of such neglected methods of research might best be done by specialists who could prepare concise accounts of the theory and practice of a particular method and a critical compilation of the results.

Finally, the reorientation of a science that results from a discovery of fundamental importance, is apt to be accompanied by some reconsideration of its relation to kindred sciences and the redefinition of its proper field as distinct from its common territory with the adjoining sciences. Particular aspects of mineralogy are of interest to chemists, crystallographers, geologists, miners, metallurgists, and others, who are usually concerned with the essential descriptive details of the commoner minerals and simple and effective means for identifying them. Mineralogists have a responsibility in this common territory that can be met by providing simplified mineralogies and determinative schemes which can be used without long study.

Within this common territory, however, remains the proper field of mineralogy in which, as always, the principal interest is in the recognition of all mineral species, the precise determination of their specific properties, and the arrangement of mineral species in a satisfactory classification. This is frankly descriptive natural science. I realize that this designation is sometimes applied with a hint of disparagement, suggesting that the qualifications required for its pursuit are not particularly high and that the results obtained are not particularly valuable.

This must remain a matter of opinion. The full study of a mineral species demands a fair equipment: some knowledge of classical and modern languages properly to appraise the history and synonymy of the species; a knowledge of the theory and practice of geometrical crystallography to measure a crystal on the reflecting goniometer, project the planes, select proper axes and elements, assign indices to the observed forms, calculate elements and angles, and construct a faithful drawing; a knowledge of the theory and practice of x-ray measurements and analysis to permit the determination of the space-group and the dimensions of the unit cell from single crystal photographs and, if necessary, to transform the results of the geometrical work to conform to the structural results; to prepare a properly indexed x-ray powder pattern for the mineral; to determine the atomic content using the specific gravity and the chemical composition; and in favourable cases to fix the parameters of all the atoms; a knowledge of the theory and practice of optical mineralogy to determine, in the case of a transparent mineral, the orientation of the optical ellipsoid with reference to the crystal axes, the values of the principal refractive indices, the optic axial angle, the optic sign, and the absorption, and the variation of these properties with wavelength; and in the case of an opaque mineral to determine the reflecting power, reflection pleochroism, and anisotropism in polished surfaces under the reflecting polarizing microscope; to determine the hardness, the specific gravity, if necessary on a minute sample, and occasionally the magnetic and electric properties; and finally, or perhaps at the outset of the work, to discover the qualitative chemical composition of the mineral by dry and wet tests, perhaps aided by the spectrograph, and to prepare and analyze a clean sample to a summation that comes within one per cent of a hundred. If all this seems easy, do try it sometime. Whether it is worthwhile I shall not dispute.

Next to this basic work, which is the mineralogist's undivided business, comes the study of mineral associations and the concurrent laboratory research which seeks to reproduce single minerals or paragenetically related groups of minerals with a view to finding the physico-chemical conditions under which they may have formed in nature. Great as the importance of this work is, especially in relation to the origin of igneous rocks, pegmatites, and ore deposits, it must be granted that a precise knowledge of the properties of minerals themselves is a prerequisite for work upon their origin.

What is the incentive for work in pure mineralogy? Nothing exalted, I fear: merely curiosity and delight in the Mineral Kingdom, an urge to observe all the properties of each species, be it common or rare, valuable or worthless, with equal precision, to record these observations in style and form worthy of the elegance of Nature herself, and to bring out relationships that are clearly indicated by the facts of observation.

Special interest and sometimes special pleasure attends the re-examination of those many incompletely defined mineral substances which are relegated to the limbo of doubtful species in descriptive mineralogy. These ill-defined substances must be found to contain either nothing new or something new. With authentic material and better luck or better equipment than that of the original investigator it may prove that the doubtful substance is merely one or more known minerals, and if this is the result we have a useful clarification; or it may prove that the ill-defined material consists wholly or in part of a new species whose properties can be completely ascertained. On a few occasions it has been my good fortune to bring one of these wanderers into the fold, and then I, at least, "rejoiced more of that sheep than of the ninety and nine that went not astray."

This, of course, is not the end of mineralogical research but rather the beginning. As I have indicated, the origin of minerals is of immediate interest to mineralogists. All branches of applied mineralogy are legitimate lines of research, but I am inclined to the view that success in these directions depends mainly on the facts of mineralogy and technology and the financial pressure of governments or business. Intensive work on one or another property of minerals, such as the structure, the morphology, or the optics, will yield information of great detail; but such work begins to lose touch with mineralogy when the interest centres more on the property than on the mineral. In this connection my wife has reminded me of the following story. "Antaeus, the son of Terra, the Earth, was a mighty giant and wrestler whose strength was invincible so long as he remained in contact with his Mother Earth . . . Hercules encountered him, and finding that it was of no avail to throw him, for he always rose with renewed strength from every fall, he lifted him up from the earth and strangled him in the air." Let us keep our feet on the ground and remain strong.