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An improved polarizing microscope.

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I. *Introduction.*

In recent years there has been little essential change in the design of the petrological microscope. F. E. Wright[2] directed attention to the improvement that could be obtained by using a full-sized condenser with a large polarizer, but the high cost of the latter seems to have restricted its use to a few special models.

With the introduction of 'polaroid', a thin, intensely pleochroic film mounted between glass disks, this restriction no longer holds. A polarizer can be supplied of sufficient size to cover an ordinary Abbe condenser, while the analyser no longer requires the compensating lenses which usually accompany a calcite prism, with the indirect result that the definition of the interference-figure is improved.

The microscope now to be described has been designed to give effect to these changes. In considering the requirements of petrologists much help has been derived from two reports issued by the Petrological Microscope Committee, which was instituted by the Mineralogical Society and the Geological Society of London. These recommendations, while leaving open the actual design, provide a very helpful account of the equipment now regarded as essential for research and teaching. A further condition is that the instrument should be produced with due regard to economy in price, and for this purpose it is advantageous to utilize a model already in production. Fortunately it has been possible to adapt with the minimum of alteration a recently designed biological stand (Cooke, Troughton, and Simms M1000 series). The resulting instrument possesses the quality and accuracy necessary for all ordinary research work, but it will not accommodate the existing large models of the universal stage. On the optical

[1] Published by permission of the Director, Geological Survey and Museum.

[2] F. E. Wright, The methods of petrographic-microscopic research. Carnegie Inst. Washington, 1911, Publication 158.

side the present arrangement seems quite suitable for universal stage research; it is clear, however, that any adequate instrument designed to accommodate the largest stages must have a specially large stand, and relatively few examples will

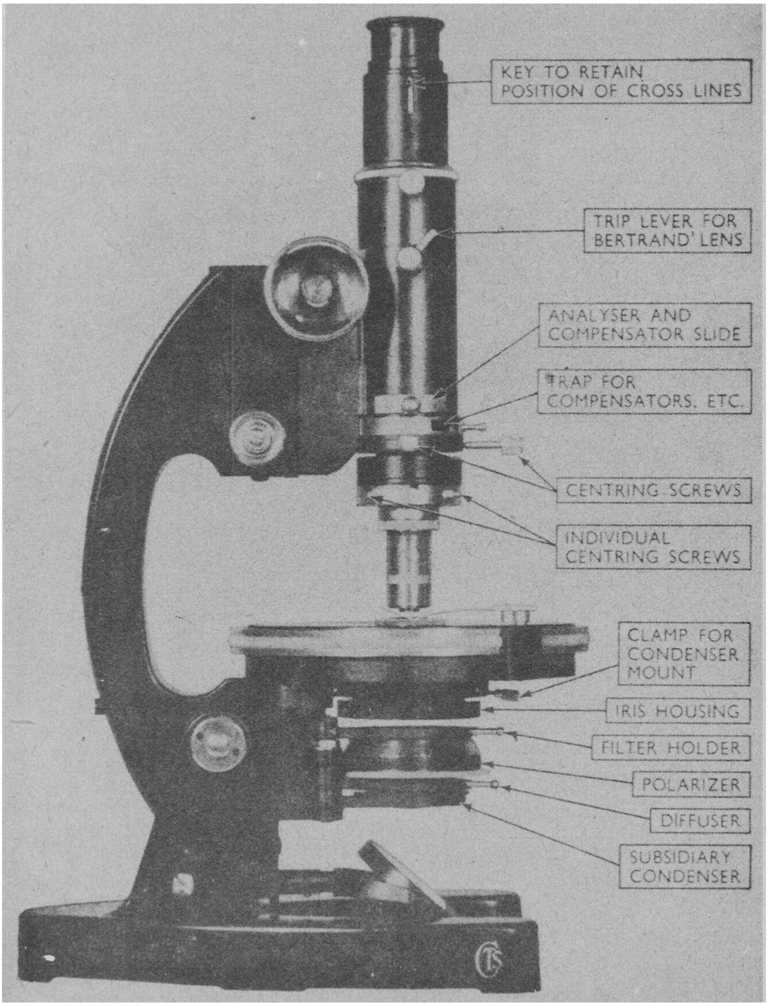

FIG. 1. Improved polarizing microscope.

be required; its cost will presumably be therefore substantially greater than that of the model here described.

The general arrangement of the instrument is illustrated in figs. 1 and 2. Commonly accepted dimensions have been adopted for the stage, tube slots, &c., so that many existing compensators and other accessory apparatus can be used, and provision has been made for wide-angle eyepieces. A standard reflector unit, which can be inserted without increasing the tube length, renders the instrument available for ore-microscopy. The Bertrand lens[1] is of special design, which eliminates the need for refocusing the objective in order to form an image upon the Bertrand diaphragm.

II. *The stand.*

The foot, limb, and focusing movements are of standard biological pattern, while the stage, substage, and tube have been designed for petrological work.

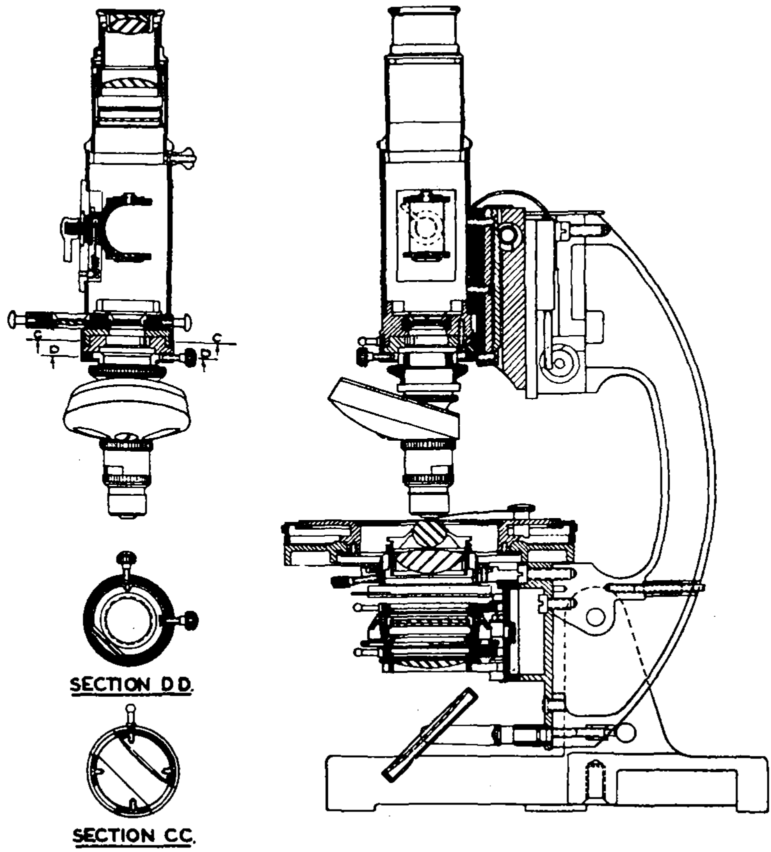

Fig. 2. Improved polarizing microscope (in section).

Two additional projections under the foot, while not normally touching the bench, prevent the microscope from being readily overturned. The hinge gives great stability in all positions, and a lock has not been thought necessary. The fine adjustment reads to 0·002 mm. and is sprung so as to relieve the pressure if the objective touches the cover-glass.

III. *The substage.*

Before the advent of polarizing film substage design was largely determined by the small size of the calcite prism. The condenser rarely exceeded ½ inch in

[1] The Bertrand lens described is covered by British Patent Application No. 24755/44, which is controlled by the Department of Scientific and Industrial Research.

diameter, and elaborate optical arrangements were used to make the best of the rather poor conditions of illumination provided. With such a condenser the field was restricted to about 0·5 cm.; the wider fields required for the lower power objectives could only be obtained by removing either the whole or the upper part of the condenser whenever these were brought into use.

The present substage is shown in part section in fig. 2. The condenser is of a standard Abbe type, giving N.A. 1·25 when immersed in oil, and is retained in a sleeve at the desired height by means of a strong locking-screw. The field is wide enough to supply all objectives up to 1½ inches. On changing objectives the only adjustment required is that of the aperture iris. With the large condenser the adjustable centring-screws, which were mainly concerned with centring the small image of the calcite polarizer, are no longer required.

Wright[1] has discussed the polarizing effect of glass surfaces for rays incident obliquely. Such incidence occurs in all condensers, dry object-slips, and objectives, and produces a certain degree of rotation in the quadrants of the interference-figure, the general effect being as though a very weakly positive crystal had been interposed. It has been suggested that the surfaces in an Abbe condenser may be specially liable to this action, but it seems clear that any such result can only be a question of degree in an effect which is never likely to be absent. With all microscopes, for minerals of extremely weak birefringence, reliance should be placed upon direct measurements of the sign made on a section of the crystal and not upon the appearance of the interference-figure.

Below the condenser is a screen-holder in which can be placed dark-ground stops, colour screens, or apertometer scales visible in the interference-figure. The gypsum or other compensators sometimes used here would now be rather large and it is probably better to use smaller plates inserted in the tube slots in the usual way.

The polarizer is a disk incorporating polarizing film, rotatable in a graduated swing-out mount with arrests at 0° and 90°. Under it is a screen-holder which normally carries a ground-glass diffuser, and another holder containing a low-power auxiliary collective lens. These are particularly useful when the source of light is narrow or distant. To cover the required field and to supply an aperture up to 1·4 N.A. it has hitherto been necessary to employ a large area of sky or a lamp brought close to the microscope. The collective lens now used supplies in effect a magnified image of the source, and the diffuser eliminates the image of window-frames, &c. Very fair illumination can, in fact, be obtained from an ordinary 100-watt bulb at about a yard from the microscope, although a high-intensity lamp is recommended for general purposes.

All the lower components are mounted in separate swing-out fittings and can be displaced so as to permit the immediate removal of the condenser for the application of oil, &c.

IV. *Illumination.*

It has been usual to define critical illumination as the supply of light when an image of the source is formed by the condenser either in the plane of the object or, in practice, slightly above or below that level. From another standpoint, that

[1] F. E. Wright, The formation of interference figures. . . . Journ. Optical Soc. Amer., 1923, vol. 7, p. 779. [M.A. 2–369.]

of the efficient working of the objective, the condition usually desired is that the correct working aperture should be uniformly filled with light for every point in the visible field.

The first of these definitions can only be verified by examining the image of the edge of the source or of a mark (if present) in its surface, which is otherwise indistinguishable. A perfectly uniform source will emit light equally in all the required directions, and conditions above the condenser will be as indicated in fig. 3. The image of a point *p* in the source will be formed by the conical beam indicated by darker lines at the point *p'*. The plane *aa'* contains the image of the source, but, as has been said, there is nothing to distinguish this image unless the source is irregular. When both the field (in *aa'*) and the aperture (interference-figure) are uniformly illuminated the whole central region above the condenser can be regarded as illuminated by intersecting parallel beams derived from points in the lower focal plane of the condenser. Under these conditions the lighting at a point *q* above or below *p'* will be substantially the same as at *p'*. The object may therefore be placed at any point in the central region. In the present microscope, when the diffuser is in position, the image of the source is completely suppressed. There is no special 'aplanatic cone' in the central region. Defects in the correction of the condenser, and lack of achromatism, affect chiefly the conditions at the boundary of the field, while the central region will still give sufficiently good illumination. With the large condenser a mounting slip of any ordinary thickness can be used without refocusing the condenser, and a substage focusing rack is not considered necessary.

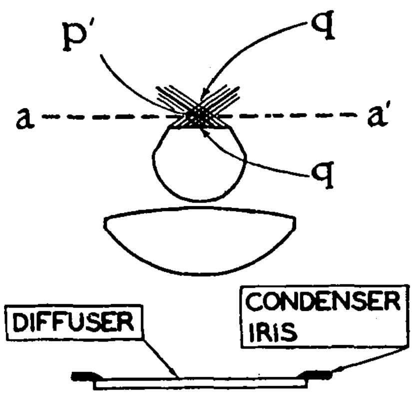

FIG. 3. Illumination by an Abbe condenser with diffuser.

Flat and concave mirrors of the usual type have been provided; it should be noted, however, that the large condenser now employed requires a much wider beam than the prism polarizer. The diffuser should be uniformly illuminated over a width of about one inch, and this is usually best obtained by using the flat mirror with light from a bright source which need not be specially large. With very low-power objectives, and for photography with low powers, the condenser should be removed and the ground glass arranged to supply a uniform field.

When very strong lighting is required, e.g. for a weak interference-figure, or for the spectroscope, the diffuser should be removed and an image of the source focused on the object in the usual way, by locking the condenser at the required height. A field iris, if required, can be used either on the lamp or in an eyepiece.

V. *The stage.*

The design follows ordinary practice, with a substantial milled edge, the diameter being 12 cm. Wider stages become inconvenient for routine work on account of the larger hand movement required in making the rotation. One vernier is provided, reading to 0·1°, and there is a removable ring-plate.

VI. *The tube.*

Considerable changes have been introduced, including a new Bertrand lens fitting.

(1) Eyepieces.—The usual wide and narrow field types are available, and the range of focusing has been extended to permit the focusing of compensators in the slotted objective when the Bertrand lens is in position.

(2) Eyepiece tube.—Tubes for wide and narrow eyepieces are interchangeable by a removable bayonet head, which also gives access to the Bertrand lens fitting. The drawtube is omitted.

(3) Bertrand lens.—The customary slide has been replaced by a rotary fitting which remains within the tube and is completely dust-proof. A serious disadvantage of the ordinary Bertrand arrangement has been the need for refocusing the image to coincide with the diaphragm, which was placed immediately above the Bertrand lens. This image is normally situated about 2·5 cm. above the Bertrand lens, and the present fitting comprises a single rotary holder which carries both the lens and the diaphragm at the proper distance above it. When the holder is rotated to the horizontal position the lens and diaphragm move to the sides of the tube and the centre is left clear. An adjustable screw stop on the holder ensures that the Bertrand lens coincides with the axis of the microscope, and the diaphragm is also in an adjustable plate by which it is brought to include the centre of the image. No iris is provided, since the centre of the field can be identified without difficulty by inspecting the diaphragm with a hand-lens when the eyepiece tube is removed. The diameter of the diaphragm opening has been chosen to cover an area of 0·05 mm. diameter on the object when the ⅛-inch objective is in use. This is rather larger than the extreme minimum claimed for the older Bertrand fittings, but the loss of light and difficulty in centring become very marked for the smallest openings. The present diameter is about twice the thickness of a rock section.

As has been said, the initial adjustment of the present Bertrand fitting should ensure that the interference-figure is centred to the cross-wires of the eyepiece. Hand-centring movements on the Bertrand lens have been omitted. With the present larger condenser it may be useful to follow Wright's procedure and insert an aperture scale and cross-lines in the screen-holder immediately below the condenser, so that they are visible in the interference-figure.

(4) The analyser.—With polarizing film this is simply a thin double glass disk mounted in a sliding holder of the usual type; a rotating mount with a movement through rather more than 90° can be supplied, but is not always needed. The compensating lenses are no longer required, but a disk of clear glass is mounted in the opening usually left vacant; this compensates for the change in focus otherwise due to the thickness of the analyser plate.

(5) Tube slots.—These are of standard size, capable of taking the Berek compensator, and are protected by the usual sliding cover (section cc, *fig.* 2).

(6) Centring movement.—In several recent microscopes this has been omitted; it is, however, of considerable service. For example, the centre is never exactly the same after the tube has been raised to accommodate a thick polished speci-

men; any small correction required can be applied by the hand-centring screws without disturbing the adjustment of the objective holders or collars. A new design has been adopted, in which the centring movements are approximately parallel with the cross-wires (section DD, fig. 2).

(7) Objective changers.—A standard precision objective-changing clutch with centring collars is available alternatively with a rotary changer.

VII. *Ore-microscopy.*

The ordinary cover-glass reflector, though optically the most satisfactory, gives too weak a reflection for use with polarized light, and a prism has usually been supplied interchangeably. Cover-glasses are now available with highly reflecting coatings, the results being comparable with those for a prism, with the advantage of employing the full aperture of the objective. Both cover-glasses and prism usually have a polarizing action, and special devices have been introduced to avoid this in apparatus which is to be employed for the measurement of bireflection. On this question reference should be made to the work of M. Berek[1] and of L. Capdecomme and J. Orcel.[2] The latter authors have proposed to utilize the irregularity in field due to this polarizing action for determinative purposes. With this object a reflector of ordinary type may be retained, while for photography, or other purposes that require uniform extinction over the whole field, the anisotropy is neutralized by the insertion of a sheet of mica before the reflector.

For ordinary determinative work a special simple reflector unit is available (figs. 4 and 5), provided with a coated cover-glass and attachable to the tube by an objective screw. It can be inserted without increasing the tube length, so that ordinary objectives can be used, if desired, with reflected light. When the microscope is to be used for transmitted light the reflector unit need not be removed: it is sufficient for general purposes to turn the cover-glass to the horizontal position; it must not, however, be left inclined, on account of its polarizing action.

No stage rack is provided, but a special rising centre fitting (superstage) has been designed, similar in purpose to the 'mushroom stage'. The latter, which is attached to the substage rack, has the disadvantage of being rather unstable in construction, while only a small independent divided circle is employed. The present device has a similar range of vertical movement, but readings are taken on the main circle of the microscope stage, and the centre of rotation is still the axis of the microscope. The fitting is attached by swinging out the substage fittings and removing the condenser; the central tube of the superstage is then inserted in the stage opening and the plate is fixed to the stage by two screw-heads.

Conventional orientation of the polarizer.—For transmitted light the general tendency in recent years has been to prefer a N.–S. vibration-direction for the polarizer. There are, however, no very strong physical reasons for this.[3] When a reflector unit is in use the most efficient illumination is obtained if the polarizer

[1] M. Berek, Optische Messmethoden im polarisierten Auflicht.... Fortschr. Min. Krist. Petr., 1937, vol. 22, p. 1. [M.A. 7–250.]

[2] L. Capdecomme and J. Orcel, Détermination des propriétés optiques des cristaux opaques. . . . Revue d'Optique théorique et instrumentale, 1941, vol. 20, p. 47.

[3] F. E. Wright, The position of the vibration plane of the polarizer in the petrographic microscope. Journ. Washington Acad. Sci., 1915, vol. 5, p. 641.

is set so that the vibration-direction is in the plane of the reflecting surface. Consequently, when the lamp is in front of the microscope the reflected beam is to be extinguished by setting the analyser at the N.–S. position. With a fixed analyser this position must be retained for transmitted light also, in which case the vibration-direction of the substage polarizer will require to be E.–W. This has therefore been adopted as the normal position, as in many English microscopes.

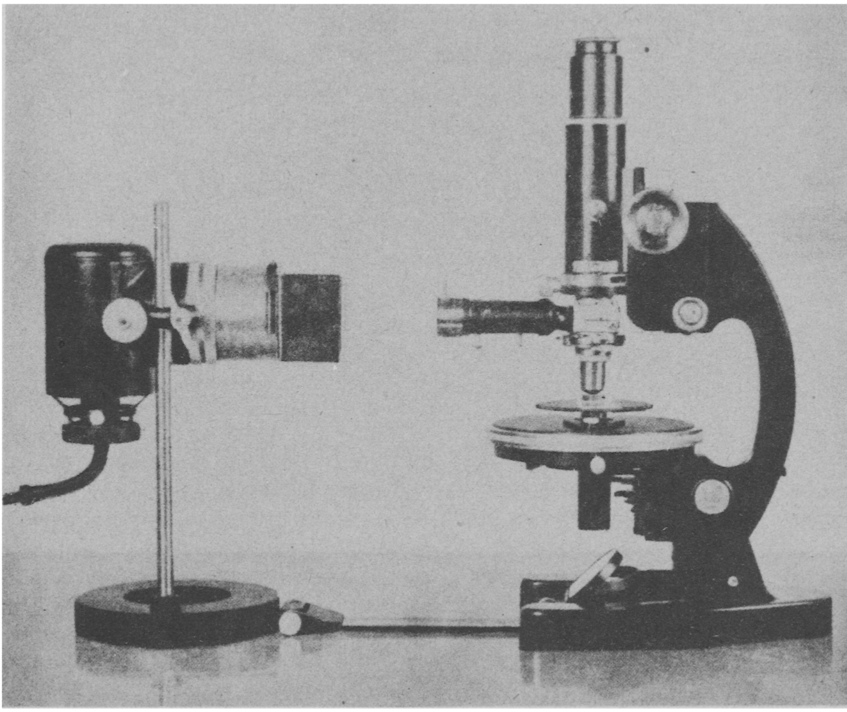

FIG. 4. Microscope with reflector, superstage, and lamp for ore-microscopy.

Adjustment of the reflector unit.—(1) With transmitted light in many microscopes the condenser or the ground glass of the lamp is focused on the object, but for reflected light the lamp is used without a ground glass. The image of the filament is then to be focused on the field iris at the front of the reflector, and so upon the object, while the condenser iris is seen in the interference-figure and serves as aperture iris.

(2) The cover-glass must, of course, be symmetrically mounted so that its surface, when in the position of use, is normal to the plane containing the axis of the microscope and that of the reflector tube. This setting is permanently made and is unlikely to be disturbed in ordinary use.

(3) It is convenient to use a fixed analyser and to adjust the axis of the reflector tube to coincide with a principal plane of the analyser. An isotropic polished object is examined in a strong light, with the reflector unit in approximately the correct position. The polarizer should then be displaced a little to either side of

the 'extinction' position. The field usually appears yellow for one direction of the displacement and blue for the other, thus indicating lack of coincidence with the symmetry plane of the analyser. If the reflector unit is now rotated slightly about the microscope axis a position can be found by trial in which these tints

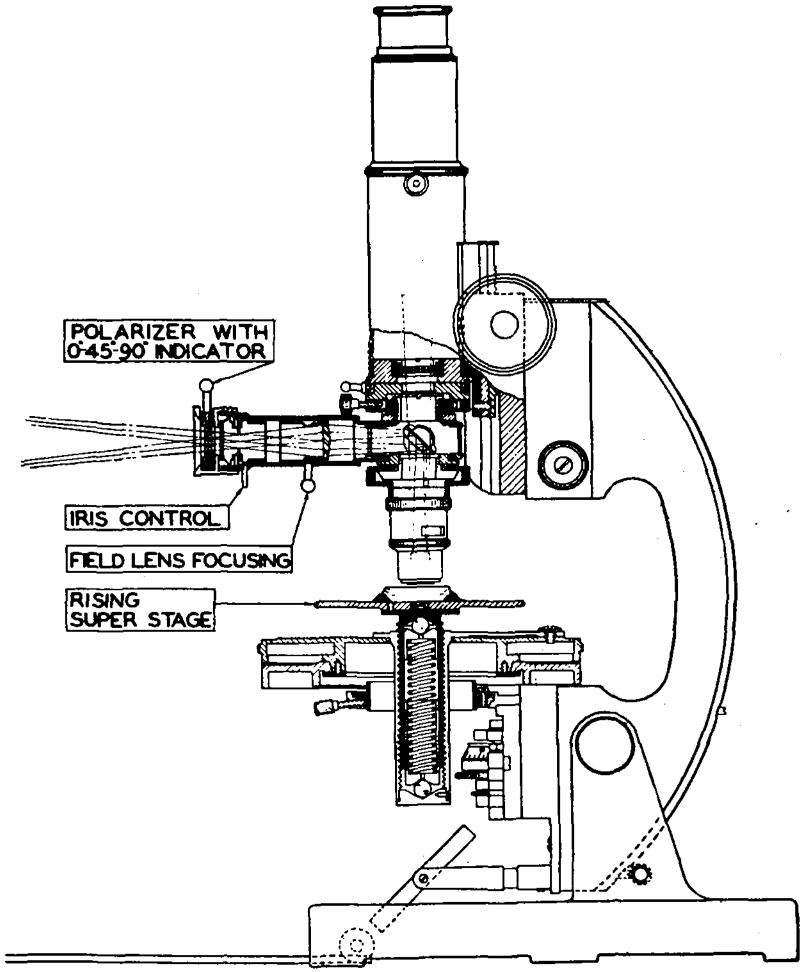

Fig. 5. Microscope with vertical illuminator and rising centre to stage (part section).

are absent, any colour seen being the same on both sides and due to the mineral used. With a very strong light the same effects are visible within the field on either side of a dark band which can be adjusted to the centre of the field (Capdecomme and Orcel, loc. cit., p. 69). Further accuracy in setting can often be obtained by the stauroscopic method, using the interference-figure, and for special purposes the use of a Nakamura plate has been proposed, but this requires to be inserted in the ocular. When the true extinction position has been found the four extinction-directions at 90° can be verified in monochromatic light on a bireflecting mineral such as stibnite, and the colour effects due to dispersion of the extinction or of the bireflection can be well seen.

VIII. *Accessory apparatus.*

The following equipment is recommended:

Slotted objective.

Graduated quartz-wedge.

Sensitive tint and ¼-wave compensators for the tube slots.

Nakamura biquartz plate (if great accuracy is required in measuring extinctions).

Light filters, including photomicro. green, and plain glass circles.

'Spot' stops for dark-ground illumination, and apertometer scale with cross-lines.

Micrometer eyepiece.

Stage micrometer.

Reflector unit.

Superstage for ore-microscopy.

IX. *Outline of determinative methods.*

Many procedures have been devised for the measurements commonly undertaken with the petrological microscope. They are fully described in the text-books, and the present outline is intended merely to indicate a group of methods which are likely to yield the most satisfactory results with the present microscope.

(1) *Thickness.*—This is best measured with an objective of wide aperture and fairly high power, to reduce the depth of focus. Readings for the upper and lower surfaces of the grain are taken with the fine focusing adjustment. The apparent thickness must, of course, be corrected for the refractive index of the crystal.

(2) *Refractive index.*—Approximate values can be obtained by reading the apparent thickness of the mineral and the apparent thickness of a neighbouring grain of known refractive index, the readings being inversely as the refractive indices. If the crushed mineral is available liquid immersion methods are, of course, preferred.

(3) *Birefringence.*—Although compensators like that of M. Berek afford probably the most convenient means of determining the birefringence, the graduated quartz-wedge is also sufficiently accurate and has the merit of cheapness. In many microscopes the tube slots are too high to be focused by the Bertrand lens, and slotted oculars are not always available. It has then been almost impossible to use the quartz-wedge, but this difficulty has now been overcome by the use of the slotted objective, introduced by Messrs. Cooke, Troughton, and Simms. The tubular section of a ⅛th-inch objective, above the lenses, is provided with slots of standard size, through which a compensator can be inserted just above the interference-figure. The graduations of the wedge are read by means of the Bertrand lens, with slight refocusing of the eyepiece. Wright introduced wedges in which a parallel compensating plate was mounted under the wedge, so that the zero (black) band appeared within the end of the wedge. The same result is obtained with the present microscope by placing a first-order compensator in the tube slots and then orientating the objective slots so that the wedge is in the compensating position; the zero band is then seen near the end of the wedge.

Birefringence can only be measured accurately in parallel light. In the present case the compensation is made over the central part of the interference-figure, which is formed by rays nearly normal to the section. By closing the condenser iris the central circle can be isolated and very accurate settings of the compensation band can be made, either to the cross-wires of the eyepiece or to a cross inserted in the screen-holder below the condenser and so visible in the interference-figure. The zero band is afterwards read with no object present. A calibration scale should be prepared for the wedge by reading the interference-bands visible in sodium-light between crossed, and parallel, polarizers. A great advantage of this method is that the intensity of the light is not reduced when the condenser iris is closed, although the image in a slotted eyepiece is much weakened under the same conditions.

(4) *Extinction.*—(*a*) For general purposes the 'stauroscopic' method of setting the dark band (isogyre) to cross the centre of the interference-figure is often sufficiently accurate. A strong light should be used, with a narrow opening of the condenser iris.

(*b*) In a few cases, where the isogyre is too broad to be adjusted in this way (e.g., near a bisectrix), a Nakamura quartz plate can be inserted in the objective slots with its boundary across the centre of the interference-figure.

(*c*) Higher accuracy can only be expected when the aperture is still further reduced. The half-shadow plate must then be inserted in the image plane of the ocular. For this purpose an ocular of the Wright type is necessary, but the methods (*a*) and (*b*) will probably suffice for all ordinary determinative work.

X. *Alternative simple equipment.*

For those who require polarizing equipment adaptable to the standard biological microscope a substage unit has been designed to fit into the ordinary condenser holder. It consists of a tube carrying the standard condenser, aperture iris, rotatable polarizer, and a recess for a ground-glass diffuser or light filter. With the polarizer at the zero position it should be adjusted in the condenser holder to give extinction with the analyser, and to focus the image of the lamp condenser on the object.

The analyser is of the 'cap' type, rotatable or fixed, and is to be attached to the top of the eyepiece tube. Since a glass disk with polarizing film is employed, the thickness is considerably less than that of a calcite prism.

There is no Bertrand lens, but interference-figures can be observed by removing the eyepiece. Since the optical scheme is substantially the same as that already described, such an instrument can give very satisfactory results where speed in manipulation is not of the first importance.