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FOREWORD

An International Summer School in ore microscopy was held at Cambridge, England, in the summer of 1963. The primary objective was to spread the knowledge of quantitative methods used in reflected-light microscopy. Furthermore, bringing together students and world leaders in the field from many nations can be expected to have a far-reaching effect on future developments in ore microscopy.

This first International Summer School in Reflected-light Microscopy became a reality chiefly because of the vision and effort of Dr. S.H.U. Bowie of the Geological Survey in London and Dr. N.F.M. Henry of Cambridge University. They, with a small organizing committee, were instrumental in obtaining the support of the Scientific Affairs Division of NATO, and the school was set up as one of the Advanced Study Institutes. A NATO grant covered the expenses of the delegates while at Cambridge, and some of the travelling costs of the European delegates were also defrayed. The Committee was fortunate in obtaining, as well, the loan of much new apparatus for use during the period. In spite of the extra apparatus, and the facilities already available in the Department of Mineralogy and Petrology at Cambridge University, the Committee found it necessary to restrict the membership to a single representative from each of some two dozen countries.

Late in 1962 Dr. Henry, who acted as Secretary for the School, requested that I, as Canadian representative on the Ore Microscopy Commission of the International Mineralogical Association, advise him regarding a suitable nominee to whom he might extend an invitation to fill the one space, in Section A on Ore Minerals, allocated to Canada. He asked that preference be given to a worker of comparatively long experience who would be in a position to acquire and place in use a variety of modern apparatus and who would have facilities for disseminating the knowledge as widely as possible throughout his own country. It seemed to me that Dr. E.H. Nickel of the Mineral Sciences Division of the Mines Branch in Ottawa fulfilled these requirements eminently, particularly since the Department supported in principle not only Dr. Nickel's attending the School but also the provision of facilities and apparatus and the spreading of knowledge throughout Canada by means of official reports. Before transmitting this selection to Dr. Henry, however, the Executive of the Mineralogical Association of Canada were consulted and asked to either ratify the choice or submit the name of an alternative candidate. The result was immediate unanimous approval from this body. When Dr. Nickel's name was proposed, Dr. Henry expressed his pleasure and stated that the Committee were more than satisfied with the choice.

Dr. Nickel's report, which follows, is an account of his attendance at the International Summer School at Cambridge, and well illustrates the range of topics and the degree of detail with which they were discussed. It will be of more than ordinary interest to those active in the field of ore microscopy. It is initially being distributed to members of the Mineralogical Association of Canada, but copies may be obtained by anyone interested upon application to this Branch.

Ottawa, Canada,
January 16, 1964.

Maurice Haycock,
Head, Mineralogy Section,
Mineral Sciences Division.

Mines Branch Information Circular IC 156

REPORT ON THE CAMBRIDGE INTERNATIONAL SUMMER SCHOOL FOR QUANTITATIVE METHODS IN REFLECTED-LIGHT MICROSCOPY

by

E. H. Nickel*

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SYNOPSIS

The International Summer School for Quantitative Methods in Reflected-light Microscopy was held at Cambridge, England, from June 23 to July 2, 1963. This report summarizes the lectures and laboratory sessions given in the following courses: preparation of polished sections, the reflecting microscope, reflectivity of ore minerals, micro-indentation hardness, rotation properties in reflected light, electron-probe micro-analysis, systematic mineral identification based on hardness and reflectivity, and ore mineral textures.

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Direction des mines

Circulaire d'information IC 156

RAPPORT SUR LES COURS D'ÉTÉ INTERNATIONAUX DE CAMBRIDGE SUR LES MÉTHODES QUANTITATIVES EN MICROSCOPIE À LUMIÈRE RÉFLÉCHIE

par

E.H. Nickel*

RÉSUMÉ

Des cours d'été internationaux sur les méthodes quantitatives en microscopie à lumière réflechie ont été donnés à Cambridge en Angleterre du 23 juin au 2 juillet 1963. Le présent rapport donne un aperçu des conférences et des travaux de laboratoire dans le cadre des cours suivants: préparation des sections polies, le microscope à réflexion, la réflectivité des minerais, dureté de la micro-indentation, propriétés de rotation en lumière réfléchie, micro-analyse par sondage électronique, identification systématique des minéraux fondée sur la dureté et la réflectivité, et textures des minerais.

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INTRODUCTION

The Cambridge International Summer School for Quantitative Methods in Reflected-light Microscopy developed from discussions initiated by Dr. N.F.M. Henry of the Department of Mineralogy and Petrology, Cambridge University, and Dr. S.H.U. Bowie of the Atomic Energy Division of the Geological Survey of Great Britain. The use of quantitative methods in the microscopic study of opaque minerals has been retarded by theoretical and experimental difficulties, and a summer school was organized for the purpose of spreading knowledge of quantitative methods among mineralogists.

The summer school was held during the period June 23 to July 2, 1963, and was entirely financed by a grant from the Scientific Affairs Division of the North Atlantic Treaty Organization. The teaching members were selected from among the acknowledged leaders in ore mineralogy; the ordinary and observer members were drawn from more than twenty countries. A list of members of the summer school is given in Appendix I (pp. 43-46) and the course timetable in Appendix II (pp. 47-49).

The author considers himself fortunate in being invited to attend the summer school as the Canadian delegate. He is grateful to the Department of Mines and Technical Surveys for providing travelling expenses to Cambridge and return. The NATO grant provided funds to overall expenses at Cambridge.

This report is an attempt to summarize the proceedings of the summer school and is intended to provide ore mineralogists with an outline of current methods in the quantitative investigation of ore minerals. The author hopes that this report will stimulate interest in the quantitative study of ore mineralogy in Canada.

PREPARATION OF POLISHED SECTIONS

Professor A.F. Hallimond described his method of preparing polished sections of ores in one lecture and one practical session.

Equipment

The Cooke (Vickers) standard polishing machine developed by Professor Hallimond was used at the summer school. The basic features of the machine are as follows: A 6-inch motor-driven steel lap rotates at about 120 rpm. Three specimens are loosely held in a holder positioned eccentrically over the lap. The lap is fitted with a raised band that accommodates a glass disc on which may be mounted a variety of materials, as desired. The specimen holder is caused to rotate by friction developed between the specimens and the lap. The weight applied to the specimen holder can be varied.

Procedure

Mounting: The sample is mounted in a cold-setting plastic. "Ceemar" (available from E.M. Cromwell and Co. Ltd., Bishop's Stortford, Herts., England) is recommended because it has approximately the same hardness as the minerals in a normal lead-zinc ore, and consequently wears down at the same rate during the grinding and polishing procedure.

Pre-Polishing: The mounted sample is first ground with a relatively coarse rolling abrasive (3F silicon carbide) on a steel lap. This is followed by a finer rolling abrasive (Norbide 600) in silicone, the latter being used in preference to water because of its much lower volatility. The prepolishing stage is completed by grinding on a glass lap with 305 emery in silicone. The section now has a matte surface characterized by surface scratches and fractures.

Polishing: In contrast to the pre-polishing stage, which uses rolling abrasive, the polishing itself is done by a fixed abrasive followed by a floating abrasive.

In the polishing stage, fine diamond powder (maximum diameter 2 microns) suspended in silicone is used on an aluminum lap surface. The lap is prepared by glueing heavy paper-backed aluminum foil (available from F.G. Kettle, High Holborn, London) to a glass disc. Only about one-half drop of the diamond suspension is used at one time. The diamond powder becomes embedded in the foil and assumes the character of a fixed abrasive. After polishing the sample for 2 to 5 minutes, the lap is lightly cleaned with alcohol on a tissue, another half-drop of the diamond-bearing fluid is added and the polishing procedure repeated. This procedure is continued until all the larger pits and scratches are removed and the surface is covered with fine scratches.

The final polishing is done with a thick suspension of fine gamma-alumina in water ("Gamma-alumina cream"). A considerable excess of this is applied to a piece of sueded Nylon Simplex cloth stretched over the iron lap, and the sample holder is weighted as lightly as possible. The light weight and the excess of the polishing cream result in a floating action, the section being separated from the lap by a finite thickness of the cream.

A better polish can be given to very soft minerals by the use of magnesia in oil or in silicone, or by using 1/4-micron diamond paste, and holding the mount lightly in the hand.

General Remarks

Six different specimens, exhibiting a wide range of physical characteristics, were polished during the practical session. These were:

1. Lead-zinc ore
2. Stibnite and quartz
3. Covellite
4. Magnetite
5. Graphite schist
6. Niccolite with spinel

The length of time required for the polishing procedure, being related primarily to the hardness of the minerals and to the condition of the surface before polishing, varied with the samples. The average length of time was in the neighbourhood of half-an-hour.

Although the length of the practical session was insufficient to realize the full potential of the method described, nevertheless polished surfaces quite acceptable for most routine purposes were obtained. There is a tendency for rather pronounced relief to be formed between hard and soft minerals during the final polishing stage; this can be reduced somewhat by keeping the duration of the final polishing as short as possible.

The chief advantages of this method of polishing ore samples are that the equipment is relatively inexpensive, the operating procedure is simple and the time required for the production of polished sections is quite short.

References

1. A.F. Hallimond, "On Slow Polishing", Neues Jahrb. Miner., Abh. 94, 1441-1446 (1960).
2. ________________, "Polishing Mineral Specimens", Mining Mag. 108, 197-202 (1963).

THE REFLECTING MICROSCOPE

Introduction

The basic features of the reflecting microscope, including its adjustment and operation, were outlined in lectures by Professors Hallimond and Cameron. These lectures were directed primarily toward a description of the new Vickers Research Polarizing microscope, which was the model available to members of the summer school.

Description of the Vickers Research Polarizing Microscope

As in the case of most other polarizing microscopes available in recent years, the Vickers microscope has a variety of interchangeable units, which makes it possible to use the same basic stand for a wide range of applications. This instrument does not have a built-in light source, but an illuminator may be attached to a cross-bar in the foot.

The reflecting system is different from that used on most other types of ore microscope. The light entering the vertical illuminator is totally reflected toward a glass plate by an inclined mirror located to one side of the microscope tube axis. The light beam is then deflected vertically downward by the glass plate located directly in the tube axis, passes through the objective, and strikes the polished section, thereafter passing back up through the objective and glass plate. This system has an advantage over some others in that complete polarization figures of good intensity can be obtained.

The working space between the microscope stage and the objective is too restricted to permit the use of most of the commercially-available European universal stages. However, the smaller Cooke three-axis stage can be used.

Another distinctive feature of the microscope is that the axis of rotation of the stage and the microscope axis are brought into coincidence by centring the stage, <u>not</u> the objectives, as is usually the case.

Adjustment

1. Light Source

The lamp is placed about 5 inches from the reflector unit, and the filament is focused on the front of the reflector tube and is then later slightly defocused. With the lamp iris diaphragm open, the lamp is adjusted so that the image of the field iris is seen on the surface of the object. This image is centred by inclining the glass reflector. The alignment is completed when:

(i) the filament image occupies the field centrally;
(ii) the lamp iris is seen centrally at the back of the objective (this indicates the correct positioning of the front of the lamp);
(iii) the back of the objective is evenly illuminated (this indicates the correct positioning of the lamp direction).

Finally, the lamp is defocused by moving the lamp condenser forward towards the microscope until the field is more uniformly lit, while the light at the back of the objective is still sufficiently uniform. This illuminating system is "critical" or "defocused", rather than "Kohler". "Kohler" or "focused" illumination is rather better for photography, but it is more complicated and is not quite as well adapted for producing uniformly illuminated polarization figures.

2. Adjustment of the Polarizer

a. The substage illumination is turned on and carefully centred.
b. The iris diaphragm of the Wright ocular is closed until it makes a small circle.
c. The Nakamura plate is placed in the slot of the Wright ocular with the boundary at 45° to the crosswires and passing through the crosswire junction. The boundary between the two halves of the plate is focused by moving the eyepiece up and down.
d. The objective is removed.
e. With the substage polarizer at 0°, the Wright ocular is rotated until the two halves of the Nakamura plate exactly match (and are dark).
f. The reflecting plate is rotated forward and backward as far as it will go. The two halves of the Nakamura plate should match throughout the operation. If they do, the analyzer vibration direction is exactly parallel to the plane of incidence of the reflecting plate. The exact setting of the analyzer, as read from the scale and vernier, is recorded as A_0. Stage "h", below, is then proceeded with.

g. If rotation of the reflecting plate destroys the match of the two halves of the Nakamura plate, the analyzer vibration direction is not parallel to the plane of incidence of the reflecting plate. Then:

   (1) The analyzer is turned 0.1° clockwise, and the polarizer is turned until a perfect match is obtained. The reflecting plate is rotated. If it has no effect, stage "h" is proceeded with. If the match is destroyed, however, the analyzer is rotated another 0.1° and the reflecting plate is again rotated. This is continued until proper orientation of the analyzer is obtained. If clockwise rotation does not work, counterclockwise rotation is necessary, proceeding in steps of 0.1°. The procedure can be a tedious one, but is only done once for any microscope.

h. A levelled polished surface of an isotropic mineral is placed on the stage and viewed in properly centred reflected light, without an objective. With the analyzer exactly at A_o, as determined above, the polarizer is rotated until the Nakamura plate shows a perfect match. The vibration direction of the polarizer is now exactly perpendicular to the plane of incidence of the reflecting plate. A piece of transparent adhesive tape may be used to fix the polarizer in this position permanently.

3. Setting an Objective to Extinction

Most objectives, whether labelled strain-free or not, show some strain. Any such objective should be set to a position of extinction, which may be done by the following procedure. Polars must be exactly crossed.

a. A levelled section of an isotropic mineral (or a silvered plane mirror) is brought into focus. The Bertrand lens is then introduced into the optical path, and the conoscopic figure (polarization figure) will be seen. The condensing lens on the lamp is used to give a uniform background of illumination, i.e., to eliminate the image of the lamp filament.

b. The objective is loosened in its mount by unscrewing it slightly. The objective is turned while watching the polarization figure, which should remain a black cross as the objective is turned. If the centre of the figure becomes grey, or if the cross breaks into two isogyres, the objective is strained. The objective is turned to a position at which the figure is a black cross. This is a position of extinction for the objective. Paper collars can be inserted between the objective and its socket so that, with the objective screwed snugly into its mount, it is at a position of extinction. Unless an objective is mishandled, it is seldom necessary to repeat this procedure.

4. Determination of Rotation Due to Glass Reflector

By means of the rough scale the polarizer is set, in turn, at approximately 15°, 12 1/2°, 10°, 5°, 0°, -5°, -10°, -12 1/2°, -15° from the crossed position. The analyzer is read at each setting, as follows:

(a) with the glass reflector horizontal (true rotation of the incident beam),
(b) with the glass reflector inclined (apparent rotation).

Example:	(a)	(b)	(d)
	0°	0°	0°
	5°	5.25°	0.25°

The difference between these readings (d) is then plotted against the true rotation angle (a). The curve is nearly linear, and will give the correction to be applied to measurements made through the inclined glass reflector.

Selected Reference

1. A.F. Hallimond, "Manual of the Polarizing Microscope". Cooke, Troughton and Simms, Ltd., York, England (1953).

REFLECTIVITY OF ORE MINERALS

One lecture and one practical period, both presented by Professor Bowie, were devoted to the measurement of reflectivity. In addition, Professor Cameron devoted a portion of one of his lectures to the theoretical aspects of reflectivity measurement.

Theory

The reflectivity of a mineral is expressed as a percentage of the intensity of reflected light to the intensity of incident light. For an isotropic mineral, the reflectivity (R) is a function of the refractive index of the mineral (n), the refractive index of the immersion medium (n_o), and the absorption coefficient (k):

$$R = \frac{(n - n_o)^2 + k^2}{(n + n_o)^2 + k^2}$$

For isotropic minerals, the reflectivity is the same regardless of the orientation of the section.

In anisotropic minerals, however, plane polarized light is reflected as two rays (ω' and ϵ') vibrating at right angles to each other, and having different reflectivities. In uniaxial minerals (tetragonal and hexagonal) ω is normal, and ϵ is parallel, to the c-axis. Consequently, in a general section of a uniaxial mineral, one of the vibration directions will always correspond to true ω, and the other will be ϵ', which has a value lying between ω and ϵ, corresponding to true ϵ only when the section contains the c-axis. The reflectivities of the two rays are expressed by:

$$R_\omega = \frac{(n_\omega - n_o)^2 + k_\omega^2}{(n_\omega + n_o)^2 + k_\omega^2} ; \quad R_\epsilon = \frac{(n_\epsilon - n_o)^2 + k_\epsilon^2}{(n_\epsilon + n_o)^2 + k_\epsilon^2}$$

In anisotropic minerals of lower symmetry the optical behaviour varies with the symmetry, and becomes more complex as the symmetry declines. In general, the absorption axes are not necessarily parallel to the principal vibration directions. This means that, although the true reflectivities of rays vibrating parallel to the X, Y, or Z optical directions can be measured in suitably oriented sections, these values cannot be simply related to the refractive indices in these directions.

Measurement of Reflectivity of Ore Minerals (This section is a slightly edited version of a lecture presented by Professor S. H. U. Bowie.)

Introduction

The total reflectivity of a polished mineral surface may be defined as the ratio of the integrated intensity of the light reflected at all angles to the intensity of the incident beam, and may be measured for any given angle of incidence. It is not possible to obtain this value using an ore microscope, so the less well-defined property of specular or direct reflectivity is used. Specular reflectivity is an arbitrary value defined, for practical convenience, as the ratio of the intensity of the light reflected within a small solid angle about the reflection angle (r) to the intensity of the incident beam. Theoretically, if the surface were perfectly polished, the reflected light would be wholly specular. However, in practice, part of the light flux is diffused and is reflected in directions other than that which satisfies the condition that the angle of incidence (i) equals the angle of reflection (r). The path of a single incident ray becomes a cone of light with a strong central ray at the angle of reflection and the other rays falling off sharply as the divergence from this angle is increased.

Reflectivity as Measured Using the Vertical Illuminator

It is more than 50 years now since the relative brightness of two adjacent mineral grains was used as an aid in the identification of opaque minerals, but no method of measuring reflectivity was available until 1927 when Orcel (1) introduced the alkali-metal cell which is used in much the same way as the modern selenium barrier-layer cell. In 1937 Berek (2) introduced the now well-known slit microphotometer. In 1953 Hallimond (3) described a Cooke visual photometer based on the same principle as that of Berek, but differing in construction by the substitution of a small reflector surface for the Lummer-Brodhun comparison prism, by the use of three polars and by the incorporation of a separate light source. With both these instruments, measurements with a precision of about 2 per cent of the measured value can be made, though the latter is much less tedious to use than the former.

In a microscope fitted with a vertical illuminator, light either falls somewhat obliquely on the object, as in the case of the prism illuminator, or incidence is near normal as in the case of the cover-glass illuminator. However, since all objectives are convergent, only in the case of the axial ray illuminating the centre of the specimen does $i = 0°$. For all other rays, in which $i \neq 0°$, R is dependent on the angle of incidence. The departure from $i = 0°$ increases with the convergence of the objective; thus, it is to be expected that there will be slight differences in reflectivity value depending on the numerical aperture of the objective employed. However, this is not serious and is only apparent if there is a wide gap between the reflectivity of the standard and that of the comparison material. The results obtained by Berek on the dependence of reflectivity on aperture angle, using a slit microphotometer, are not the same as results obtained in the Atomic Energy Division of the Geological Society of Great Britain, using a cover-glass illuminator, nor is there an appreciable improvement in comparing reflectivities obtained using objectives of different numerical aperture when the values accepted are with the polarizer in the 45° position. Changing the polarizer from the 0° to 45° position has the effect of reducing the total light reflected by about 30 per cent. In measuring the reflectivity of an isotropic mineral, therefore, it is recommended that all measurements be made with the vibration plane of the polarizer coincident with that of the cover-glass reflector, and that the reflectivity of an unknown be measured relative to a standard of similar reflectivity. For anisotropic minerals, it is recommended, for the same reason, that the uniradial reflectivities be measured and not the value with the polarizer in the 45° position as proposed by Berek.

Choice of Photoelectric Cell

Several types of photometer have been used in recent years. For example, the Photovolt 514M is used by Cameron (4) in the U.S.A., and specialized apparatus has been developed by Marshall and Jones in England for investigations into the optical properties of coal constituents. At the Summer School, a selenium-cell photometer was used, together with an amplifier of new design developed by Evans Electroselenium Ltd. (EEL) in collaboration with the Atomic Energy Division of the Geological Survey of Great Britain.

In this apparatus, the measuring cell is fitted into the eyepiece-accessory slot of the reflecting microscope so that visual observations or photoelectric measurements can readily be made on the same mineral grain. When the cell is in position, its output is fed to a primary galvanometer in which the light spot is arranged to fall on two large selenium cells connected in opposition. The current generated when there is unequal illumination of the two cells is then fed to a secondary spot galvanometer. The sensitivity achieved with this arrangement is such that the reflectivity of mineral grains down to about 20 microns in diameter can be measured in "white" light.

Other types of photoelectric cells are available for reflectivity measurement, each with advantages and disadvantages in use. Silicon cells and cadmium-sulphide cells, for example, both have considerably greater sensitivity at the red end of the spectrum than does the "normal" human eye; the cadmium sulphide cell has the added disadvantage of a relatively slow response. Most photomultiplier tubes have a greater sensitivity towards the blue end of the spectrum and are subject to fatigue on exposure to light. On the other hand, the selenium cell has a spectral sensitivity close to that of the human eye, which makes it possible to compare results obtained with this type of equipment directly with those made by visual photometry. The main disadvantage of a selenium cell is its lack of sensitivity, but this can largely be overcome by the use of a suitable amplifier.

Stabilization of Light Source

One of the major problems in the use of photoelectric methods for measuring reflectivity is the stabilization of the light source. Several methods have been suggested including the use of complicated electronic stabilizers, but it has been found that the light source can be effectively stabilized as follows: A constant voltage transformer is used to supply a partially stabilized current to a heavy-duty accumulator charger that supplies the necessary direct current to the lamp. A heavy-duty battery is connected in parallel with the lamp so that any decrease in current supplied through the charger is compensated for by current taken from the battery, and any excess current from the charger is diverted through the battery. It is necessary to give the battery a charge periodically. When this is done, it is advisable to allow the voltage to settle for an hour or so before using the equipment.

Calibration of Apparatus

One of the main disadvantages of the early barrier-layer cells was the variability in sensitivity over their surface. Obviously this can not be tolerated if precise measurements are to be made, and even now it is still recommended that tests be made to ensure that the cell has a uniform response over its entire surface. This can easily be done by placing a disc, from which a one-eighth sector has been machined out, beneath the cell and rotating it through 360°. If no variation in the galvanometer reading is obtained, the response of the cell is sufficiently uniform.

The next step in the calibration of the instrument is to determine whether the combined response of the cell and galvanometer is linear. This can be done in three ways without reflectivity standards. First, a highly reflecting mineral is placed on the stage and the field iris opened until a reading of 100 is obtained on the galvonometer. Discs from which sectors (e.g. 1/8, 1/4, 1/2 and 3/4) have been cut are then inserted in turn into the cell holder and the readings noted. These should fall on a straight line. The second test involves the use of a series of accurately calibrated neutral density filters that are placed, in turn, in front of the lamp holder after the galvanometer has been set to read 100% with no filter in position. These must be uniform, perfectly clean and placed normal to the light beam. The third method is to use one neutral density filter only with a transmission factor of about 75%. As before, the galvanometer is set to 100% without the filter; the filter is then inserted and the reading noted and the galvanometer reset to this value without the filter in position. Thus if the first reading with the filter is 75%, the galvanometer is set to 75% without the filter, and the filter reinserted; the new value should be 56.25%; the procedure is repeated, yielding successively lower values. It is important to use a filter with a fairly high transmission factor in order to obtain information on the upper portion of the calibration curve.

Choice of Reflectivity Standard

The choice of a suitable reflectivity standard has been the subject of discussion for many years, but none has yet been universally accepted. This results partly because specular reflectivity is only capable of arbitrary definition, because it varies with the angle of acceptance of the test instrument, and because of the difficulty in making measurements at normal incidence. Ideally, standards should cover the range of reflectivity normally found in ore minerals, should have little dispersion, and should be isotropic. They should also be free from inclusions and flaws, should be easily polished without being scratched, and should have a high resistance to tarnish.

A highly-refracting mineral like diamond has been suggested as a primary standard, the reflectivity being calculated for light of different wavelengths from the corresponding refractive indices. However, a transparent medium of this type is only suitable for use with low-power objectives: with high-power objectives, divergence of light within the specimens produces internal flare that augments the true reflectivity by amounts which may vary up to 8 per cent or more in the case of diamond. Thus, for investigations in which high-power objectives are commonly used, transparent minerals do not make suitable standards no matter how carefully they are cut to avoid reflections from the back surface. Sphalerite, transparent quartz, corundum and other materials that have in the past been suggested as standards are, therefore, not recommended. Recently, experiments have been made in an attempt to use different metals deposited on cover glasses, but this presents a difficulty in focusing as well as in interference from the glass surface.

Pyrite has been used for many years as a reflectivity standard and is probably the most useful mineral for this purpose, though it is known that compositional variations have a slight effect on its reflectivity. Recent measurements, using a low-power objective, on 19 specimens from a wide variety of occurrences show values, relative to a diamond standard, of 54.6 ± 0.5, with 90 per cent of the results falling within the range 54.6 ± 0.2, for measurements made with a tungsten filament light source operating at

2850 - 2950°K. Some pyrite specimens also exhibit slight anisotropy, but measurements made at the Atomic Energy Division show that any bireflection caused by this is less than 0.2% of the reflectivity value.

As none of the standards yet proposed is entirely satisfactory, experiments are at present being undertaken at the Atomic Energy Division on the use of basal plates of silicon carbide (suggested by Hallimond) as a low-reflectivity standard and spectrochemically pure molybdenum as a high-reflectivity standard. The silicon carbide is nearly opaque and thus should prove free from the uncertainties, experienced with diamond, due to internal reflections and back-scattering.

Practical Session on Reflectivity Measurements

Apparatus

The apparatus provided for the practical laboratory session consisted of a Vickers Research Polarizing Microscope, an eyepiece fitted with a selenium cell, an amplifier, and a Unigalvo 50 DR galvanometer. A Schott continuous band interference filter was used to measure spectral reflectivity. This instrument provides a continuous spectrum of wave bands with a half-band width of 250 A.

Procedure

The procedure used for measuring reflectivity was as follows: The standards are first placed on the stage, brought into focus and a scratch-free area selected. The ocular is then replaced by the selenium cell and the field and tube irises adjusted until a reading of 20.3 is obtained using the silicon carbide standard. A box with a circular hole in the top and painted dead-black inside is then substituted for the standard and a second reading taken on the galvanometer. The zero setting can then be adjusted to read zero, or the amount of primary flare (black-box reading) can be noted and subtracted from subsequent readings to allow for scattered light which is reflected mainly from the back lens of the objective. If the former technique is employed, the standard is then replaced and the irises adjusted slightly to restore the reading to the standard value. All subsequent readings with the same objective and setting of field and tube irises should then be read off directly.

The next step is to place the unknown on the stage, focus carefully, and select a suitable area. The new reading obtained on the galvanometer should be the reflectivity value. To allow for any slight drift of the galvanometer or for any change in the lamp flux, readings should be taken on the standard and the unknown within the shortest time possible. It is also important to ensure that the field iris and tube iris are coincident, for, if this is not so, stray light from outside the area delineated by the field iris can have an appreciable effect on the reflectivity value. Particular attention should be given to ensuring that both standards and unknowns are level since, if this is not the case, anomalous bireflection will be observed.

Changing the area delineated by the irises has an effect similar to that resulting from changing the numerical aperture of the objective. That is, when compared with a low-reflectivity standard, the value for any mineral decreases with decreasing field area. This, however, does not apply for the whole range of numerical apertures encountered, since the value of pyrite for n.a. 0.15 is 54.07 as compared with 53.52 for an objective of n.a. 0.45. Reflectivity values in the 45° position also show a dependence on numerical aperture; hence, there is no advantage in reflectivities measured in this manner. They are preferably made with the polar in the 0° position, when a maximum value is obtained, thus enabling measurements to be made on grains of minimal size.

To measure the spectral reflectivity the procedure is as before except that a Schott continuous band interference filter is employed to give monochromatic light. The filter is placed so that it just touches the end of the vertical illuminator unit and is normal to the light beam. When this filter is used, measured values are too high by approximately 8.5% of the true value, due to back-reflection from the mirror surface of the interference filter. Provisional measurements show the percentage increase to be constant, so once it is determined the appropriate corrections can be made.

The reflectivity of silicon carbide decreases only slightly with increasing wavelength in the visible spectral region and, therefore, makes a convenient spectral standard. Alternatively, pyrite, for which spectral values have been determined by the National Physical Laboratory in London, can be used.

The simplest procedure in measuring spectral reflectivity is to take a series of "black-box" readings at the required wavelengths, then to take a series of readings with the standard and finally a series with the unknown. This permits an automatic correction for the spectral sensitivity of the cell to be made, and, if it is arranged so that the maximum reading in the series approximates to a deflection 100% on the galvanometer, then the spectral curve for an unknown can be calculated quite quickly.

Sources of Error in Reflectivity Measurements

In a colloquium conducted by Dr. Piller, the possible sources of error in reflectivity measurements were discussed. These can be enumerated as follows:

I - Specimens and Standards

a. Degree of polish;
b. Presence of internal reflections;
c. Lack of precise levelling.

II - Microscope

a. Mechanical instability, i.e., focusing devices, stage, etc.;
b. Stray light, reflected light from lens and glass surfaces, quality of blooming, and stray light at lens mountings;
c. Differing aperture;
d. Inaccuracy of focus;
e. Varying field diameter.

III - Measuring Device

a. Instability of light source;
b. Instability of amplifiers;
c. Fatigue of photocell;
d. Non-uniform sensitivity of cell surface;
e. Poor quality of filter or monochromator;
f. Dispersion effects, if white light used.

Calculation of Refractive Indices from Reflectivity Values

Because of the relationship of reflectivity to the refractive indices of the substance and of the immersion medium, the refractive index of a mineral can be calculated from reflectivity values obtained in different immersion media. This relationship is expressed thus:

$$n = \frac{n_A^2 - n_B^2}{2\left\{n_A\left(\frac{1 + R_A}{1 - R_A}\right) - n_B\left(\frac{1 + R_B}{1 - R_B}\right)\right\}} ,$$

where n = refractive index of the mineral,

n_A = refractive index of immersion medium A,

n_B = refractive index of immersion medium B,

R_A = reflectivity of mineral in medium A,

R_B = reflectivity of mineral in medium B.

Dr. Piller presented several charts showing the relationship between reflectivity measured in air, reflectivity in oil (with refractive index of 1.515), the refractive index, and the absorption coefficient. The charts show that at relatively low values of reflectivity and absorption coefficient the accuracy of refractive index determinations is highest. On the other hand, the accuracy decreases with increasing reflectivity and absorption coefficient. Dr. Piller expects to publish a paper on this subject in The American Mineralogist.

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MICRO-INDENTATION HARDNESS

The measurement of hardness of ore minerals by micro-indentation methods was covered in one lecture and one practical period, both given by Dr. Bowie. In addition, one lecture and one practical period were devoted to the systematic identification of ore minerals by a combination of micro-indentation hardness and reflectivity.

Dr. Bowie distributed copies of his lecture to all members of the summer school. This lecture is so comprehensive, that, with the exception of some minor changes, it is given here in its entirety.

Hardness Measurement in Theory and Practice

Introduction

The hardness of a mineral can be measured in six basically different ways, but only three are suitable for determining the hardness of mineral grains. These are the scratch test, the static indentation test, and the test for abrasion or polishing hardness.

Scratch hardness tests have been widely used by mineralogists since Mohs' scale was proposed in 1820, and it is remarkable how regular is the relationship between the Mohs values for the first nine minerals in the scale and their respective Vickers hardness numbers. The gap between corundum and diamond, however, is very much greater than that between any other adjacent minerals in the series. An attempt to refine scratch test techniques by mechanical means was made by Talmage (1) in 1925 and promising results were obtained. However, the method never became standard practice, mainly because of the delicate nature of the instrument used and because of the difficulty in distinguishing scratching from fracturing in hard minerals.

Van der Veen (2) in 1925 and, more recently, Schneiderhöhn (3) and Uytenbogaardt (4) have made use of polishing hardness to compare the relative hardness of two adjacent minerals. As polishing techniques have improved, however, this method has tended to be less commonly used, since with the use of diamond abrasives on metallic laps this property is generally not observable.

The modern trend has been towards the use of static indentation tests using low-load diamond indenters. Unfortunately, there are no less than five main shapes of indenter in use, namely, Vickers pyramid, Knoop pyramid, triangular pyramid, simple cone, and double cone. This multiplicity has had the effect of retarding what might otherwise have become a universally adopted method of hardness determination.

The history of the use of static indenters for determining the hardness of minerals commenced during World War II with the work of O'Neill(5), Siebel (6) and Winchell (7) and, since this time, numerous instruments have been used and numerous hardness data published. The original and most commonly used types of indenter are the Vickers indenter and Knoop indenter, and it would appear that neither the triangular nor cone-type indenters that were introduced later have any advantage over the earlier two. The Knoop indenter is an elongated pyramid with two faces making an angle of 130° to each other and the other two making an angle of 127° 30'. The shape of a perfect impression is that of a parallelogram in which one diagonal is about seven times the length of the other and thirty times the depth of the impression. The Vickers indenter is a square pyramid with a 136° included angle between opposite faces so that a perfect indentation is a square with diagonals seven times the depth of penetration.

Low-Load Micro-Indentation Hardness Tester

The method of operating the various low-load static indenters is basically similar. In each the diamond is brought into contact with the mineral surface and a known load is applied. Loads available with different models vary from 0.1 g to 500 g. The apparatus on loan at the Summer School, manufactured by Associated Automation Ltd. to the design of Guest, Keen and Nettleford Ltd., was used to illustrate the technique of low-load micro-indentation testing.

The GKN instrument has the advantage over others in that it is designed for use on any good bench microscope. It consists of an upper mounting plate with a threaded adapter to secure it to the base of the vertical illuminator in place of the normal objective. Below this plate is a rotatable plate that carries the diamond pyramid and two centralizing objectives. The indenter is mounted on a counterpoised beam suspended by two beryllium-bronze leaf springs, set at right angles to ensure rigidity to horizontal and vertical deflections, but with freedom to rotate.

To test the hardness of a mineral grain, the indenter is rotated into position in place of an objective and the substage of the microscope is raised until the polished section is just clear of the diamond pyramid. The fine-focusing control of the microscope is then used to lower the indenter with a slow steady movement until it rests on the mineral surface. The application of the full load is indicated electrically by a miniature neon lamp which is arranged to be in circuit when the beam is in balance. When the specimen takes the load, the circuit is broken and the neon lamp glows with reduced intensity. The load is applied for 15 seconds, then the indenter is removed, first by using the fine-focusing control, and then by the coarse adjustment on the substage. The objective is then brought back into position, the indentation oriented by means of a mechanical stage, and the distance across the diagonals measured by means of a screw-micrometer eyepiece.

Theoretically, the hardness value is the ratio of the load applied to the surface area of the indentation and can be calculated by use of the formula:

$$H = (2L \sin\theta)/d^2$$

where H is the diamond pyramid hardness number, L is the load in kilograms, d is the length of the diagonal in millimetres, and θ is half the included angle between opposite pyramid faces. Thus, in the case of a 136° indenter $2 \sin \theta = 1.8544$, so that:

$$H = 1.8544L/d^2$$

For convenience, hardness numbers are normally read off tables which give solutions to the above equation for standard loads.

Factors Affecting Hardness Determinations

To measure the hardness of a mineral it is not sufficient to merely make a hole in the mineral surface and measure the diagonals. A number of factors must be taken into consideration.

a) Instrumental Errors

Three instrumental factors are of importance and should not be overlooked when it comes to the comparison of results obtained with different instruments. These are:

1. The load applied must be known accurately.
2. The angle θ must be accurately machined and constant over the portion of the indenter face used in tests.
3. The diagonals must be measured accurately.

Inaccuracies in applying the load commonly result from the faulty operation of the instrument, from inertia or vibration effects, from lateral movement of the indenter, and from variations in the time over which the load is applied. It is, therefore, essential to ensure that the apparatus is properly equipped to give accurate and reproducible results on a hardness standard before it is used for mineral determination purposes.

b) Vibration Effects

Perhaps the most common source of error in low-load hardness testing is vibration caused by electric motors, heavy traffic,and shocks such as a door slamming or a weight being dropped on a floor. Every precaution must, therefore, be taken to reduce this effect as much as possible. The method employed in the Atomic Energy Division laboratories is to mount the whole apparatus, complete with microscope, on a heavy stone slab which is supported on a Sorbo-rubber mat and six instrument shock absorbers. With this arrangement, reproducibility of results over the range of hardness commonly encountered in ore minerals is better than 5 per cent of the measured value.

c) Time of Indentation

The exact time of indentation is not so important when measuring the hardness of minerals as is the case in measuring the hardness of such materials as plastics and lacquers, in which penetration by the indenter increases markedly with time. However, a certain amount of creep occurs in minerals, so that the time of measurement must be standardized. It is not considered advisable to prolong the indentation time to as much as 60 seconds, since the longer the period of loading the greater the chance of vibration effects producing erroneous results. Hence, a compromise has to be reached,and this is now generally accepted as 15 seconds.

d) Measurements of the Impressions

The normal procedure in measuring impressions is to use a rotating drum eyepiece micrometer on an optical microscope, and the accuracy is thus dependent on the resolving power (R) of the objective. This is:

$$R = 0.5\lambda / n.a.$$

where λ is the wavelength of the light used and n. a. is the numerical aperture of the objective. With an oil immersion lens of n. a. = 1.30 using white light (average $\lambda = 0.55\mu$) the resolving power is about 0.2μ; hence the calibration of the instrument can theoretically be made to an accuracy of $\pm 0.4\mu$, which amounts to about ± 8 per cent of the hardness number at 2000,or about ± 0.6 per cent at a hardness number of 20. For very precise work, therefore, it is advisable to standardize on monochromatic light near the blue end of the spectrum both for calibration of the instrument, using an optical grating, and for subsequent diagonal measurements.

When measurements are made on the projected image of the indentation at a magnification of X1000 on the screen, the diagonals can be measured with an accuracy of somewhat better than $\pm 1\mu$. With such equipment, however, eyestrain is a problem unless a strong light source, such as a mercury vapour lamp, is used for illumination.

The greatest difficulty in making indentation measurements is in recognizing the extremities of the diagonals due to the disturbance of material around the impression. Furthermore, the apparent length of the diagonals varies with the numerical aperture of the objective employed. The amount by which the length, L, is too short has been shown to be equal to $\lambda/2$ n.a. for a 136° indenter, where λ is the wavelength of the light used and n.a. the numerical aperture of the objective. Thus, it would be preferable if the wavelength of the light used and numerical aperture of the objective could be standardized.

e) Effect of Polishing Method

The hard amorphous surface layer normally produced in polishing may result in the hardness value appearing greater with low loads, but since this layer is usually no more than 10-20 μ thick (but may be 100 μ or more), the hardness value is not likely to be affected when loads of 100 g are used. However, for loads of 10 g or less the effect of the surface layer may become more serious. Over the range of hardness from VHN 70 to 600, no appreciable difference can be attributed to polishing, whether by diamond dust, magnesium oxide and gamma-alumina on lead laps or by gamma-alumina on a cloth lap. The mean values obtained were all found to be within or, in the case of sphalerite and löllingite, just outside the standard deviation limits of the measurement.

f) Orientation of Mineral Grain

Little work has yet been done in relating hardness values to precise crystallographic directions, but it has been observed that some minerals show marked directional hardness anisotropy.

This is particularly noticeable in fibrous and prismatic crystals of minerals such as löllingite, pyrolusite, enargite, zincite, millerite and niccolite. The range in hardness value in löllingite, for example, is from VHN 421 to 920, depending on orientation alone. This feature is of considerable value in mineral diagnosis, though it presents a problem in obtaining maximum and minimum or mean hardness values when only a few grains are available in the section under examination.

g) Degree of Crystallinity and Composition

Variations in hardness due to the degree of crystallinity have been noted particularly in the case of hematite and goethite — the values for microcrystalline varieties being only about 70 per cent of those obtained on coarsely crystalline material. Hardness number variations can also be expected with changes in chemical composition, but insufficient work has yet been done on this to establish trends. Pudovkina (8), for example, has shown that high-iron sphalerite tends to have a lower VHN than low-iron sphalerite. However, since the reverse was noted by Henriques (9), further investigations are necessary.

h) Effect of Elastic Recovery

The hardness number assigned to any particular substance is usually based on the dimensions of a recovered impression, and it has been assumed that the recovery in diagonal length is independent of the load. This would mean that, for low loads, there would be a tendency for the hardness number to increase. Theoretically, however, the hardness number should be independent of the load, which implies that the contraction of the diagonals is proportional to the unrecovered diagonal lengths, and this has, in fact, been shown to be the case in recent investigations.

It is now generally agreed that the reasons for apparent increase in hardness with decreasing load are:

1. The slip mechanism producing deformation is not quite the same for small indentations as for large ones.

2. Polishing usually produces a hard amorphous layer that would lead to higher values being obtained when the depth of the penetration is small compared with the thickness of the layer.

3. Faulty adjustment of the test instrument.

4. Inertia in beam-type testers becomes important when the mass of the beam is greater than that of the applied load. The inertia results in the obtaining of anomalously high hardness values for low loads on equipment not designed for low-load testing. For this reason, instruments designed for test loads of 10 to 100 g should not be used with 0.1 to 1 g test loads if useful results are to be obtained.

Shape and Quality of Indentations in Minerals

Much of the preceding discussion applies to perfect indentations, which are not often encountered in practice. Usually there is some pile-up or sinking-in of the mineral at the edges and this behaviour makes accurate focusing difficult. Also, the shape of the indentation is often not square, but rather a parallelogram with concave or convex sides. These features, though making the accurate determination of hardness more difficult, are nevertheless of considerable diagnostic value. Several types of indentation occur, the most common being: perfect (p), slightly fractured (sf), fractured (f), concave sided (cc), and convex sided (cv). The pile-up adjacent to the indentation usually causes fracturing that may be related to cleavage, parting or twinning, and this also is of diagnostic value. An example of two minerals with similar hardness, but with quite different shapes of indentation, are chalcopyrite and pentlandite. The former mineral produces impressions with nearly straight edges, while in the latter the impressions are markedly concave.

The indentations produced in prismatic sections of chalcocite, covellite, ilmenite and hausmannite vary considerably with orientation. In one direction the indentations have two opposite sides concave and two convex; on rotation through 45°, however, the indentations are elongate or kite-shaped, with slightly concave edges. In such instances of marked hardness anisotropy, it is usually preferable to take separate readings on each diagonal than to attempt to get an average value by taking the mean hardness in two directions.

In some minerals such as graphite and molybdenite, impressions are ill-defined and prove extremely difficult to measure accurately. Fortunately this is rare, as is surface flaking or cracking adjacent to indentations even in brittle minerals such as pyrite, though with loads of more than 100 g this can be a serious drawback in obtaining precise results.

Number of Indentations Necessary

It is normally easier to produce an average hardness number for a particular mineral than it is to establish the range, since an approximation to the former can be obtained by indentations on a few randomly orientated grains. A mean value therefore would seem to be recommended, except in cases of marked hardness anisotropy.

The precise number of indentations necessary to obtain a useful average is a matter of judgement rather than statistics, and it suffices to say that each investigator should subject himself to a self-consistency test by determining the probable error in a series of determinations. This is done as follows:

If the hardness numbers h_1, h_2, h_3 ---------h_n are obtained in n tests on the same specimen and the respective deviations from the mean are d_1, d_2 ---------d_n, then the probable error of any individual observation is expressed by

$$0.6745 \sqrt{\Sigma d^2 / (n-1)}$$

and the probable error of the mean is

$$0.6745 \sqrt{\Sigma d^2 / n(n-1)}$$

Results by Winchell (7) and by the staff of the Atomic Energy Division show that the probable error on individual readings is about 3 per cent. It is advisable to reject the occasional badly fractured indentation, otherwise a much larger spread will be obtained.

(This is the end of the transcript of Dr. Bowie's lecture.)

Practical Session on Hardness Measurements

The low-load GKN micro-indentation hardness tester described in a previous section, and mounted on a Vickers ore microscope was used in this laboratory session. Two test blocks of nickel-chrome steel with nominal hardnesses of VHN 300 and VHN 800 were used as standards. (These standards are available through Associated Automation Ltd., 70 Duddin Hill Lane, London N.W. 10, England.) The hardnesses of certain specimens of oxides, sulphides and sulphosalts were measured.

Discussion on Hardness Measurements

In a discussion on the accuracy of hardness measurements, Professor Hallimond emphasized the importance of the illumination in obtaining good resolution of the micro-indentation image. He recommended use of a diffusion screen in the light path. Dr. Piller recommended that the objective aperture should be standardized for the measurement of indentations.

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ROTATION PROPERTIES IN REFLECTED LIGHT

Two lectures on this subject were given by Professor E.N. Cameron, and several laboratory periods, under Professor Cameron's direction, were devoted to the measurement of the rotation properties of ore minerals.

Theory

The theory of reflected-light optics is very complex, and will not be dealt with in detail in this report. The basic principles are as follows: When plane-polarized light strikes a polished surface, some of the light is absorbed, some may be transmitted, and the remainder is reflected. The reflected light, in the general case of an absorbing, anisotropic mineral, comprises two beams vibrating in the plane of the section at right angles to each other, but out of phase and with different amplitudes. These two components combine to produce an elliptical vibration, which can be analyzed by ascertaining its rotation properties. The properties measured are the angle of rotation (A_r) and the phase difference (2δ), both properties being characteristic for a particular mineral species. The rotation angle (A_r) is a function of the refractive index of the immersion medium (n_o) and the refractive indices in the vibration directions of the ordinary and extraordinary rays (n_ω and n_ϵ, respectively):

$$Ar = \frac{n_o (n_\epsilon - n_\omega)}{n_\epsilon n_\omega - n_o^2}$$

The phase difference (2δ) is a measure of the ellipticity of the ellipse of vibration.

Equipment

For the quantitative measurement of rotation properties, it is essential to have a polarizing ore microscope equipped with an analyzer that can be rotated through at least 90° and a vernier that permits its position to be read to 0.1°. The objectives should be as strain-free as possible.

Accessories required for the measurement of the rotation angle are a Wright slotted ocular and a Nakamura plate.

For the measurement of phase differences, an elliptical compensator, equipped with scale and vernier, is required. The most suitable compensator is a rotating mica plate with an optical thickness of 1/6 λ to 1/20 λ.

Measurement of Rotation Properties

Detailed instructions for the adjustment of the microscope and the measurement of rotation angle and phase difference were provided by Professor Cameron. These are as follows:

a. Adjustment of Microscope - The following special adjustments of the microscope must be made in the order given, prior to measurement:

1. The polarizer must be oriented accurately with the vibration plane parallel to the rotation axis of the reflecting plate; white light may be used for this. The crossed position of the analyzer is determined and recorded as A_o.

2. Each objective to be used in measurement must be set at a position of extinction and carefully centred.

3. Adjustments under 1 and 2 must be checked by observing the levelled section of covellite, with nicols crossed, in light of $\lambda = 589 \mathrm{m}\mu$. If adjustments are correct, extinction positions will be 90° ± 0.5° apart.

4. With the nicols exactly crossed, and observing the polarization figure of magnetite, the zero position of the mica compensator is now determined at $\lambda = 589 \mathrm{m}\mu$. Record this position as G_o.

5. The orientation of fast and slow rays of the mica plate is to be determined, using a gypsum (full-wave) plate.

b. Measurement of A_r for Pyrrhotite

1. Place the polished section of pyrrhotite on the stage and examine under exactly crossed nicols. Use a 16 mm objective. Pick a grain that appears to show brightest anisotropism. Use light of $\lambda = 589\,m\mu$.

2. Determine the four extinction positions of the grain, and record. They should be nearly 90° apart. If not, alternate pairs of positions should show the same degree-interval. Calculate the bisectrix between two adjacent extinction positions. This gives one 45° position.

3. Turn the stage to bring the grain to the 45° position.

4. Insert the Nakamura plate in the Wright ocular, with the plate boundary oriented at 45° to the ocular crosshairs and passing through the crosshairs junction.

5. Rotate the analyzer until the two halves of the Nakamura plate exactly match. Record the setting of the analyzer as A_1.

6. Rotate the stage 90°. The mineral is now at a second 45° position.

7. Rotate the analyzer until the Nakamura plate again shows a perfect match of the two halves. Record the setting of the analyzer. Call it A_2.

8. Calculate $A_r = (A_1 - A_2)/2$. This is the observed A_r. This value must be corrected for rotation by the glass reflector (p. 7) to obtain the true A_r of the mineral.

c. Qualitative Determination of the Phase Difference $\Delta_{x,y}$.

1. Using a low-power objective, focus on a grain of covellite showing strong anisotropism. Determine the extinction directions of the grain. Rotate the stage to bring the grain to a 45° position.

2. Insert the filter, adjust to $\lambda = 589\,m\mu$.

3. Rotate the analyzer clockwise. If this produces extinction, proceed with 4. If not, rotate the stage 90°.

4. Remove the filter from the system.

5. Insert the gypsum plate. The colour of the grain will be yellow, indicating that the sign of $\Delta_{x, y}$ is negative.

d. Determination of Phase Difference with Mica Compensator, at $\lambda = 589$ mμ.

1. Find a grain of covellite showing strong anisotropism. Determine the extinction positions. Use a low-power objective.

2. Rotate the stage to bring the grain to a 45° position.

3. Rotate the analyzer counterclockwise. If this produces extinction, proceed with step 4. If not, rotate the stage 90°.

4. Attach a high-power objective, focus, and centre if necessary. Remove the eyepiece and substitute a pinhole eyepiece, or insert a Bertrand lens and focus on the polarization figure, which will now be seen. It will consist of two isogyres, in the northeast and southwest quadrants.

5. Insert the mica compensator in the tube slot.

6. Rotate the mica compensator and analyzer simultaneously until the isogyres combine to form a cross. The centre of the cross must be black. This is the position of compensation.

7. Record the settings of analyzer and mica compensator as A_1 and G_1, respectively.

8. Rotate the stage 90° and repeat step 6, recording the settings of the analyzer and mica compensator as A_2 and G_2, respectively.

9. From the value of $A_r = \left(\frac{A_1 - A_2}{2}\right)$ and the values of G_1 and G_2, calculate β_G (i.e., the angular rotation of the mica compensator from its zero position coincident with the analyzer to its position of compensation).

The following possible cases arise, depending on the amount and direction of rotation of the compensator:

(i) The angular rotation of the compensator is in the same direction as that of the analyzer, but larger:

$$\beta_G = \frac{G_1 - G_2}{2} - A_r$$

(ii) The angular rotation of the compensator is in the same direction as that of the analyzer, but smaller:

$$\beta_G = A_r - \frac{G_1 - G_2}{2}$$

(iii) The compensator and analyzer are rotated in opposite directions:

$$\beta_G = A_r + \frac{G_1 - G_2}{2}$$

If the mica plate is rotated clockwise and the analyzer counterclockwise, the sign of β_G is positive; if the mica plate is rotated counterclockwise and the analyzer clockwise, the sign of β_G is negative.

10. Calculate the phase difference $2\ \delta$ from the formula:

$$\sin 2\ \delta = \sin 2\beta_G \sin \Delta_G$$

where $\Delta\ G$ is the phase difference for the mica plate for the wavelength of light in use, and β_G is the corrected angle for compensation.

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ELECTRON PROBE MICRO-ANALYSIS

One lecture was given on this subject, and one practical session was devoted to the operation of the new model of an electron probe microanalyzer developed by Dr. J. V. Long of Cambridge. Both sessions were conducted personally by Dr. Long. A lecture on the application of the electron probe to the study of ore minerals was given by Professor Millman.

General

The principle of the electron probe microanalyzer is as follows: A finely-focused beam of electrons is directed on to the surface of the material to be analyzed. This produces a secondary fluorescent radiation that is characteristic of the elements in the sample, and which can be analyzed by suitably placed spectrometers.

Electron probe microanalyzers are now being made by six different manufacturers, and it is estimated that approximately 150 instruments are in use at the present time, although the number is increasing rapidly. All of these instruments operate on the same basic principle, but vary in a number of features, such as provision for optical viewing, type of scanning mechanism, arrangement of the spectrometers, and details of construction.

If the sample is non-conducting, it must be given an electrically conducting surface. This is generally done by evaporation. Coating materials used successfully are aluminum, copper, and carbon. Carbon is preferable because it does not obscure the reflected light properties as much as do the metals.

Operating Conditions

Operating voltages are generally between 20 and 40 kV. High current and long working distance are desirable. The current obtainable depends on several factors:

$$i = \frac{K V_o (d)^{8/3}}{(Cs)^{2/3}},$$

where i = current,

K = a constant,

V_o = accelerating voltage,

d = diameter of probe, and

Cs = spherical aberration of magnetic lenses.

The depth of penetration depends on the energy of the electron beam, and is generally between 1 and 2 microns.

Corrections Required in Analysis

In elemental analysis, the accuracy of the results is influenced by absorption, fluorescence, and the atomic number effect. The absorption is a function of take-off angle and the absorption coefficient of the substance being analyzed, and can be calculated; the effect of this factor can be reduced by increasing the take-off angle. The fluorescence effect is due to the fluorescent radiation of one element exciting the fluorescent X-radiation of a second element, and can also be calculated. The atomic number effect arises from two factors--the electron backscatter, and the deceleration process in the specimen. These two factors are mutually conflicting, and no means has yet been found to calculate the net result accurately.

Features of the New Prototype Constructed by J. V. Long

The new instrument designed by Professor Long has been changed considerably from his earlier instrument. Like the earlier model it will be manufactured and marketed by the Cambridge Instrument Company Limited.

The new model has "reversed optics", i.e., the electron gun is below the specimen and the electron beam travels upward. The sample holder is constructed to accommodate polished sections, thin sections, and polished thin sections, as well as a standard. The sample holder is positioned by two micrometer screws that can be read to about 2 microns. The section can be illuminated by both transmitted and reflected light, using one light source and a system of mirrors, and polarizing and analyzing filters are incorporated in the optical train.

For electron probe analysis, the optical system is withdrawn from the electron beam path by a simple arrangement. The electron beam can be used for spot analysis, linear analysis, or areal scanning. In areal scanning, an area 0.5 mm square is scanned by rapid deflection of the electron beam. The fluorescent image of the sample is projected on to a viewing screen. The size of the area scanned can be reduced while maintaining the same size of projection, thereby achieving a magnification of the field image. With a scanning area 20 microns square, an image magnification of about 3000X is possible.

In addition to the fluorescent image, an electron detector provides an electron back-scatter image which is projected on to a second screen.

For quantitative analysis, an automatic typewriter is wired to the spectrometer output so that the actual numbers of counts (per unit of time), for the sample being analyzed and for the standard, are typed out.

Dr. Long is currently working on a further modification in which the take-off angle is expected to be in the neighbourhood of 75°. He hopes to achieve this by positioning the spectrometer inside the objective lenses.

Application of the Electron Probe to the Study of Ore Minerals

Professor Millman reported that an electron probe has been in operation at the Royal School of Mines for the past 2 1/2 years. During this period of time, several problems in ore mineralogy have been investigated by means of the instrument. Examples include:

a) Study of the Opaque Minerals in the Merensky Reef of the Bushveld Complex

The electron probe has proved indispensable in identifying the different platinum-palladium phases present, and several new mineral phases have been discovered by the use of this instrument.

b) Vanadium-and Nickel-Bearing Magnetites

Electron-probe microanalysis of magnetite containing up to 7% $V_2 O_3$ has shown that this element is distributed homogeneously and is, therefore, believed to be in solid solution. On the other hand, trevorite, the nickel-bearing analogue of magnetite, has been found to occur as a separate mineral. It is optically indistinguishable from magnetite.

c) Titanium Content of Exsolved Ilmenite

This instrument has been used to determine the titanium content of tiny ilmenite lamellae exsolved from magnetite in a basalt from India.

d) Congolese Columbo-Tantalates

The Nb-Ta minerals from certain Congolese occurrences are found in complex intergrowths, The electron probe enabled minerals such as simpsonite, thoreaulite, calcium-microlite and lead-microlite to be distinguished. Furthermore, electron probe microanalysis of mill products showed that the high tungsten content of columbite-tantalite concentrates was due to the presence of separate tungsten minerals, ferberite and huebnerite.

e) Manganese Ores from Greece and Egypt

Nine manganese-bearing minerals have been found in these ores. Electron probe microanalysis showed zonal distribution of iron in single crystals of braunite. The instrument also demonstrated that some psilomelanes are found to be lacking in barium, an element that has hitherto been considered an essential constituent of psilomelane.

f) "Merumite" from British Guiana

An electron probe microanalysis of a substance believed to be merumite showed that it was actually composed of a mixture of Cr_2O_3, V_2O_5 and Al_2O_3.

g) Hydrometallurgical Problems

The electron probe microanalyzer has been successfully used in a number of hydrometallurgical problems, particularly in the study of reactions. For example, chromite leached with sodium hydroxide has been shown to develop a thin rim of magnetite through which the chromite must diffuse for the reaction to proceed. The inhibition of wolframite leaching by sodium hydroxide has been shown to be due to the depletion of tungsten and the enrichment of iron and manganese in the outer layers of the grain.

h) Summary of Problems Suitable for Investigation by the Electron Probe Microanalyzer

The types of mineralogical problems particularly amenable to investigation can be summarized as follows:

a) Isomorphous series, zoning, etc.
b) Natural diffusion fronts
c) Artificial diffusion fronts
d) Colloform structures
e) Exsolution textures

SYSTEMATIC MINERAL IDENTIFICATION BASED ON HARDNESS AND REFLECTIVITY

A lecture on a system of mineral identification based primarily on measurements of micro-indentation hardness and of reflectivity was presented by Professor Bowie. One practical session was devoted to identifying an unknown ore mineral by this method. The procedures followed have been discussed in preceding sections. Following are some comments made by Professor Bowie on the systematic identification of ore minerals:

Introduction

It is just over 50 years since Campbell (1) made the first important contribution to the systematic determination of ore minerals by suggesting the possibility of identifying opaque minerals using a reflecting microscope and observing such properties as colour and etch reactions. The importance of this technique was quickly realized and by 1916 Murdoch (2) had published his well-known system of opaque mineral identification based primarily on colour and scratch hardness. Further contributions to the systematic determination of minerals were later made by Davy and Farnham (3), Schneiderhöhn (4), Van der Veen (5), Ramdohr (6), Short (7), and Uytenbogaardt (8).

Short's system was widely adopted, and was the standard system when Bowie commenced work on ore minerals in 1946. Bowie soon became aware of the difficulties and ambiguities associated with this scheme, which is basically dependent on scratch hardness, etch reactions and microchemical tests, and he resolved to attempt to make ore mineral identification more rapid and at the same time more reliable. Thus, in odd intervals available between undertaking determinative work on uranium ores, Bowie tried to improve the method of measuring reflectivity devised by Orcel. It soon became clear that the accurate determination of reflectivity was a valuable aid to mineral identification, but that there were overlaps in reflectivity values which meant that reflectivity is not unique for each mineral species any more than is refractive index for transparent minerals. Hence, Bowie looked for some other property that might be measured with equal precision, and by 1953 it was apparent that the combined use of reflectivity and micro-indentation hardness provided a useful basis for the systematic determination of ore minerals.

System of Identification

Provided a good polished surface is prepared with the minimum of surface deformation, reliable values for reflectivity and hardness can be obtained quickly and easily on most ore mineral grains down to about 20 to 30 μ in diameter. When the mean values of reflectivity are plotted against those of micro-indentation hardness, an excellent spread is obtained and a large number of minerals can be identified without further study (see Fig. 8 in Bowie and Taylor (9)).

Five main groups of minerals of similar composition, structure and bonding are apparent from the examination of the reflectivity-hardness plot. Thus the metals and metalloids with metallic bonding are relatively soft but have a high reflectivity. At the other extreme, the metallic oxides with ionic bonds are relatively hard and have a low reflectivity. Between these two groups are a wide range of sulphides, sulpho-salts and cobalt-nickel-iron sulphides, with both covalent and ionic bonding, which have medium reflectivity and a wide range in hardness. Some anomalies occur within these broad groups--for example, cuprite, pyrolusite and naumannite occur among the sulpho-salts --but any unknown can generally be assigned to one of the five main groups on the basis of hardness and reflectivity alone.

Group I. Oxides of Medium Reflectivity

Magnetite can be distinguished from jacobsite, the only other isotropic mineral with similar hardness and reflectivity, because it is softer and a few per cent higher in reflectivity. Braunite and hausmannite, which have almost the same reflectivity, hardness and colour, can be differentiated by the degree of anisotropism, polarization colours and internal reflections. Similarly, wolframite can be distinguished from manganite by its weak anisotropism, weak bireflection and greenish grey polarization colours. The "Oxides of Low Reflectivity" present no problem and the "Oxides of High Reflectivity" are also readily distinguishable with the exception of coronadite and hollandite, which may not be determined without a comparison microscope or careful hardness measurements on good material.

Group II. Cobalt, Nickel and Iron Sulphides and Arsenides

All the cobalt, nickel, and iron sulphides and arsenides so far examined fall into a group of hard, highly-reflecting minerals. These are divided on optical properties into isotropic and anisotropic species. Reliance is placed mainly on accurate reflectivity and hardness determinations to distinguish individual species in the isotropic sub-group. Gersdorffite and ullmanite with identical reflectivities can be distinguished by their different hardnesses. In the anisotropic sub-group there is not likely to be any confusion.

Group III. Sulphosalts

The sulphosalts have medium reflectivity and hardness and are sometimes difficult to distinguish on the basis of these properties alone. Kobellite and boulangerite, for example, might be confused, but if a few grains in different orientation are available, the much stronger bireflection of boulangerite is diagnostic. Similarly, berthierite and zinkenite have overlapping reflectivity and hardness values, but bireflection is marked in the case of berthierite and weak for zinkenite. In addition, the polarization colours are distinctive. Tetrahedrite and freibergite are probably the most difficult to distinguish on the basis of this system. However, their colours are distinctive and cannot be confused if examined under a comparison microscope.

Group IV. Other Sulphides

The sulphides not already dealt with lie around the sulphosalts on the hardness-reflectivity plot and can be identified almost entirely on the basis of these two measurements. For example, chalcophanite is isolated and, apart from this, its extremely marked and characteristic bireflection and pure white polarization prevent its confusion with any other mineral. Similarly, sphalerite is clearly separated from all other minerals. Alabandite has similarities with tenorite, but is isotropic, whereas tenorite is markedly anisotropic.

Group V. Metals, etc.

The fifth group of minerals comprise metals, tellurides and selenides. These are all highly reflecting and relatively soft and can be distinguished from one another with no difficulty.

Other Techniques of Identification

In addition to reflectivity and hardness, a number of other properties are of value in identifying ore minerals. The following notes are taken from lectures given by Professors Bowie and Cameron:

Colour

Colour was recognized by Murdoch as a useful aid in mineral recognition, but few opaque minerals show distinct colours. Most are white or exhibit various shades and tints of grey, and, as it is not easy for the beginner to recognize delicate differences in shade or colour, this property has not been used as much as it might have been in ore mineral identification. The main difficulty in the use of colour is one of definition. Available charts all give stronger colours than are observed in the sulphide minerals, and, until suitable standards are prepared, full use of colour in opaque mineral identification can only be made by utilizing a comparison eyepiece. In this equipment, two microscopes are bridged by a comparison eyepiece and illumination is provided by two identical high-efficiency tungsten-filament lamps operating at the same colour temperature. Any minor difference in illumination intensity, sometimes associated with the ageing of the lamp, can be controlled by a rheostat. The unknown is compared directly with the standard by placing one on each microscope and examining the two half fields in juxtaposition.

Anisotropism and Polarization Colours

The colours observed under crossed polars in anisotropic minerals are due principally to the dispersion of the bireflection. They can be seen both in air and in oil, but, as they are more pronounced in oil, polarization colours are normally given for oil-immersion. Using the method of Capdecomme and Orcel (10) to adjust the polarizer to extinction, Hallimond (11) has shown that sections in the 45° position often exhibit characteristic colours. Bowie and Taylor (9) adopted this method in the study of over 100 ore minerals and confirmed that, if the polars are accurately crossed and the effect of strain in the objective reduced to a minimum by rotating it in its holder until maximum darkness is obtained, most anisotropic minerals in the 45° position display one or two predominant colours or shades of these colours. These differ from the colours quoted in standard textbooks on ore minerals, which normally give a diversity of colours for the same mineral. For example, niccolite, which has a characteristic polarization colour in shades of blue-green, is usually given in the literature as being anisotropic with strong colours ranging from yellowish, greyish-green, bluish-green to violet-blue. This lack of consistency is most likely due to maladjustment of the microscope, to orientation of the polarizer, or to the use of strained objectives.

Polarization Figures

These are of little value because they are a function of the optical system used. However, they can aid identification when compared with the polarization figures of known minerals. Also, a semi-quantitative scale can be set up using a particular microscope and optical system. Quantitative values cannot be obtained,because the isogyres are not sufficiently sharp.

Chemical Methods

All systems have serious shortcomings, but chemical tests are useful as supplementary methods. Short's method (7) of etch reactions is the most highly developed system; its principal deficiencies are that many mineral species have been revised since his work, many minerals now recognized as species are not included, and there are frequent ambiguities in the system. Qualitative microchemical tests may be useful, but cannot be considered satisfactory as a complete scheme. The chromographic contact print method recently developed and amplified by Williams and Nakhla (12) may also be of assistance.

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6. P. Ramdohr, "Die Erzmineralien und ihre Verwachsungen". Akademie Verlag, Berlin (1950); third ed. (1960).

7. M.N. Short, "Microscopic Determination of the Ore Minerals". U.S. Geol. Surv. Bull. 825 (1931); second ed., 914 (1940).

8. W. Uytenbogaardt, "Tables for Microscopic Identification of Ore Minerals". Princeton University Press, Princeton (1951).

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10. L. Capdecomme and J. Orcel, "Détermination des Propriétés Optiques des Cristaux Opaques à l'aide du Microscope Métallographique Polarisant", Rev. d'optique théorique et instrumentale 20, 47-114 (1941).

11. A.F. Hallimond, "Manual of the Polarizing Microscope". Cooke, Troughton and Simms, Ltd., York, England (1953).

12. D. Williams and F.M. Nakhla, "Chromographic Contact Print Method of Examining Metallic Minerals, and its Application", Trans. Inst. Min. Met. 60, 257-295 (1951).

ORE MINERAL TEXTURES AND PARAGENESES

Professors Uytenbogaardt and Millman presented lectures on ore textures and their significance in the interpretation of the origin and paragenetic relationships of ore minerals. Details of these lectures will not be given here, since this material is readily available in standard textbooks on ore mineralogy, such as Ramdohr or Edwards. Several practical sessions were arranged for the examination of polished sections of ore minerals and ore mineral suites provided by Professors Millman, Uytenbogaardt and Vincent.

Professor Millman provided polished sections from a great many different ore deposits to illustrate some of the more common textures found in ore minerals, including:

Exterior growth shape
Interior zoning and twinning
Colloidal form, zoning and banding
Simple infillings
Crystal and breccia overgrowths
Crustification
Segregation and rim exsolution
Lamellar-type exsolution

Emulsion-type exsolution
Pseudographic-type exsolution
Replacement margins, disseminations
Vein and fracture replacement
Margin and cleavage replacement
Core and zonal replacement
Selective and serial replacement
Pseudoeutectic replacement
Organic relic pseudomorphs
Hypogene relic pseudomorphs
Supergene relic pseudomorphs
Fracturing and cataclasis
Translation twinning
Recrystallization
Folding and boundinage
Pressure shadows
Radiation damage

Professor Uytenbogaardt provided a number of suites of polished sections from different types of ore deposits. These included:

Chromite ore (Cedar Hill, Pa., U.S.A.)
Magnetite ore (Modum, S. Norway)
Titano-magnetite ore (Smålands, Taberg, Sweden)
Titano-magnetite ore (Egersund, Sogndal, Norway)
Oxidic zinc ore (Sterling Hill, N.J., U.S.A.)
Sulphidic nickel ore (Flaat mine, Evje, Norway)
Sulphidic iron-rich copper ore (Boliden, Sweden)
Sulphidic iron-poor copper ore (Prince Leopold mine, Kipushi, Congo)
Silver-rich copper-lead-zinc ore (Slädekärr, Sweden)

Professor Vincent supplied a large suite of polished sections from the Skaergaard layered basic intrusion in Greenland. The samples had been taken from different portions of the intrusion, and the polished sections had been prepared to show the different relationships of the iron-titanium minerals as differentiation of the intrusion proceeded. Ilmenite and titaniferous magnetite occur as interstitial accessories in various phases of the intrusion. The titaniferous magnetite exhibits different exsolution textures which are believed to be functions of initial composition and cooling history. In some phases, ulvöspinel was the first mineral to exsolve; in others, ilmenite occurred alone, or had crystallized first, followed by ulvöspinel. Some specimens show evidence of ilmenite having been produced from original ulvöspinel by sub-solvus oxidation.

Professor Vincent also provided a suite of polished sections of specimens from Schmoo Lake, Lac la Blache, Quebec. These sections showed titaniferous magnetite with particularly well-developed exsolution bodies of ulvöspinel and transparent spinels in various proportions.

MISCELLANEOUS

This section records some of the comments made by members of the Summer School during conversations and in more formal discussions. Since most of these comments do not logically belong in the previous sections, they have been brought together here.

Illuminators

Professor Cameron reported that the built-in illuminators supplied with most ore microscopes are adequate for routine work, but that, for special work on rotation properties and reflectivity measurements requiring a high degree of precision, light sources with a greater intensity should be used.

Dr. Sandrea recommends the use of ribbon filament lamps for reflectivity measurements, since he has found that spiral filaments produce an uneveness in illumination that may affect the final results.

Levelling of Sections

Professor Uytenbogaardt stressed the importance of maintaining the surface of the polished section precisely perpendicular to the microscope tube axis. The correct levelling of the section can be checked by conoscopic observation with a low-power objective. If the section is not level, the image rotates as the stage is rotated.

Monochromatic Light

Although continuous band interference filters were used during the practical sessions at the Summer School, they are not completely satisfactory for precise work because of their relatively wide half-band width (approximately 250A).

Commercial monochromators can be used, but the intensity of light output is too low for some purposes.

Professor Cameron suggested the use of individual interference filters. These can be obtained for a wide range of wavelengths, although sometimes supplementary filters are required to eliminate secondary peaks. Good interference filters have a half-band width of 100 to 200A.

Crystal Orientation by Reflected Light

Dr. K. von Gehlen discussed the orientation of polished sections of opaque minerals by reflected-light optics.

If the mineral has discernible cleavage traces, the polished section can be mounted on a universal stage and turned into a position in which the cleavage planes reflect the incident light back into the microscope. The angular position of the grain can be read from the calibrated arcs on the universal stage.

The orientation of uniaxial minerals showing appreciable bireflection can be ascertained from the degree of bireflection exhibited by the section:

$$\frac{\Delta R}{R_{\omega}} = \frac{R_{\epsilon} - R_{\omega}}{R_{\omega}}$$

where ΔR is the difference between maximum and minimum reflectivities in the grain. R_{ω} is the reflectivity parallel to the vibration direction of the ordinary ray. R_{ϵ} is the reflectivity normal to the ordinary ray. Thus, when the direction of view becomes nearly parallel to the c-axis of the crystal, the value of R_{ϵ} approaches that of R_{ω}, and $\frac{\Delta R}{R_{\omega}}$ approaches zero. When the direction of view is normal to the c-axis, then the value of $\Delta R/R_{\omega}$ is at its maximum.

In uniaxial minerals, the distance between the isogyres of the conoscopic interference figure is a function of the angular distance from an optic axis. Measurements are valid only for a particular calibrated microscope. Accurate measurements are difficult to make because of the diffuseness of the interference figure. Furthermore, if the c-crystallographic axis is oblique, this method cannot distinguish which end of the axis is up. This could be resolved by making another section at an angle to the first.

CONCLUSIONS

The Cambridge International Summer School provided an intensive eight-day course on recent developments in quantitative methods in reflected-light microscopy. Not only were the formal lectures and the practical sessions of great value in bringing the members abreast of important current developments in the field of ore mineralogy, but an invaluable opportunity for exchanging information between workers in different countries was also provided. The organizing committee is to be highly commended for its efforts in this undertaking, and it is hoped that their intention of assisting the dissemination of knowledge on quantitative methods in ore microscopy will be amply realized.

APPENDIX I

MEMBERSHIP OF INTERNATIONAL SUMMER SCHOOL, CAMBRIDGE

Organizing Committee

S.H.U. Bowie
W.A. Deer
A.F. Hallimond
N.F.M. Henry

A.P. Millman
D.G. Murchison
R. Phillips
E.A. Vincent

Teaching Members

S.H.U. Bowie	Atomic Energy Division, Geological Survey, London
E.N. Cameron	Dept. of Geology, Univ. of Wisconsin
A.F. Hallimond	Consulting Mineralogist, London
N.F.M. Henry	Dept. of Mineralogy and Petrology, University of Cambridge
J.M. Jones	Dept. of Geology, King's College, Newcastle-on-Tyne
J.V.P. Long	Dept. of Mineralogy and Petrology, University of Cambridge
A.P. Millman	Dept. of Geology, Imperial College, London
D.G. Murchison	Dept. of Geology, King's College, Newcastle-on-Tyne
R. Phillips	Dept. of Geology, Univ. of Durham

A.H.V. Smith	Coal Survey Lab., National Coal Board, Sheffield
E.F. Stumpfl	Dept. of Geology, University College, London
W. Uytenbogaardt	Geological Institute, Free University, Amsterdam
E.A. Vincent	Dept. of Geology, Univ. of Manchester

Observer Members

M. Font-Altaba	Dept. of Crystallography, Univ. of Barcelona
A. Hayhurst	Refractories Research Lab., Sheffield
H. Piller	Optical Research Lab., Oberkochen
A. Sandrea	Mineralogical Lab., Museum of Natural History, Paris
J.H. Taylor	Dept. of Geology, King's College, London
A.H. van der Veen	Metallurgical Research Lab., Arnheim
F.M. Vokes	Mineralogical-Geological Museum, Univ. of Oslo
K. von Gehlen	Mineralogical Institute, Univ. of Erlangen

Ordinary Members

L. Aires Barros	Lab. of Mineralogy, Higher Technical Institute, Lisbon
H.L. Barnes	Dept. of Geophysics and Geochemistry, Pennsylvania State University

A. Beugnies	Dept. of Geology, Polytechnic Faculty, Mons, Belgium
Miss A. Challis	Geological Survey of New Zealand
W. Elseadawy	Egyptian Coal Project (at present in Department of Botany, University College of N. Wales, Bangor)
P. Ervamaa	Geological Survey of Finland, Otaniemi
K.R. Glasson	Dept. of Geology and Geophysics, Univ. of Sydney
A. Jensen	Mineralogical Museum, University of Copenhagen
M.P. Jones	Dept. of Mining and Mineral Technology, Imperial College, London
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S. Olivero	Institute of Applied Geology, Univ. of Rome
J.J. Prins	Mining Dept., Technological University, Delft

M. Radukic	Dept. of Mineralogy and Petrology, Univ. of Belgrade
E. Sass	Dept. of Geology, Hebrew University, Jerusalem
F. Siddiqui	Dept. of Geology, Univ. of the Punjab, Lahore
J.H. Sullivan	Dept. of Geology, Univ. of Sheffield
W. Tufar	Federal Experimental and Research Establishment, Arsenal, Vienna

APPENDIX II

TIMETABLE OF COURSES

Monday, June 24

9:00	Theory of Reflected Light by E.N. Cameron
10:00	The Reflecting Microscope by A.F. Hallimond
10:45	Practical: Adjusting and Manipulating the Vickers Microscope (supervised by A.F. Hallimond)
2:00	Reflectivity of Ore Minerals by S.H.U. Bowie
3:30	Practical: Measurement of Reflectivity (supervised by S.H.U. Bowie)

Tuesday, June 25

9:00	Micro-Indentation Hardness by S.H.U. Bowie
10:15	Rotation Properties in Reflected Light, Part I by E.N. Cameron
11:30	Practical: Operation of the Prototype of the New Electron Probe Microanalyzer developed by J.V.P. Long (supervised by J.V.P. Long)
3:30	Practical: Polishing of Ore Minerals (supervised by A.F. Hallimond

Wednesday, June 26

9:00	Polishing Ore Minerals by A.F. Hallimond
10:15	Practical: Micro-Indentation Hardness Measurement (supervised by S.H.U. Bowie)
2:00	Practical: Measurement of Rotation Angles and Phase Differences of Ore Minerals in Reflected Light (supervised by E.N. Cameron)

4:30 The Electron Probe Microanalyzer by J. V. P. Long

Thursday, June 27

9:00 Micro-Indentation Hardness and Reflectivity as a Basis for Systematic Ore Mineral Identification by S. H. U. Bowie

10:15 Rotation Properties in Reflected Light, Part II by E. N. Cameron

11:15 Practical: Identification of Unknown Minerals by Hardness and Reflectivity Measurements (supervised by S. H. U. Bowie)

2:00 Practical: Identification of Unknown Minerals by Hardness and Reflectivity Measurements (supervised by S. H. U. Bowie)

5:35 Colloquium: Errors in Reflectivity Measurements, by H. Piller

Friday, June 28

9:00 The Significance of Ore Mineral Textures, Part I by A. P. Millman

10:15 Practical: The Micrography of Ore Mineral Textures, Part I (supervised by A. P. Millman)

2:00 Ore Mineral Paragenesis, Part I by W. Uytenbogaardt

3:30 Practical: Parageneses and Ore Deposits, Part I (supervised by W. Uytenbogaardt)

5:35 Colloquium: Crystal Orientation by Reflected-Light Methods, by K. von Gehlen

Saturday, June 29

9:00 The Significance of Ore Mineral Textures, Part II by A. P. Millman

10:15 Practical: The Micrography of Ore Mineral Textures, Part II (supervised by A. P. Millman)

2:00 Ore Mineral Paragenesis, Part II by W. Uytenbogaardt

3:30 Practical: Parageneses and Ore Deposits, Part II (supervised by W. Uytenbogaardt)

Monday, July 1

9:00 Practical: Study of Polished Sections of Ore Mineral Suites, Part I (supervised by A. P. Millman and E. F. Stumpfl)

2:00 Practical: Study of Polished Sections of Ore Mineral Suites, Part II (supervised by R. Phillips and E. A. Vincent)

5:35 General Discussion: Quantitative Methods and Instruments in Reflected-Light Microscopy

Tuesday, July 2

9:00 Practical: Open session for review of previous practicals.

Note: The Summer School consisted of a basic course followed by two specialized sections--ore minerals and coal petrology--only one of which could be attended by any one person. The author chose the section on ore mineralogy; consequently, the timetable given here is the one to which the author and other members of his group adhered.

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