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HISTORY OF THE STUDY OF ORE MINERALS*

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When faced with the problem of delivering a presidential address, it seems but natural to turn to the efforts of one's immediate predecessors in office in an attempt to get some inkling of what is expected in that line. Following this procedure, I was confronted with the brilliant speeches of the two busy B's, Bayley and Bowen, and felt somewhat discouraged as I knew I could not hope to emulate either the erudition of the one or the classical background of the other. However, a careful perusal of their addresses makes it sufficiently obvious that at least one aspect of mineralogical science, namely the subject I have chosen for my address, has been left virtually untouched. There seemed, therefore, little danger of any considerable amount of repetition, at least during the last three-year period.

As there has been a very extensive development within the field of ore mineral study during the last three or four decades, it seemed appropriate at this time to take stock of our knowledge and the important contributors to it. Any human historical document must be, in the very nature of things, somewhat incomplete. However, when an attempt is made to confine such a document within the narrow limits of a presidential address, it becomes quite impossible to give anything more than the high-lights, leaving the rest of the story to the highly-trained imagination of the intelligent audience. With this preamble, in the short time at my disposal, may I be permitted to give a brief outline of some of the developments in the study of ore minerals. Before I start please notice that I have said "some of the developments," and, if you are inclined to be critical over the almost certain omission of notable contributions, please note that in the preparation of this one historical effort there was compiled a reference list of over one hundred and seventy-five papers and text-books, of which over one hundred and fifty were summarized.

In any chronological recording of events it is always impossible to give the final word except in terms of contemporary progress, and it is

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always difficult to say just when the particular process of reasoning that led to the establishment of a new branch of any science may have had its inception. Perhaps however, as a convenient sort of spring-board that we may use before diving into the subject proper, we may cite the observations on meteorites of Baron von Widmanstätten in 1809. While the famous figures bearing his name, which were later noted on metals also, were not observed in the first instance on minerals and not under the microscope, nevertheless they must have been studied under reflected light from a polished surface and so may be considered as a sort of stepfather of this branch of our science. Although noted at this time by Widmanstätten, the first published mention of these figures was made in 1812 by K. A. Neumann (1812), who developed them on polished sections of the Elbogen meteorite by etching with nitric acid. Next we have Berzelius (1814) polishing a surface of pyrrhotite and noting by macroscopic methods the presence of another mineral, probably pentlandite, which cut across it in the form of narrow veinlets. But, although other investigators, such as Chladni (1819) and Von Schreibers (1820), continued the macroscopic study of meteorites, it was not until the time of Sorby, that any very substantial advance was made in this particular direction. Sorby, as you all know, was the first to develop the use of the petrographic microscope for the study of rock-forming minerals in thin sections. Inspired by this very notable contribution, this eminent investigator turned his attention also to the microscopic study of iron meteorites, using for this purpose polished sections of this extra-terrestrial material. A natural step was the use of this reflected-light method for the study of metals and alloys (1887), and so he was also largely responsible for the birth of the sister subject of metallography. But, while this method of studying polished surfaces under the microscope has been available since about 1865, it was not until twenty years later that it was applied to the study of ore minerals. At that time Baumhauer (1885) examined macroscopically polished sections of copper minerals from Chloride, New Mexico, using concentrated nitric and hydrochloric acids as etch reagents to differentiate the various minerals. The following year the same investigator (1886) applied this method to the study of smaltite-chloanthite ores from four German localities. From this time until the end of the last century there seems to have followed a fourteen-year period when this method was very little used, and interest in it during that time was kept alive only by the work of such scientists as Becke (1886), Drude (1888–1890), Weinschenk (1890), and Beijerinck (1897–1898), reference to which will be made later.

With the start of the present century, however, interest seems to have been revived and progress has been rapid and continuous for the last thirty-eight years. An inevitable concomitant of this progress was the rapid diversification of interest and the development of different angles of attack. Once there was established the collaboration of the polished section and the microscope, many avenues of approach were opened up for the investigator in this field. When considering the best way to record the progress along these different avenues, your historian decided it would be more systematic and less confusing to explore each avenue in turn rather than to attempt a presentation of a composite picture in terms of contemporaneous development. If some of them appear to be short, seeming more like lanes than avenues, please remember this is probably due to the lack of interesting trees along the way, and don't blame it on the poor recorder. A review of the whole field of endeavor would be quite impossible in an address of this kind. It seemed possible nevertheless to select about twelve different angles of approach, which might be here listed, arranged for the most part in alphabetical order, the exceptions being the first of a more general character and the last of a specialized nature. They are as follows:

1. Studies of general methods employed.
2. Studies of abrasives and polishing methods.
3. Studies of chemical methods.
4. Studies of the electrical conductivity of ore minerals.
5. Studies of mill-products.
6. Studies of optical methods.
7. Studies of physical properties of ore minerals.
8. Studies in quantitative macroscopic and microscopic analysis.
9. Studies in the synthesis of ore minerals.
10. Studies in technique.
11. Studies by *x*-ray methods.
12. Studies in special fields.

General Methods

Taking these up in the order mentioned it is very interesting and instructive to note, first, the many records of achievement from 1906 to 1931 in the general field of ore-mineral study. During this period the science owes a great debt to investigators in many countries. There might be mentioned in this connection the names of Orcel (1925–1928). Legraye (1925–1927) and Legrange (1927) in France; of Berg (1915), Granigg (1915–1920), Hummell (1925), Ramdohr (1924) and Schneiderhöhn (1920–1931) in Germany and Austria; and of Campbell (1906), Ray (1914), Bruce (1914) and Fairbanks (1928) on this continent. As a result of the efforts of these and other investigators substantial progress has been made in the direction of improvement of the general methods employed for the determination of ore minerals. The only discordant note in this symphony of progress has been the invention of a number of unsatisfactory aliases as titles for this branch of mineralogy. Still the author has to confess that, while he does not like any of the titles so far conferred on it, namely mineralography, mineragraphy and chalcography, he has not himself been able to find one that measures up to the needs of the case. Text-books and reference volumes on the subject were written during this period by Murdoch (1916), Davy and Farnham (1920), Van der Veen (1924), Farnham (1931), Short (1931), Ramdohr and Schneiderhöhn (1931), and we are especially indebted to these scientists for their valuable contributions in this direction.

Abrasives and Polishing Methods

Let us now consider the development in methods of polishing. As the efficiency and accuracy of this branch of mineralogical science was largely dependent on the maximum degree of polish of its working sections, it was but natural that investigation looking towards the betterment of polishing methods should have attracted many observers. At the present time it seems a far cry from the crude methods of hand-polishing employed at the beginning of this century to the highly specialized machine processes of the present time, but the one has led very naturally to the other through intermediate steps of varying degree. As examples of the earlier hand-polishing methods one might quote the observations of such workers as Campbell and Knight (1906–1907) and Ellsworth (1916). These methods were soon supplanted by machine operation with finer and finer abrasives used in the various stages of polishing, and notable contributions were made by such workers as Whitehead (1917) and Short (1926). Probably the greatest contribution in this part of the field was made by Vanderwilt (1928), who, departing largely from the old idea of rolling-grain abrasion, used the principle of fixed-grain abrasion in lead and copper laps. Contemporaneous with this development, or perhaps preceding it, we have the mounting of the mineral specimen in a mounting medium, first of sealing wax backed with plaster of Paris, later of bakelite made under heat and pressure. Still more modern practice as outlined by Dunn (1937) of the Geological Survey of India and others, mentions the successful use of cellulose acetate in place of the bakelite. Following along with these two developments we have the progress in the direction of abrasives used in the polishing process. Where formerly coarse carborundum powders were used, the common practice of to-day includes a very narrow range of abrasives from 5 micron alundum powder to the finest tin oxide or magnesia flour. This has brought with it the slight disadvantage of a longer period of operation, but there seems no reason to suppose that more intensive investigation in this part of the field may not again make possible the curtailment of the time required for polishing.

Chemical Methods

Of all the avenues of approach followed by investigators of ores, none has been more consistently followed than the avenue of microchemical research. From the time of Becke (1886), when such etch reagents as nitric and hydrochloric acids and potassium chlorate were used to differentiate minerals of the magnetite group, until the present day, notable contributions to our knowledge of this phase of the subject have been made by scientific workers. These contributions have taken the form either of a multiplication of etch reagents, or the development of new methods of application. In the former, two schools of thought soon emerged, the one represented by such eminent foreign scientists as Van der Veen (1924), Ramdohr and Schneiderhöhn (1931), using many reagents, each one adapted to the differentiation of one or a few minerals, and the other followed by such writers as Murdoch (1916), Davy and Farnham (1920), Farnham (1931) and Short (1931), using a limited number of reagents with more general application to a whole host of ore minerals. In the development of new methods of application there must be mentioned the staining methods of Granigg (1915–1920), Head and Crawford (1929) and Gaudin (1935), the electrochemical and photochemical methods of McKinstry (1927), the investigations of Osborne (1931) into the relative merits of the immersion and drop methods of applying reagents, the research of Fraser and Dreyer (1937) into the role played by interfering ions and the important contribution by Galopin, Geysin, Gutzeit, Hillier and Wenger (1933–1936) of the "á la touche" method, whereby the minerals are attacked by a solvent absorbed in a gelatin paper, which is later treated by reagents. These should be considered as important milestones in the path of progress. The text-books of Chamot (1915) and Behrens-Kley (1921), and that portion of Short's text-book (1931, pp. 115–201) dealing with this phase of the subject should also receive honorable mention in this connection.

Electrical Conductivity

Still another attractive angle of approach lay in the study of the electrical conductivity of ore minerals. The earlier investigations in this direction, such as those of Beijerinck (1897–1898), Koenigsberger and Reichenheim (1906), Borgström and Dannholm (1916), Wartman, Braun, Dufet, and many others tested this property either on macroscopic specimens or on mineral powders, while later researches by such workers as Davy and Farnham (1920), Kerr and Cabeen (1925), and Harvey (1928) were carried out on polished sections under the microscope. Their observations, although covering a wide range of mineral specimens, were made chiefly on sulphide, arsenide, and oxide compounds and seemed to indicate very clearly not only that the conductivity of a natural opaque mineral is not constant, but that it may show variations of from hundreds to even millions of per cent. The chief factors causing these wide variations were considered to be the presence of impurities, non-uniform temperature, change in orientation, variation in size of mineral crystals, destruction of the crystal lattice by heating, grinding, fracturing, or oxidation, and exposure to light. As a by-product of these investigations we have the use by McKinstry (1927, pp. 671–673) and others, of a low-voltage current to increase the susceptibility of certain ore minerals to etch reagents.

Mill-products

While most students of ore minerals were content to confine their investigations to polished sections of solid mineral specimens, a great deal of research was also carried out in the related fields of ore dressing and milling. The earlier efforts in this part of the field for the most part were confined to the study of these fragmental products in the rough state. In this connection there might be cited the investigations of Head (1925), and of Coghill and Bonardi (1919). The use by the latter two workers of a binocular microscope and a camera lucida for sketching the outlines of the mineral grains before counting the particles, represents an application in this direction of methods used much earlier by Sollas (1891) and Joly (1903). Investigation in this part of the field was rendered more efficient in later years not only by the use of mounting media similar to those used for solid specimens, but also by notable improvements in methods of polishing such fragmental material. At first, as with the solid mineral specimens, ordinary sealing wax poured into a rectangular brass container was used as the mounting medium. In these mounts, sometimes the mill-products were mixed all through the wax, sometimes they were confined within the narrower limits of a brass or copper ring placed within the larger container. These mounts were soon found to be unsatisfactory, particularly during the warm summer months, as the wax had a strong tendency to flow. With the discovery of the resin materials, redmanol and bakelite, vastly superior mounting media were uncovered and found a wide application. Outstanding contributions in this field were made by Head and Slavin (1930) and by Fairbanks (1924). For such cases as require observation of those parts of the mineral fragment other than that exposed at the polished surface, transparent mounts of "lucite" or "pontalite," manufactured by the Dupont Chemical Co., have been used by Haycock and others. Transparent media have also been developed by the Bakelite Corporation and by the French Ivory Co. For those who are interested in this phase of the subject, these and other mounting products are mentioned in some detail in the "Handbook of Chemistry and Physics," published by the Chemical Rubber Publishing Co. of Cleveland. It is not the purpose of this article even to mention the many complicated processes involved in all the phases of milling practice. However two recent developments, having to do with the classifying of products below 200 mesh in size, and the assembling of such fine materials in sufficient quantities for microscopic analysis, impinge very strongly on the field of mineralogical research and so must receive at least a passing mention. With the devising of the Haultain (1937) infrasizer and superpanner it is now possible to examine even those constituents of the ore that are to be found only in minute quantities. The far-reaching effects of the investigation of such mill-products needs no emphasis at this time and it seems certain that in the near future it will find an even wider application than heretofore.

Optical Methods

For many years optical methods of approach have engaged the attention of research workers in many parts of the world. For the most part these have followed three main directions, namely, investigation of maximum reflectivity and other optical constants, determination of anisotropism in polarized light, and spectroscopic research. Of these the determination of optical constants of ore minerals seems to have attracted many workers. This type of investigation was probably started by Drude (1888) when he obtained for stibnite such optical constants as the indices of refraction and coefficients of absorption, using a spectrometer equipped with rotatable nicols in the collimator and telescope tubes. Two years later the same worker determined the optical constants of various metals and alloys (1890), using Kundt's method of diverting a beam of light through a metal prism. Drudes' methods were also employed by Forsterling (1908) to determine the reflectivity and other optical constants of hematite. Substantial advance in this part of the field was not attained until the development of photometric methods for determining reflectivity, first by Orcel (1927) and Schneiderhöhn (1928), later by Frick (1930) and Moses (1936). The application of these methods has made possible the precise determination of the reflecting power of various ore minerals and has placed another valuable tool in the hands of workers in the field of ore mineral study. Observations on the anisotropism of ore minerals seem to have been started early in this century by Koenigsberger (1908) who used a Savart plate, a plate of known refractive index, a reflecting prism and a contrast biplate of smoky quartz. His work was followed by that of F. E. Wright (1920), who developed methods for determining the degree of anisotropism involving the use either of a special cleavage plate of calcite or of two biprisms of quartz, called the bi-quartz wedge plate. Other workers in this field include Glaser (1924), Orcel (1928), Sampson (1923, 1929) and Goranson (1933). Spectrographic studies of the ore minerals seem to have been much less popular than the other two approaches from the physical side. The names of but five workers in this part of the field have come to the writer's attention, namely Schneiderhöhn (1929), Claussen (1934), Berthelot and Orcel (1930) and Harcourt (1937). Of these Schneiderhöhn conducted spectrographic analyses on the platinum ores of the Bushveld Complex, Claussen did similar work on galena, sphalerite, and pyrite from many localities, and Harcourt used this method to distinguish enargite and famatinite. No doubt I will be reminded later of the names of other workers in this field, but at present these are the only five that have come to my notice. To complete the picture on the optical side, mention must be made of the extensive observations of Guild (1917), Schneiderhöhn (1922 B), McKinstry (1927) and Stephens (1931) on the effect of strong light sources on silver minerals, and also of the investigations of Myers (1924) on the advantages of oblique illumination.

Physical Properties

We shall next turn our attention to a very brief consideration of studies in the field of physical properties. While most investigators in the field of ore mineral study have relegated to a place of secondary importance observation of such physical properties as hardness, color, and streak, a few workers have studied these properties intensively. Although most workers have made use of hardness as a means of identifying the ore minerals, the determination of this property has been rather imperfect in most cases. Some form of steel needle or other simple hardness-tester, in the opinion of many workers, has been amply sufficient for the purpose. Nevertheless, attempts have been made by some workers to determine this property more accurately. In 1923 Bierbaum made a study of the hardness of bearing metals, using an instrument, called a microcharacter, for measuring the width of the cut. This instrument, which was later used by Hodge and McKay (1934) for determining the microhardness of minerals, consists essentially of a tiny diamond under which the mineral to be tested is moved, a constant load being maintained by a small weight mounted on a lever-spring system. The width of the cut, called the microcut, produced by this device, is measured by means of a filar micrometer eyepiece. Hodge and McKay determined the microhardness of nine members of Mohs' scale of hardness to be as follows: talc 1, gypsum 11, calcite 129, fluorite 143, apatite 517, orthoclase 975, quartz 2700, topaz 3420, corundum 5300. Talmage (1925 B), another worker in this field, used a scratch-sclerometer with a diamond blade substituted for the original steel needle and established a seven-way classification of hardness. This method has now become standard practice in many scientific laboratories.

The same worker (1925 A) has conducted research on the diagnostic value of color in identifying ore minerals. By using either a comparison microscope or two microscopes equipped with a comparison ocular, and with the color contrasts intensified by the use of color-screens, he was able to establish the fact that the absolute color value of any opaque mineral is constant. Still another worker, Gaubert (1923), investigated such physical properties as form, transparency and streak, the last mentioned property being studied either on a glass slide or on an unpolished quartz plate.

Quantitative Analysis

Another attractive avenue of investigation followed by many during the last ninety years has led in the direction of quantitative macroscopic and microscopic analysis. While it is true that most of the efforts in this direction have been confined to determining the quantitative relations of the rock-forming minerals, some investigators at least have turned their attention towards a quantitative determination of the opaque minerals in ores. Time does not permit of a detailed account of all the research conducted in the field of quantitative study, but mention must be made in passing of the notable contributions of such pioneers as Delesse (1848) and Rosiwal (1898), who first enunciated the important principle that the volumetric might be directly related to the areal or even the lineal proportions, provided enough area or enough lineal measurement was included to take care of the third dimension. Most of their observations were made on hand-specimens of coarse-grained rocks, although Rosiwal made some of his measurements under the microscope. In later times, for the development of methods involving the use of the planimeter and of the integrating stage, we are indebted to such workers as Johannsen (1919), Shand (1914) and Wentworth (1923). The latter method, although necessitating the purchase of a costly accessory to the microscope, is at present in common use in those laboratories where a considerable number of quantitative microscopic analyses is carried out each year. All of the above-mentioned workers directed their attention towards a determination of the quantitative relations of the rock-forming minerals. Their methods however have also been used by many scientists in a study of similar relations of ore minerals. R. E. Head (1921) has applied them to a quantitative study of the copper and iron minerals in a porphyry ore, while the writer (1930 A) has been privileged to test some of these older methods, to devise slight variations of the old Delesse and Rosiwal methods, and to apply these methods in the direction of a quantitative determination of the ore minerals at Cobalt, Ontario (1930 B).

Mineral Synthesis

An interesting angle of attack which, more especially in recent times, has attracted several workers is that of mineral synthesis. This method seems to have been employed first by Weinschenk (1890) who was successful in synthesizing many sulphide minerals. Later this method was used by Beutell and Lorenz (1916) as a means of explaining the variable composition of such arsenide minerals as smaltite, chloanthite, skutterudite and loellingite. In more recent times it has been extensively employed by such workers as Ramdohr (1926), Schwartz (1928–1932), Gaudin and McGlashan (1938) to explain the intimate and complex intergrowths of iron, copper, and silver minerals. In this modern practice sometimes the minerals are synthesized from chemical salts, sometimes the natural mineral intergrowths are subjected to heat treatment and the effects noted with rapid quenching and with slow cooling. Remarkable duplications of natural intergrowths have been attained by the latter method in many instances. The preparation of pure synthetic minerals for polished surface study is also suggested by Schwartz (1932) as an aid in evaluating the etch reactions of the ore minerals.

Technique

As a very valuable by-product of the progress along the main avenues of approach, there has been developed an improvement in technique of manipulation that has proved of material assistance to research workers in this field. To mention but a few of these developments, there is the method used by Short (1926) and others, of impregnating friable ores with balsam or bakelite, that devised by Donnay (1930) for using reflected light on thin sections by polishing the rock chip first and then grinding to the required thickness for thin sections, the method of Orcel (1925) for determining the rotation of the plane of polarization, the use by Osborne (1928) of glass cylinders to confine the etching liquid to a small portion of the polished surface, and the use by Schneiderhöhn (Wagner 1929), Haycock (1931), Harcourt (1937) and others of a small dental drill for obtaining small samples for microchemical analysis.

X-ray Methods

Investigation by *x*-ray methods, which has been used extensively to explore the atomic structure of rock-forming minerals, up to the present time has not been used by many workers for determining the structure of ore minerals. Notable contributions have been made in this direction by Wyckoff (1921) who investigated the crystal structure of alabandite, by Kerr (1924) who found the powder method best adapted to the study of ore minerals, by Ramsdell (1925) who checked the isomorphism of various groups of sulphides by this method, and by Frebold (1926) and Waldo (1935) who used this method for the identification of iron and copper minerals, respectively. The possibilities of further exploration along this main avenue are indeed great and it seems certain that earnest collaboration in the future between *x*-ray workers and microscopists will be the greatest factor in adding to our knowledge of ore minerals.

Special Fields

In the very broad field of studies of special ores, mention can only be made of a few striking examples. One of the most popular of these special fields is the study of the common association of cobalt-nickel-silver ores, as shown by the classic localities in Germany and Cobalt, Ontario. The ores from the German districts have been studied intensively for the past fifty years while those from Cobalt have been the subject of scientific scrutiny for over thirty years. The names of such investigators as Baumhauer (1886), Beutell (1916), Flörke (1922) and Oftedal (1928) are prominently connected with the study of the German ores, while Campbell and Knight (1906), Ellsworth (1916), Bastin (1917), Schlossmacher (1921) and Thomson (1930 B), carried out observations on the ores from Cobalt. A more general study of the three common associations for silver ores, namely silver-lead-zinc, copper-silver, and cobalt-nickel-silver, was made by Guild (1917), while Emmons, Stockwell and Jones (1926) conducted a special study by *x*-ray methods of the two forms of silver sulphide.

Another field of special study has to do with the nickel ores at Sudbury Ontario, and other localities. In this direction such observers as Campbell and Knight (1907), Lindgren and Davy (1924), Short and Shannon (1930), and Buddington (1924) have carried out investigations on pentlandite and on the rarer nickel minerals. For over fifty years copper ores have been studied in polished section under the microscope and the names of such investigators as Baumhauer (1885), Graton and Murdoch (1913), Borgström (1916), McLaughlin (1917), Ramdohr (1928) and Fackert (1928) might be cited in this connection.

In the study of iron ores such observers as Hussak (1904), Brunton (1913), Singewald (1913 A & B), Bayley (1923) and Watson (1922) have confined their attention to interesting microstructures to be found in the magnetite-ilmenite, magnetite-rutile, and magnetite-hematite associations, while Schneiderhöhn (1920 B), Sosman and Hostetter (1918), and Wagner (1928) conducted investigations either on zoned hematites or on iron ores in general. Little work has been done on ores of platinum but Aminoff and Parsons (1928) studied by *x*-ray methods the crystal structure of sperrylite, and Wagner (1929) published an exhaustive treatise on the "Platinum Deposits and Mines of South Africa." In this connection it should be mentioned that the microscopic study of the South African platinum ores was carried out by Schneiderhöhn, this being included in Wagner's book.

Studies of the manganese ores have also attracted the attention of scientists in many parts of the world. The names of Déribéré, Hermann, Siegert, Esparseil, Maggiore, and Gavasheli might be mentioned in this connection. Special reference should also be made to the work of Cooke, Howes, Warren and Emery (1913) on psilomelane and manganite, and to the work of Thiel (1924) on manganese minerals in general. Another special field of more than common interest is that of mineral intergrowths. The significance of these intergrowths has been sought after by such workers as Rogers (1916), Uglow (1922), Newhouse (1927–1931), Grigoriev (1928), Gruner (1929) and Schwartz (1928–1931). As mentioned in an earlier part of this paper, some of these intergrowths at least, which may have originated from unmixing or replacement, have been successfully reproduced by synthetic laboratory methods.

In concluding our discussion of advances made along these different avenues, it would be quite misleading to omit special mention of those investigators of ores whose published works lie rather in the field of economic geology than in the study of ore minerals. For the most part these scientists are to be found in academic surroundings and, while in a few cases they have left some published records of their research activities in the direction of ore mineral study, their main contribution has been in stimulating an interest in ore minerals on the part of their colleagues and advanced students and assisting them in their various forms of research. There are many of these on this continent. The writer has knowledge of and has had personal contact with two outstanding examples of this type of academic figure. They are Professor Graton of Harvard University and Professor Lindgren of Massachusetts Institute of Technology. The writer wishes at this time to pay tribute to the inspiration and encouragement that, in common with many others, he has received at their hands. There are many other quiet workers of the same type who ask for no other reward for their efforts than the advancement of this science through the efforts of others. To them also all students of ore minerals owe a great debt of gratitude.

Future Development

And now that we have explored some of the avenues of approach which have been followed by students of ore minerals, what can we say of the possibilities of future development in this branch of mineralogical science? Without going outside the avenues already mentioned, which of these methods of approach seems to promise the most productive results? While admitting the strong possibility of further improvement in the direction of general methods, polishing methods, technique and the study of physical properties, it seems likely that progress in the next decade or two will be carried out in the directions of improvement of chemical, electrical, and optical methods, of further study of the structure of ore minerals using the powerful tools of mineral synthesis and x-ray investigation in collaboration with microscopic research, and in the more intensive study of those fragmental materials which are to be found either in placer deposits or in the products of the mining-mill. It seems probable, also, that the attention of students in this field will be diverted more and more to the study of special suites of ores in the hope that much more light may be shed not only on the qualitative but also on the quantitative relations of the ore minerals present.

References

Aminoff, G., and Parsons, A. L., Crystal structure of sperrylite, *Univ. Toronto Studies, Geol. Ser.*, **27,** 5–10, (1928).

Bastin, E. S., Significant mineralogical relations in silver ores of Cobalt, Ontario, *Econ. Geol.*, **12,** 219–236 (1917).

Bateman, A. M., Some covellite-chalcocite relationships, *Econ. Geol.*, **24,** 424–439 (1929).

Baumhauer, H., Ueber die mikroskopische Beschaffenheit eines Buntkupfererzes von Chloride, N. M., *Zeits. Kryst.*, **10,** 447 (1885).

———, Ueber die Struktur und die microskopische Beschaffenheit von Speiskobalt und Chloanthit, *Zeits. Kryst.*, **12,** 17–33 (1886).

Bayley, W. S., The occurrence of rutile in the titaniferous magnetites of Western N. C. and Eastern Tenn., *Econ. Geol.*, **18,** 382–392 (1923).

Becke, F., Ätzversuche an Mineralien der Magnetitgruppe, *Tscherm. Min. Petr. Mitt.*, **7,** 200–249 (1886).

Behrens, H., and Kley, P. D. C., Microchemical Analysis. *Leipzig* (1921).

Beijerinck, F., Ueber das Leitungsvermögen der Mineralien für Elektricität, *Jahrb. Min., Beil Bd.*, **11,** 403–474 (1897).

Berg, G., Mikroskopische Untersuchung der Erzlagerstätten. *Berlin* (1915).

Berthelot, Ch., and Orcel, J., Les Minerais; Étude, préparation, mecanique, marché. Encycl. Miniere et Metallurgique. *Paris* (1930).

Beutell, A., Mikroskopische Untersuchung des Speiskobalts und Chloanthits, *Centralbl. Min.*, 180–185; 206–221 (1916).

Beutell, A., and Lorenz, Fr., Synthese von Speiskobalt und Loellingit, *Centralbl. Min.*, 10–22 (1916).

Berzelius, J. J., *Gilb. Ann.*, **48,** 209 (1814).

Bierbaum, C. H., A study of bearing metals, *Trans. A.I.M.E.*, **69,** 972–983 (1923).

Borgström, L. H., and Dannholm, J., On electrical conductivity of sulphide-arsenide minerals and its determination, *Öfvers Finska Vetensk. Soc. Förh.*, **58,** Afd. A, No. 21, 30 pp. (1916).

Borgström, L. H., Algodonit und whitneyit, *Geol. Fören. Förhandl.*, **38,** 95–100 (1916).

Bruce, E. L., Microscopic tests on opaque minerals, *School of Mines Quart.*, **35,** 187–193 (1914).

Brunton, S., Some notes on titaniferous magnetite, *Econ. Geol.*, **8,** 670–680 (1913).

Buddington, A. F., Alaskan nickel minerals, *Econ. Geol.*, **19,** 521–541 (1924).

Campbell, W., The microscopic examination of the opaque minerals, *Econ. Geol.*, **1,** 751–766 (1906).

Campbell, W., and Knight, C. W., A microscopic examination of the cobalt-nickel arsenides and silver deposits of Temiskaming, *Econ. Geol.*, **1,** 767–776 (1906).

———, The microstructure of nickeliferous pyrrhotite, *Econ. Geol.*, **2,** 350–366 (1907).

Chladni, E. F. F., *Journ. Chem. Physik* (Schweigger), **26,** 196–202 (1819).

Chamot, E. M., Elementary Chemical Microscopy, *New York* (1915).

Claussen, G. E., Spectrographic analysis of certain galenas, sphalerites, and pyrites, *Am. Mineral.*, **19,** 221–224 (1934).

Cooke, S. R. B., Howes, Warren, and Emery, Mineragraphic identification of psilomelane and manganite, *Am. Mineral.*, **16,** 209–212 (1931).

Coghill, W. H., and Bonardi, J. P., Approximate Quantitative Microscopy of Pulverized Ores, *U. S. Bur. of Mines, Tech. Paper* **211** (1919).

Davy, W. M., and Farnham, C. M., Microscopic Examination of the Ore Minerals. *New York* (1920).

Delesse, A., *Annales des Mines*, 4th Series, **13,** 379–388 (1848).

Donnay, J. D. H., Thinned polished sections, *Econ. Geol.*, **25,** 270–274 (1930).

Drude, P., Beobachtungen über Reflexion des Lichtes am Antimonglanz, *Weidem. Ann. Phy.*, **34,** 489–531 (1888).

———, Bestimmung der optischen Konstanten der Metalle, *Weidem. Ann. Phy.*, **39,** 481–554 (1890).

Dunn, J. A., Polished and thin-section technique in the laboratory of the Geological Survey of India, *Records of Geol. Survey of India*, **72,** pt. 2, 207–226 (1937).

Ellsworth, H. V., A study of certain minerals from Cobalt, Ontario, *Rep. Ont. Bur. of Mines*, **25,** pt. 1, 205–243 (1916).

Emmons, Stockwell, Jones, Argentite and acanthite, *Am. Mineral.*, **11,** 326–328 (1926).

Fackert, W., Ein neues Kupferkiesätzmittel, *Metallwirtschaft*, H. **43,** Oct. (1928).

Fairbanks, E. E., Notes on mineragraphic technique, *Econ. Geol.*, **19,** 213 (1924).

Fairbanks, E. E., The Laboratory Investigation of Ores. *New York* (1928).

Farnham, C. M., Determination of the Opaque Minerals. *New York* (1931).

Flörke, W., Mikrographische Beobachtungen an Nickel-und-Kobalterzen, *Metal u. Erz*, **20,** 197–206 (1922).

Försterling, C., Die optischen Konstanten von Eisenglanz, *Neues Jahrb. Min., Beil. Bd.* **25,** 344–365 (1908).

Fraser, H. J., and Dreyer, R. M., Mutual interference in the microchemical determination of ore minerals, *Am. Mineral.*, **22,** 949–976 (1937).

Frebold, G., Über eine Methode zur Bestimmung undurchsichtiger Mineralien, besonders von Erzen, mit Hilfe der Röntgenstrahlen, *Centralbl. Min.*, **A,** 278–281 (1926).

Frick, H., Measurements of the reflectivity of ore minerals, *Neues Jahrb. Min., Beil. Bd* **61A,** 31 (1930).

Galopin, R., Différenciation chimique des mineraux métalliques par la méthode des empreintes, *Schweiz. Min. u. Petr. Mitt.*, **16**(1), 1–18 (1936).

Gaubert, P., The determination of minerals by the microscopic examination of their streak, *Compte Rendu,* **177,** 960–962 (1923).

Gaudin, A. M., Staining minerals to aid in their identification in quantitative microscopy, *Econ. Geol.*, **30,** 552–562 (1935).

———, and McGlashan, D. W., Sulphide silver minerals—A contribution to their pyrosynthesis, etc., *Econ. Geol.*, **33,** 143–193 (1938).

Glaser, L. C., Metallographie im polarisierten Licht, *Zeits. techn. Phys.*, **5,** 253–260 (1924).

Goranson, E. A., The behavior of ore minerals in polarized light. Ph.D. *Thesis.* Harvard University (1933).

Granigg, B., Zur Anwendung metallographische Methoden auf die mikroskopische Untersuchung von Erzlagerstätten, *Metall. u. Erz.*, **12,** 189–200; **13,** 169–177; **17,** 56–61 (1915–1920).

Graton, L. C., and Murdoch, J., The sulphide ores of copper; some results of microscopic study, *Trans. Am. Inst. Min. Eng.* (May), 741 (1913).

Grigoriev, J., Structures of mineral intergrowths in ores, *Mitt. Russ. Min. Ges.*, **57,** 11–56 (1928).

Gruner, J. W., Structural reasons for oriented intergrowths in some minerals, *Am. Mineral.*, **14,** 227–237 (1929).

Guild, F. N., A microscopic study of silver ores, *Econ. Geol.*, **12,** 297–353 (1917).

Gutzeit, Geysin, Galopin, Essai de détermination chimique indirecte des minerais en surface polie par l'application de la méthode "à la touche," *Soc. Phys. et Hist. Nat., Genève, C.R.* **50**(2), 192–196 (1933).

Gutzeit Gr., and Galopin, R., Différenciation chimique par la méthode "à la touche," de quelque sulphosels voisins en surface polie, *Soc. Phys. et Hist. Nat., Genève, C.R.* **51,** 53–61 (1934).

Harcourt, G. A., The distinction between enargite and famatinite, *Am. Mineral.*, **22,** 517–525 (1937).

Harvey, R. D., Electrical conductivity and polished mineral surfaces, *Econ. Geol.*, **23,** 778–803 (1928).

Haultain, H. E. T., Splitting the minus-200 with the superpanner and infrasizer, *Trans. C.I.M. & M.*, **40,** 229–240 (1937).

Haycock, M., *Econ. Geol,* **26,** 415–420 (1931).

Head, R. E., Quantitative microscopic determination of chalcopyrite, chalcocite, bornite, and pyrite in a porphyry ore, *U. S. Bur. Mines, Ser.* **2** (1921).

———, A new method of preparing briquetted mineral grains for microscopic study, *Eng. & Min. Journ.*, **19,** 889–890 (1925).

———, and Crawford, A. L., Utilizing staining methods in the identification of minerals, *Eng. & Min. Journ.*, **127,** 877 (1929).

———, and Slavin, A new development in the preparation of briquetted mineral grains, *Min. & Met. Inv., Techn. Paper* **10,** *Univ. of Utah* (1930).

Hodge, H. C., and McKay, J. H., The microhardness of minerals comprising the Mohs' Scale, *Am. Mineral.*, **19,** 161–168 (1934).

Hummell, K., Über die Anwendbarkeit der Erzmikroskops für sedimentpetrographische Untersuchungen, *Geol. Rundschau,* **16,** 76–80 (1925).

Hussak, E., Über die Mikrostruktur einiger brasilianischer Titanmagneteisensteine, *Neues Jahrb. Min.*, **1,** 94 (1904).

JOHANNSEN, A., *Jour. Geol.*, **27**, 276–285 (1919).

JOLY, J., *Proc. Royal Dublin Soc.*, **10**, 83–84 (1903).

KERR, P. F., Determination of ore minerals by x-ray diffraction patterns, *Econ. Geol.*, **19**, 1–34 (1924).

———, and CABEEN, C. K., Electrical conductivity of ore minerals, *Econ. Geol.*, **20**, 729 (1925).

KOENIGSBERGER, J., and REICHENHEIM, O., Über die Elektrizitätsleitung einiger natürlich kristallisierter Oxyde und Sulphide und des Graphits. Nebst. Anhang: Über einige polymorphe Modifikationen, *Neues Jahrb. Min.*, **2**, 20–49 (1906).

KOENIGSBERGER, J., Über einen Apparat zur Erkennung und Messung optischer Anisotropie undurchsichtiger Substanzen und dessen Verwendung, *Centralbl. Min.*, 565–597 (1908).

LEGRANGE, Microscopic examination of opaque minerals, *Rev. Univ. des Mines*, **15**, 67–75, (1927).

LEGRAYE, M., L'examen des minerais en sections polies, *Rev. Univ. des Mines*, **5**, Nr. 4. (1925).

———, Examen microscopique des minerais opaques. Tables determinatives, *Rev. Univ. des Mines*, **15**, 67–75, 112–123 (1927).

LINDGREN, W., and DAVY, W. M., Nickel ores from Key West mine, Nevada, *Econ. Geol.*, **19**, 309–319 (1924).

MCKINSTRY, H. E., Magnetic, electrochemical and photochemical tests in the identification of opaque minerals, *Econ. Geol.*, **22**, 669–677 (1927).

MCLAUGHLIN, D. H., Occurrence and significance of bornite. Ph.D. *Thesis*, Harvard University (1917).

MOSES, J. H., The identification of opaque minerals by their reflecting power as measured photometrically, Ph.D. *Thesis*, Harvard University (1936).

MURDOCH, J., Microscopical Determination of the Opaque Minerals. *New York* (1916).

MYERS, W. M., Advantages of oblique illumination in mineragraphy, *Am. Mineral.*, **9**, 177 (1924).

NEUMANN, K. A., *Am. Phys.* (Gilbert), **42**, 207 (1812).

NEWHOUSE, W. H., Intimate intergrowths and mutual boundaries as proof of contemporaneous deposition, *Econ. Geol.*, **22**, 403–407 (1927).

———, A pyrrhotite-cubanite-chalcopyrite intergrowth from the Frood Mine, Sudbury, Ont., *Am. Mineral.*, **16**, 334–337 (1931).

OFTEDAL, J., Die Kristallstruktur von Skutterudit und Speiskobalt-chloanthit, *Zeits. Krist.*, **66**, 517–546 (1928).

ORCEL, J., The methods of microscopic examination of ore minerals, *Bull. soc. franc. minéral.*, **48**, 272 (1925).

———, Measurement of the reflectivity of opaque minerals with a photo-electric cell, *Compte Rendu Acad. Sci.*, 1141 (1927).

———, Notes on the characters of opaque minerals in polarized light, *Bull. soc. franc. minéral.*, **51**, 197 (1928).

OSBORNE, F. F., Technique of the investigation of iron ores, *Econ. Geol.*, **23**, 442 (1928).

———, A method of applying reagents under the mineralographic microscope, *Econ. Geol.*, **26**, 496–501 (1931).

RAMDOHR, P., Beobachtungen an opaken Erzen, *Arch. f. Lagerstättenkunde*, **34**, 30 p. (1924).

———, Beobachtungen an Magnetit, Ilmenit, Eisenglanz, und Überlegungen über das System FeO, Fe_2O_3, TiO_2, *Neues Jahrb. Min., Beil. Bd.* **54A**, 320–379 (1926).

———, Neue mikroskopische Beobachtungen am Cubanit (chalmersit) und Überlegungen über seine lagerstättenkundliche Stellung, *Zeits. Prakt. Geol.*, **36**(10), Oct., 169–178 (1928).

Ramsdell, L. S., The crystal structures of some metallic sulphides, *Am. Mineral.*, **10,** 281–304 (1925).

Ray, J. C., The reflecting microscope in mining geology and metallurgy, *Min. & Sc. Press*, 922–927 (1925).

Rogers, A. F., The so-called graphic intergrowth of bornite and chalcocite, *Econ. Geol.*, **11,** 582–593 (1916).

Rosiwal, A., Über geometrische Gesteinsanalysen. Ein einfacher Weg zur ziffermässigen Feststellung des Quantitätsverhältnisses der Mineralbestandtheile gemengter Gesteine, *Verh. der K. K. Geol. Reichsanstalt* (1898).

Sampson, E., The determination of anisotropism in metallic minerals, *Econ. Geol.*, **18,** 775, and *Econ. Geol.*, **24,** 412 (1923, 1929).

Schlossmacher, K., Mikroskopische Untersuchungsbeiträge zur Kenntnis der kanadischen Cobalt-Nickel-Silber Formation, *Zeits. Prakt. Geol.*, **29,** 131–134 (1921).

———, Course in quantitative work in ore microscopy, *Fortschr. Mineral Kryst. Petrogr.*, **9,** 161–184 (1924).

Schneiderhöhn, H., (A) Die mikroskopische Untersuchung undurchsichtige Mineralien und Erze in auffallenden Licht und ihre Bedeutung für Mineralogie und Lagerstättenkunde, *Neues Jahrb. Min.*, **43,** 400–438 (1920).

(B) Die mikroskopische Untersuchung der Eisenerze mit besonders Berücksichtigung ibrer Bedeutung für das Aufbereitsverfahren. *Stahl und Eisen* (1920).

———, (A) Anleitung zur mikroskopischen Bestimmung und Untersuchung von Erzen und Aufbereitungsprodukten, besonders in auffallenden Licht, *Selbstverlag d. Ges. Deutscher Metallhütten und Bergleute*, **292,** 154 abb. (1922).

(B) Untersuchung von Erzen. *Berlin* (1922).

———, A new photometer-ocular for measuring the reflectivity of ore minerals, *Centralbl. Mineral.*, 394 (1928).

———, The mineragraphy and spectrography of the sulphidic platinum ores of the Bushveld Complex, 206–246 in The Platinum Deposits of South Africa, by Wagner (1929).

Schneiderhöhn, H., and Ramdohr, P., Lehrbuch der Erzmikroskopie. *Berlin* (1931).

Schwartz, G. M., (A) Experiments bearing on bornite-chalcocite intergrowths, *Econ. Geol.*, **23,** 381–397 (1928).

(B) Dyscrasite and the silver-antimony constitution diagram, *Am. Mineral.*, **13,** 495–503 (1928).

———, (A) Experiments with sphalerite-chalcopyrite intergrowths, *Geol. Soc. Am. Bull.*, **42**(1), 187–188 (1931).

(B) Intergrowths of bornite and chalcopyrite, *Econ. Geol.*, **26,** 186–201 (1931).

———, A method for making synthetic minerals for polished surface study, *Am. Mineral.*, **17,** 478–484 (1932).

Shand, S. J., *Jour. Geol.*, **24,** No. 4, 394–404 (1914).

Short, M. N., The preparation of polished sections of ores, *Econ. Geol.*, **21,** 648–664 (1926).

Short, M. N., and Shannon, E. V., Violarite and other rare nickel sulphides, *Am. Mineral.* **15,** 1–22 (1930).

Short, M. N., *U. S. Geol. Survey, Bull.* **825** (1931).

Singewald, J. T., (A) Microstructure of titaniferous magnetite, *Econ. Geol.*, **8,** 207 (1913).

(B) The titaniferous magnetites of the United States, *U. S. Bur. of Mines, Bull.* **64,** (1913).

Sollas, W. J., *Trans. Royal Irish Academy*, **29** (Part 14) 471 (1891).

SORBY, H. C., Microscopic structure of iron and steel, *Iron & Steel Inst. Jour.*, 255–288 (1887).

SOSMAN, R. B., and HOSTETTER, J. C., Zonal growth in hematite and its bearing on the origin of certain iron ores, *Trans. Am. Inst. Min. Eng.*, **58,** 434–444 (1918).

STEPHENS, M. M., Effect of light on polished surfaces of silver minerals, *Am. Mineral.*, **16,** 532–549 (1931).

TALMAGE, S. B., (A) Diagnostic value of color in polished sections, *Econ. Geol.*, **20,** 168 (1925).

(B) Quantitative standards for hardness of ore minerals, *Econ. Geol.*, **20,** 531 (1925).

THIEL, G. A., (A) The manganese minerals, *Econ. Geol.*, **19,** 107–145 (1924).

(B) A study of polished surfaces in polarized light, *Econ. Geol.*, **19,** 582 (1924).

THOMSON, E., (A) Quantitative microscopic analysis, *Jour. Geol.*, **38,** 193–222 (1930).

(B) A qualitative and quantitative determination of the ores of Cobalt, Ontario, *Econ. Geol.*, **25,** 470–505 (1930).

UGLOW, W. L., Bornite-chalcopyrite intergrowths, so-called, from Legate Creek, Pacific, B. C., *Am. Mineral.*, **7,** 1–4 (1922).

VAN DER VEEN, Mineragraphy and Ore Deposition. *Hague* (1924).

VANDERWILT, J. W., Improvements in the polishing of ores, *Econ. Geol.*, **23,** 292–316 (1928).

———, A laboratory method for grading abrasives, *Econ. Geol.*, **24,** 853–859 (1929).

VON SCHREIBERS, Stein und Metallmassen. *Wien* (1820).

WAGNER, P. A., The iron deposits and mines of South Africa, *Union of S. Africa Geol. Surv.*, Mem. **26,** 268 (1928).

———, The Platinum Deposits and Mines of South Africa. *Edinburgh* (1929).

WALDO, A. W., Identification of the copper ore minerals by means of x-ray diffraction patterns, *Am. Mineral.*, **20,** 575–597 (1935).

WATSON, T. L., Rutile-ilmenite intergrowths, *Am. Mineral.*, **7,** 185–188 (1922).

WEINSCHENK, E., Beiträge zur Mineralsynthese, *Zeits. Krist.*, **17,** 486–504 (1890).

WENGER, GUTZEIT, and HILLIER, Sur un procédé d'attaque electrolytique des mineraux opaques, et sur son application à la téchnique des empreintes de surfaces polies, *Soc. Phys. et Hist. Nat., Genève, C.R.*, **51**(2), 64–67 (1934).

WENTWORTH, C. K., *Jour. Geol.*, **31,** 228–232 (1923).

WHITEHEAD, W. L., Notes on the technique of mineralography, *Econ. Geol.*, **12,** 696–716 (1917).

WRIGHT, F. E., Examination of ores and metals in polarized light, *Trans. A.I.M.E.*, **63,** 370–381 (1920).

WYCKOFF, R. W. G., The crystal structure of alabandite, *Am. Jour. Sci.* (Ser. 5), **2,** 239–249 (1921).