ATLAS OF ORE MINERALS

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and z. johan

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« I have omitted all those things which I have not myself seen, or have not read or heard of from persons upon whom I can rely. That which I have neither seen, nor carefully considered after reading or hearing of, I have not written about ».

Agricola (De Re Metallica)

Foreword

This book is written for metallogenists and students. It is intended for experts and thus is basically meant to be practical disregarding not only the theoretical aspects of phenomena related to reflectance but also details on microscopic techniques.

The writers' intention is neither to replace nor to perfect comprehensive works such as the text of P. Ramdohr (The ore minerals and their intergrowths, 1980) or the tables of W. Uytenbogaardt and E.A.J. Burke (Tables for Microscopic Identification of ore minerals, 1971).

The brief bibliography which this book contains may come as a surprise to the reader. Our concern was to group homogeneous data based solely on personal observations and measurements, avoiding compilation of inconsistent information.

This book was made possible because of the reference collection of polished sections of the Bureau de recherches géologiques et minières (BRGM), which is, to our knowledge, one of the richest collections in the world. Every mineral studied has been carefully checked by X-ray or by electron microprobe.

Being confronted every day with problems related to the determination and study of metallic minerals, we wanted this book to present as far as possible our own approach while realizing that nothing can replace years of experience in this field.

Part one of the book is devoted to the importance of metallographic methods in the study of, and prospecting for minerals, and to the use of these methods with a description of the apparatus used. Tables of commonly used characteristics help to determine species by progressively reducing the possibilities through successive elimination.

Part two is a detailed monograph of 369 minerals arranged in alphabetical order. Emphasis has been placed on the importance of chromatic phenomena under crossed nicols in determining metallic mineral species and therefore many color photographs are included. So far as we know, this is the first serious attempt of this kind. The reflectance values accompanying the description of most species have been measured under identical operating conditions.

It is the writers' hope that this book will seem easy enough for beginners, sufficiently elaborate for experts and finally, clear and appealing enough to be used by all. Our goal will be achieved if this work leads to a wider use of metallographic methods in Earth Sciences.

Ore petrologists in English-speaking countries are very fortunate that books on metallic minerals are being made available by translation; this comprehensive study by Paul Picot and Zdenek Johan will certainly be a valuable addition to personal librairies and direct use not only to the elucidation of metallic mineral assemblages in general, but particularly to some less-well-known continental associations.

D. H. WATKINSON
Professor of Geology
Carleton University, Ottawa

Principles and Interest of a Metallographic Study

Metallographic study is to metallogeny as petrography is to geology. Its goal is to identify the different mineral species of an ore specimen, to examine their mutual relationships and to study their evolution in time and space.

The first important microscopic study of metallic minerals was carried out by W. Campbell in 1906. He studied samples of ore from Sudbury (Canada). For this, he merely applied the existing microscopic method used for metals, to ore minerals. This method was developed by Osmond in 1890 and is known as « reflected light microscopy ».

Metallic minerals are strongly absorbent, generally opaque in thin section and consequently impossible to study by transmitted light and microscopic techniques used in petrography. Therefore, they must be examined in reflected light, by preparing polished sections which are then examined with a metallographic microscope.

The latter is not very different from an ordinary petrographic microscope, presumably well known to the reader. It is similarly equipped with two nicols (or polarizing plates) permitting observations in plane polarized light or under crossed nicols. It differs mainly in its side-illuminating system (opaque illuminator), conducting light from the light source through a system of condensing lenses and diaphragms and, with a prism (or a semi-transparent glass plate) perpendicular, to the polished surface. The light beam is partly absorbed, partly reflected by the mineral and passes back through the objective, the prism and ocular, to the observer's eye. We shall not go into detail concerning metallographic microscope equipment : the reader should consult the appropriate literature.

Optical phenomena in reflected light are nevertheless much more complex than in transmitted light. Thus, for example, extinction phenomena under crossed nicols or pleochroism do not have the same meaning in reflected light as in transmitted light. Hence, it is extremely difficult, if not impossible, to obtain optical constants. For instance, the measurement of indices of refraction, so simple in transmitted light, requires, in reflected light, reflectance measurements in air and in oil immersion followed by rather complex calculations. In this connection, it should be pointed out that reflectance is one of the rare optical constants that can be calculated without much difficulty. There is very sensitive equipment with photo-electric cells or photo-multipliers for measurement of reflectance. Visual estimation can also be used but this subjective determination is a function of the quality of polishing (as are physical measurements), and the influence of surrounding minerals must be taken into account. Determination may also be distorted by the color of the mineral.

Since the determination of metallic minerals in reflected light cannot be based upon optical constants, as is the case for transparent minerals, metallographic study is far more difficult and subjective, depending to a large extent, on the observer's experience. This experience is evidently acquired only through days or even months of work. The question then is the following : is the effort devoted to learning this method worth while? In other words, except for personal satisfaction that may be felt in roughly determining a mineral association, what is the interest of a metallographic study?

First, the determination of mineral species forming an assemblage and the examination of their mutual relations may be made. Detailed knowledge of the composition of a mineral deposit is the very foundation of methodical research on which genetic hypotheses can be built and from which practical results may be established.

There is no doubt that most mineralization processes result from an assemblage of phenomena which, usually, are not directly perceivable for they may not only be sequential but also superimposed; a later event may partly destroy the traces of earlier processes. Obviously, to reconstruct the stages of formation of mineralization, when nature gives us only the resultant deposit, it is indispensable to know the chemical and physical characteristics of the different phases. This is possible only through microscopic study of metallic minerals and the establishment of paragenesis, that is, of mineral associations resulting from the same genetic process.

The role of metallography in the genetic study of ore deposits is thus of prime importance. Mineral species whose presence is established, give, through their major chemical composition, information on the chemical character of a given mineralization event. Besides, a metallographic study provides information that could not be obtained by any chemical analysis. Ore microscopy permits the study of relationships between mineral phases and determination of their order of crystallization. As has already been suggested, mineralization seldom originates from a single process but involves several processes whose succession may be defined and may eventually be linked to geological events, such as tectonic processes. In this case, early crystallized minerals are brecciated and consolidated by later material. This permits the reconstruction of the chronology of genetic processes. Furthermore, by determining the chemical composition of minerals, the chemical evolution in time and space of successive parageneses, may be established.

From a theoretical point of view, such an approach is extremely important for revealing horizontal or vertical zoning whose presence may lead to practical application. A well-known example concerns chalcopyrite, pyrrhotite and pyrite mineralization worked for copper : because of strong vertical zoning at great depths, the assemblage may change to pyrrhotite and pyrite whose economic value is essentially zero.

A metallographic study is also an important part of the study of deposits for it shows the location of « trace minerals ». While major elements are important, the source of elements may be elucidated by the recognition of trace minerals whose size does not exceed tens of microns and which may be overlooked in a rapid study.

We know that there is some doubt about the significance of minor mineral species because in a given deposit any chemical element may be found in trace amounts. This is, where trace elements and trace minerals are confused. In order that an element be expressed mineralogically, a definite concentration is required and specific conditions must be fulfilled. When an element is expressed mineralogically, cannot be considered as an accidental phenomenon. Numerous studies and more than twenty years experience in this field have convinced us of this fact. For instance, we cannot speak of coincidence, when we systematically find tellurides finely disseminated in volcano-sedimentary deposits. Neither can it be accidental that the nature of these tellurides changes with the chemical composition of lavas with which the deposits are obviously associated.

Neither can we speak of coincidence when small cassiterite crystals are systematically found in sphalerite from these types of deposits.

Because of trace minerals, a metallogenic source may be established.

Metallographic study may also disclose the presence of peculiar textures and structures due to well-determined physico-chemical processes whose existence furnishes implicit information on the conditions of their formation. Textures resulting from the breakdown of solid solution, leading to the formation of two or more immiscible phases is an example of this. As this phenomenon is closely related to temperature (and sometimes also to pressure), the presence of such textures may enable the minimum temperature of deposition to be determined.

The same may hold true for textures resulting from simultaneous crystallization of two phases.

Metallographic study also gives information on the relative stability or instability of the phases. We may often observe textures formed by metasomatic replacement, which may have proceeded along some crystallographic orientation, physical anisotropic plane, interface or perhaps, free from any environmental constraint.

The existence of zones in certain minerals proving that chemical variation has occurred during crystallization, is also important. Similarly, the plastic distortion of minerals may be attributed either to syntectonic crystallization or subsequent deformation.

All things considered, these observations convey information about the texture of the minerals. The study of textures also has considerable practical interest for ore-processing.

In most deposits, the grain size is so fine that it is impossible to estimate the degree of crushing required to properly separate the different constituents. The study of grain size of minerals and the way they are intergrown permits the evaluation of « separation mesh »; that is, the grain size necessary to obtain optimum separation of the different constituents. In other respects, metallographic study is a means of controlling the efficiency of the separation procedure. For instance, a quick microscopic study of a flotation concentrate gives information on its purity or on the reasons why a process has failed.

Furthermore, the location of precious elements or undesirable elements can only be shown by using a microscope. It is desirable, for example, to know the nature of silver in a lead deposit; whether it is present in the galena structure or expressed as secondary argentite resulting from the alteration enrichment, or as primary ruby silver mineralization, etc. These affect mineral dressing and sometimes the economic value of the ore.

Therefore, this method of investigation should be rather universal since it is the first step in the recognition and interpretation of a deposit or a metalliferous province, and is used in the final phase of mining and mineral processing of ore deposits. It is difficult to understand why mining companies resort to metallography only after the final phase of mineral dressing, depriving themselves of many interesting theoretical and practical data.

Many companies often do without metallography (and many other techniques) for questionable economic reasons, although time and money would be saved if a detailed mineralogical study of the mineralization were done.

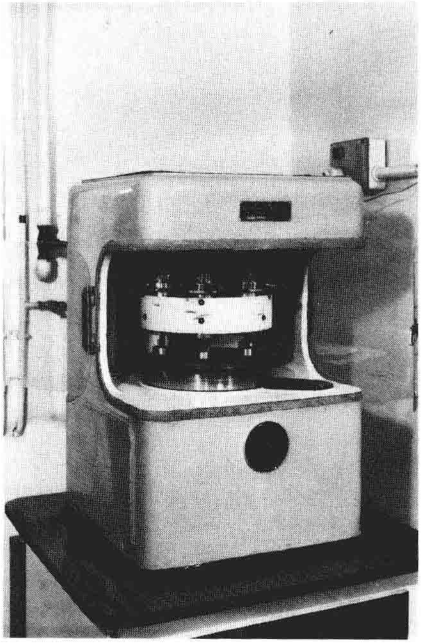
Finally, while it may be unfortunate not to have information concerning the mineralogy of many old mines, it is even more frustrating to see that even now mines are opened, mined and then disappear without leaving any trace of their operation and that no one has had the idea, initiative or curiosity to study their mineralogical problems more closely.

Metallographic analysis may reveal, on a small scale, the genesis of the deposit. If we fail to recognize it or if we disregard it, we deny ourselves information and data which may contribute to a better understanding of the deposit and possibly to a more productive deposit.

The Preparation of polished sections

(by D. Guéant)

As a rule, the methods used in metallography, may be applied to polishing metallic minerals. Polishing laps on which sections are progressively ground, then polished, are used in this method.



Early techniques involved grinding specimens with abrasive papers without first embedding them. They were polished either with alumina, cerium oxide or chromic oxide on old-fashioned lapidary laps, in which the plate -we do not know why- was mounted vertically. Polishing was generally done on cloth or baize laps. This method had many disadvantages. First, since the specimens were neither embedded nor consolidated, fragments tended to break loose during the different stages and scratched the surface. Then, progressively, samples were mounted in gum lac, sealing wax or in rhodopass. Due to the length of the final phase, the polishing cloth had a tendency to penetrate the soft minerals, thus developing relief on harder minerals. This resulted in surfaces of very high relief and a mediocre polish which masked the interesting fine inclusions of trace minerals. To remedy this situation and to avoid developing relief, polishing on lime-tree wood was attempted and this gave good results. Other attempts were made on soft metals such as tin and lead. In this field, the Germans obtained an amazing perfection of polishing. Now, the laboratories of the University of Heidelberg employ a method of polishing on lead disks (Depierreux's automatic machine, opposite photo).

The minerals thus treated have a very uniform surface without relief, breaking or scratching. This method has the disadvantage of taking too long, especially since the lead disks must frequently be resurfaced. For this reason, automatic and complex equipment is very expensive and difficult to keep in good condition.

Finally, the resulting polished sections are almost too perfect because, with this method, we are deprived of a very good criterion of determination, the relative hardness of minerals with respect to each other.

In order to obtain a polished surface without relief and without the inconvenience of having to set up the lead lap periodically, we polish on aluminium (a method recommended by A.J. Hallimond) which has the advantage of lead laps without its defects.

The method that we use may be summed up as follows :

1st step : EMBEDDING THE SPECIMEN

The specimen is cut with a circular diamond saw (Boart Diamond), then put in a drying oven to eliminate all traces of water. It is then placed in a steel or plastic ring with an inner diameter of 4 cm resting on a glass plate. A thin film of silicon grease is placed between the plate and the ring to ensure a tight contact. An adequate quantity of Stratyl A116 varnish to which has been added a small quantity of catalyst X8 and hardener Y3 for polymerization, is poured on the ring and sample. A few hours later when the varnish is completely dry, the mounting is removed. This operation is particularly easy because the polymerization of Stratyl is accompanied by shrinking.

If the sample is porous, a superficial consolidation is undertaken with Araldite AY103 which polymerizes when hot with only one catalyst. To do so, the specimen which is already embedded in Stratyl is impregnated with Araldite and placed in a warming oven at 60 or 70 °C until solid.

2nd step : GRINDING

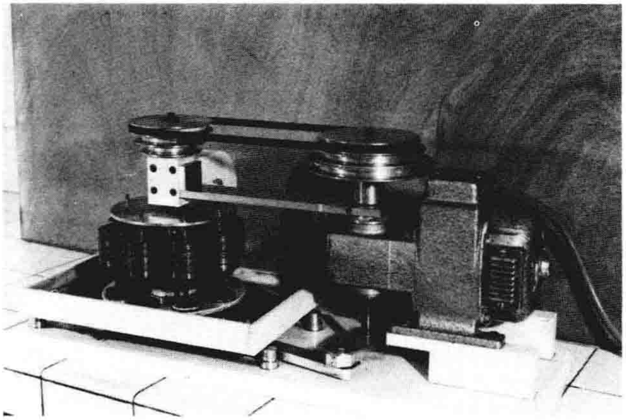
For this operation, either emery or carborundum powder is used.

In the first case, emery with Mecaprex carborundum stuck on the disk of a semi-automatic Mecapol machine is used (this machine is equipped with a sample-holder with a capacity of 6 polished sections).

Abrasives with grain sizes of 120, 240, 400, 600 mesh are used successively, at the rate of a few minutes per abrasive.

In the second case, the section is ground manually on a glass plate with carborundum powder with similar grain sizes to the preceeding ones.

The first rather brief stage of grinding is followed by a second longer stage (about 1 hour) during which 1000 carborundum is employed (6 microns). For this, a special automatic machine designed and constructed at BRGM is used. This machine consists of a moving disk with a reciprocating glass plate and a rotating sample-holder with a capacity of 8 polished sections (e.g. figure below). Once this step is over, the polished section is ready for polishing.

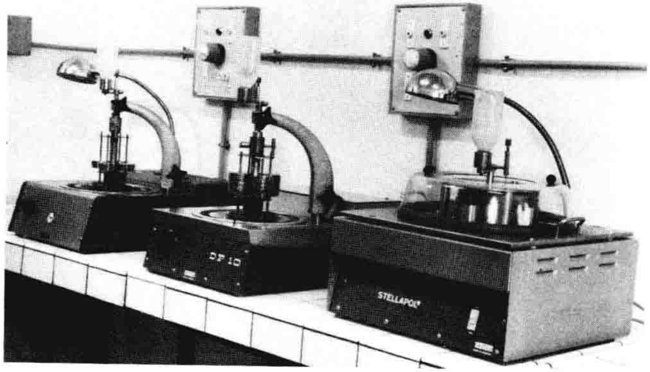


3rd step : POLISHING

A set of small Struers semi-automatic machines (opposite photo) capable of simultaneously polishing four sections is used. Aluminum paper or a very fine-textured Lam Plan Matic is stuck on the machine laps. Polishing time is as follows :
— two periods of fifteen minutes with a 6-micron diamond powder on aluminum paper ;
— two periods of fifteen minutes with a 3-micron diamond powder on aluminum paper ;
— two periods of fifteen minutes with a 1-micron diamond powder on aluminum paper ;
— and a 30-minute final polish with a 1/4-micron diamond powder on a Lam Plan Matic cloth.

A Struers Stellapol machine, in which polished sections are free and thus can be more numerous, is used for the final step. The rotating lap gives each specimen a motion, whose path is traced by a perforated cover defining a three-pointed star. After each polishing step, the sections are ultrasonically cleaned. The diamond powders are kept in suspension in silicon oil mixed with a few drops of alcohol.

As a rule, polishing is then finished.



However, in order to remove the last scratches, and to give the minerals some relief (so their relative hardness can be appreciated), the polishing stage is generally followed by a very short polish with chromic oxide on soft Winter felt. Chromic oxide is obtained by rapidly heating ammonium dichromate and is purified by heating several hours in an electric oven. Alumina (corundum powder) is recommended for very soft minerals or some metals such as Bi, Ag, Sb, Au, As.