

NOTES
ON A
NEW FORM
OF
POLARIZING MICROSCOPE

BY
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P R E F A C E .

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SOME time ago I induced Messrs. Swift & Son, the well-known makers of students' and other Microscopes, to undertake the manufacture of a new form of students' Microscope—one capable of dealing with a larger range of objects than is the ordinary students' Microscope: an instrument suitable for examining not only the smaller forms of organic life, but also the rocks, sands, and soils on which that life is maintained. I supplied them with designs, which they have carried out in an excellent manner. Hence the instrument described in the following pages. A considerable number of these Microscopes have been made and purchased by men who knew how to use them, but beginners have, I am told, found a difficulty in understanding how to use some of the parts of the instrument. The makers having asked me to write a description of the instrument, I have done so willingly, because of the trouble they have taken in the matter, and because I wished to fix the form of the Microscope, which I hope will not be departed from without good cause. In the following pages I have confined myself to its application to petrology and mineralogy.

A. D.

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NOTES

ON A

NEW FORM OF POLARIZING MICROSCOPE.

DESCRIPTION OF THE INSTRUMENT.

As will be seen from the accompanying woodcut, this new form of Microscope is essentially a student's microscope. It is compact, and capable of doing anything which can be done with larger instruments. It has special appliances for the use of polarized light, whereby the student of petrology or mineralogy can work quickly and pleasantly, as no "centering" is required, and there is an easy change from parallel to convergent light. By simply turning the analyser B' upon its hinge downward and away from the observer, the Microscope becomes suitable for the medical or botanical student. It has the usual coarse and fine adjustments. The milled head of the latter is graduated into 100 parts, each of which is equivalent, as it passes the index, to a variation of about the 35-thousandth of an inch in the distance of the objective from the object. Various appliances, such as camera lucida, draw tube, &c., can be added if desired. The first is adapted for use, either with or without the analyser. It is made to fit on either. The A eye-piece is fitted with cross wires accurately centred. One of the cross wires is marked with a spot of wax. It indicates the wire parallel to which the vibrations of the light emerging from the polarizer take place, or are according to the vibratory theory of light supposed to take place. Howsoever the eye-

piece is turned the observer always knows from this marked wire how the light is vibrating. The vibrations are parallel to the marked wire. Setting the instrument at the zero of the graduated circle D, the mark is on the horizontal wire. In some of the earlier instruments the custom of so distinguishing the wires had not been adopted. It can be done by any one possessing such an instrument by touching the wire with a camel's hair brush dipped in melted bees' wax.

A. Achromatic Condenser.—Referring to the woodcut, it will be seen that at A there is represented an achromatic condenser with iris diaphragm (not shown), also two stops to the left. To use either draw out the internal tube shown at A, place the stop on top of the tube and push it close up under the lens. One is for oblique illumination, the other stops the central light. The latter may be used for dark ground illumination with the inch or half-inch objective, the lens A' being drawn out as in the woodcut. It may also be used in the illumination of very small objects such as bacilli, under immersion lenses. To use the achromatic condenser, withdraw the polarizer B and thrust A into the fitting beneath the stage, then move it up or down to focus the light. It may be used with or without the lens A' sliding in the stage. For illumination under low powers A' is to be drawn out as shown in the woodcut.

A. A Small Lens Sliding in the Stage.—It forms the upper part of the condenser, the lower part of which is screwed into A or B respectively. The combination with B gives an angle of 155° . It is always so used for convergent light in the study of interference figures, and suits the 1-4 inch and higher powers. The interference figures of the latter are of course limited to 155° , which however is enough for all practical purposes. The combination has its focus on any opaque or in any transparent body on a glass slide of ordinary thickness.

B. The Polarizer.—It can be turned in its fitting either

alone or simultaneously with the analyser by means of toothed wheels. It has a catch which fixes it in a "crossed" position relatively to the analyser. The "diagonals" of both are then parallel to the cross wires of the eye-piece. They can all be turned simultaneously by the wheels either crossed, parallel, or with their "diagonals" inclined 45° to the cross wires.

B'. The Analyser.—It is capable of the same movements as the polarizer. It has a steady pin which moves in a slot to allow of the analyser being drawn out to enable the observer to focus the cross wires when his vision is abnormal. For this purpose the eye-lens has a long screw. There is a space between the analyser and eye-lens, through which space a quartz-wedge or 1-4 undulation plate can be passed in two directions at 45° to the cross wires. The intersection of these wires remains during the entire rotation of the eye-piece, polarizer, and analyser over any spot placed beneath it on the stage of the microscope. The tedious and generally unsatisfactory "centering" of the ordinary polarizing microscope is thus entirely obviated.

When it is desired to use the nearest approach to parallel light, the small sliding lens A' in the stage must be drawn back as shown in the woodcut and the plane surface of the mirror turned to the sky, after having withdrawn the polarizer B. Such illumination is well fitted for distinguishing slight differences of refractive index, as in comparing different feldspars immersed in balsam. A 1-inch objective or lower power should be used for such comparisons. With lower powers generally the polarizer is best used without condensing lenses. Otherwise it is seldom necessary to withdraw the lens screwed into the polarizer, because by simply lowering the combination the light becomes more and more parallel, the illumination generally remaining sufficient. When this lowering is carried further the markings on objects, cleavages, &c., become more distinct.

On the other hand, when the most convergent light is required it is obtained at once by pushing the small lens A' into the axis of the instrument and focussing some distant object, such as a window bar, simultaneously with the dust or scratches on a slide placed on the stage. The focussing of the light is effected by moving the polarizer carrying the lower lens up or down as required, the action resembling that of the "adjustment" of an object glass. For the same reason the achromatic condenser can be moved up or down when it is substituted for the polarizer. Having focussed the source of light or distant object the slightest movement of the lower lens displaces the image of the source of light and leaves the object in its brightest illumination. If that is too brilliant it can be made less so by lowering A or B in its fitting. When the best definition of a distant object is required the achromatic condenser must be used, as the uncorrected lenses of the polarizer give only misty definitions of distant objects.

C. A Small Screw.—This screw serves to lock the polarizer, analyser, and eye-piece together, so that should the observer desire to put aside the analyser he can do so, and bring it back into position without disturbing the "reading" on the graduated disk which forms part of the outer fitting of the polarizer and serves with the aid of the cross wires for measurements of "extinctions," "angles," &c.

D. The Graduated Disc.—It turns with the polarizer, analyser, eye-piece, &c., and is best moved by the finger from beneath the stage, which has been cut away for the purpose, so as to allow of ready access to the milled edge of the disc. *To ensure accuracy the readings must be taken in one direction, owing to the slight play in the wheels.*

E. A Slit in the Eye-Piece.—It is covered by a ring when not in use. A quartz-wedge may be passed through it at 45° to the crossed wires, or a micrometer scale (F) pushed into it for approximate determinations of the "angle in air" of biaxial

crystals or for other measurements; but the wedge is most conveniently applied above the eye-piece and beneath the analyser.

F. The Micrometer.—It can be turned in its own plane in its ebonite fitting, but is most conveniently set at 45° as shown.

Each division of the scale corresponds to one hundredth of a millimètre on the stage when the 1-4 inch objective of 90° and the A eye-piece are in use. The value of the divisions of the scale in the measurement of the “angle in air” of bi-axial minerals is given at page 26.

G. A Sliding Plate.—It has two apertures, in one of which is fixed a lens for transferring the “interference figures” from the back of the objective to the eye-piece. It is convenient for the beginner in the study of these figures, particularly the optic axial angles thereof, and the “dispersion.” It is only suitable for sections of minerals specially prepared, or in rock-sections for such as are large enough to fill, or nearly fill, the field of vision of the 1-4 inch objective. A Klein’s plate can be dropped into the other aperture not visible in the woodcut.

The sliding plate is fitted into a tube which moves up and down through a range sufficient to enable different objectives to be used, but they must be of nearly the same length. If the crystal fills only a very small part of the field of view, its interference figure is drowned in extraneous light coming round the sides of the crystal, or it is unduly weakened by magnification.

H. A Similar Sliding Plate.—It is intended to render visible the interference figures of the smaller grains or crystals in ordinary rock-sections. To cut off extraneous light the lens is placed as near the field-lens of the eye-piece as possible, only a very small part of the centre being used. This lens is a great convenience for rapid work. It acts in two ways. When the 1-4 inch or higher objective is in contact, or nearly so, with the cover-glass of the section, the lens combines its action with that

of the field lens of the eye-piece, and the observer sees the ordinary inverted image, but in a very small field. The image must be made central, if not so already, by pushing the sliding plate backwards or forwards, or by slightly moving the section. Drawing back the tube of the microscope a very little, by the coarse adjustment, the image of the central grain or crystal expands, and its interference figure (if any) appears. Drawing back a little further, say, an eighth of an inch, the "figure" disappears and the image of the grain or crystal again appears, but erected. Whilst the interference figure is in view a little focussing of the light must generally be done, so as to get rid of shadows of window bars, edges of the prism, cork fittings, &c., &c. *The beginner is recommended to pay particular attention to this management of the light.*

I. A Sliding Bar.—It is graduated at each end and with corresponding graduations on the stage, so that any part of a slide can be recorded where a point of interest exists, and again at any future time brought into the centre of the field of the same object glass. When not in use the bar can be pushed to the back of the stage as shown in the woodcut. It can be removed by sliding it out of its fitting. The clips on the stage are removable, so that the observer can get a rectangular movement which is often desirable. To do this push the slide along the bar and advance the bar towards the centre of the stage.

K. A Plate of Mica.—It is of such a thickness that there is a retardation of about 1-4 of a wave-length between the two rays into which a ray of polarized light is resolved when the plate is placed at 45° to the diagonals of the nicols or cross wires which are parallel thereto. The plate is set so that the trace of the optic axial plane (the line joining the two "eyes" of the interference figure) is parallel to the longer direction of ebonite frame. It will be found that it can be placed only in two directions at 45° to the cross wires when it is thrust between the analyser and the eye-piece. The directions of

what are known as the major and minor axes of depolarization (in this case the mean and least axes of elasticity of the mica crystal) are indicated on the frame in which the mica-plate is mounted. This plate, and also the wedge to be described hereafter, are useful for determining the directions of the major and minor axes of depolarization (negative and positive axes of some authors) in any doubly refracting section or flake under examination.

There is a small hole for oiling the bearings of the upper toothed wheel, and another hole beneath the stage to oil the bearings of the lower one.

The graduations on the flanges of the polarizer and analyser are intended for the general study of polarized light, and are only approximations to correct graduation. A nose-piece, as shown in the woodcut, is a great convenience. It should be fastened on the tube, so that the observer can readily see the graduations on the circle which rotates with the polarizing apparatus, and therefore a little oblique to an upright line facing the observer. It must not be placed too obliquely otherwise it will not allow of the requisite movement of the objectives, which then come in contact with the bearings of the tube of the microscope.

For artificial illumination, the instrument is best raised one or two inches from the table and inclined as in the woodcut—the axis being directed to a small flame about the size of a night light and distant five or six inches. It should be accurately focussed by moving the lower lens of the condenser. What are known as fairy lamps give a suitable flame. That is the best illumination for small bodies, such as spontaneously-moving bubbles—the “Brownian” movements of small solid bodies in liquids, and for germs, bacilli, &c.

Where it is desired to fill the field with light for studies in polarized light, interference figures, &c., a small achromatic lens covered with pale blue glass, and with a focal length of about

one and a-half inches, is much to be preferred to the usual "bull's" eye, though that may be used.

In using a small achromatized bull's eye—which need not exceed three quarters of an inch in diameter—it is to be so placed as to send nearly parallel light from the small flame placed at its focus. If a scratch is made on the surface of the lens, or if it is marked by a cross (with a scratching diamond), the observer can focus either its illuminated surface or the image of the flame. No blue glass is required where the electric light or that from incandescent zirconia can be employed. The latter leaves nothing to be desired in petrological studies, but of late the manufacturers have altered the gauze, so as to cause it to emit a yellow light, which is not much better than that from petroleum, and requires the use of a blue glass.

APPLICATION OF THIS MICROSCOPE TO PETROLOGICAL PURPOSES.

The following remarks are intended only for the use of beginners, who are supposed to have an elementary knowledge of mineralogy and such acquaintance with polarized light as may be obtained from the perusal of any good popular work on the subject, such as "Spottiswood on Polarised Light" (Nature Series, 2s. 6d.). All the experiments described therein can be repeated with the aid of the instrument which has been described.

Where the Microscope is only to be used occasionally for petrological purposes, and generally for botanical or biological purposes, a low-angled 1-4 or 1-6 inch (90° to 100°) is to be preferred. If the Microscope is to be used generally for petrological purposes, and only occasionally for botanical or biological observations, it is desirable to select a high-angled 1-5 inch objective (130° to 140°), because the interference figures are more easily recognised when the emergence of the

figure is oblique. With eighths, tenths, twelfths, and immersion objectives generally the angle is sufficiently high, but should always be known. The objective must be of the right length, in order to bring the interference figure into the eye-piece. The 1-12 immersion lens cannot, the writer understands, be made short enough to use on the nose-piece for interference figures. The nose-piece must, therefore, be unscrewed, but such a lens is not generally needed.

In order that the beginner may accustom himself to the appearance of interference figures, he should procure a book of mica plates. They are sold by mica splitters, or may be ordered through the makers of this instrument. Their cost is trifling. The mica used seems to be all from one source in India. It has an angle in air of about 70° , which should be accurately determined by a stage-goniometer. Each plate is a basal flake of uniform thickness about three inches square. Selecting one which, when placed on the stage of the Microscope and turned between crossed nicols, shows a bluish gray colour, the student should make for himself a mica wedge. It will be of great subsequent use. To do so, proceed as follows. Lay the plate on a flat, somewhat yielding surface. A quire of note paper answers the purpose. Drive a stout needle through the mica and examine the hole under the microscope. Use the 1-inch objective or lower power, having previously set the instrument at zero. It will be seen that the hole made by the needle is the centre of a six-rayed star more or less perfectly developed. Viewed between crossed nicols it will be found that when turned on the stage the field is dark in two positions. One is when one of the rays of the star is parallel to the upright wire (the instrument being at zero), the other when the same ray is parallel to the horizontal wire. Conversely, when the mica is stationary on the stage and the nicols turned, the field becomes dark each time either cross wire becomes parallel to the same ray in

the star. The six rays are the three principal cleavages transverse to the basal plane of muscovite. The one parallel to the horizontal cross wire, when the field is dark, lies at right angles to the trace of the optic axial plane. Its direction is noted, and by the aid of a hand lens and parallel ruler, a number of lines are drawn with a needle on the mica at right angles to that particular ray—each line half an inch from the other. Then cut the mica along the lines with a long pair of scissors (at one snip for each strip) into four or five strips, in one of which should be included the star-shaped figure for future reference. Superimpose them, cutting each strip one quarter of an inch shorter than the one beneath it, and fastening it thereon with a speck of gum mucilage here and there along the edges. The step-shaped wedge should be mounted in balsam between two *thin* plates of glass. So made it will act like the ordinary quartz-wedge, because its major and minor axes of elasticity lie in the same direction as in a quartz-wedge as usually cut. The mica-wedge has the advantage of showing fields of uniform colour—often very desirable when examining thin sections of rock. Such wedges may be made from very thin plates of mica in which the retardation does not exceed the one-twentieth of an undulation. These are suitable for examining minerals showing weak depolarizing power, such as apatite, chlorite, &c., when too thin for the quartz-wedge. Conversely, they may be made of thicker plates of mica or of more numerous steps. Their present purpose, in the hands of a beginner, is to enable him to thoroughly understand the effects produced when parallel or convergent polarized light is passed through any bi-axial mineral, between crossed or parallel nicols. He may, and it will be better if he does, dismiss from his mind the fact that he is working with mica. He has only to remember that he is working with a bi-axial mineral. A thin section cut at right angles to the acute bisectrix of any bi-axial mineral having approximately the same optic axial angle would act in the same manner, in so far as it is here proposed to go.

Mica has been selected because it is easily obtainable and easily cleaved. In its optical properties it is a thoroughly representative mineral ; owing to variations in chemical composition and other causes imperfectly known, its "optic angle in air" varies from 75° or more to an angle so small that the interference figure is undistinguishable from that of a uni-axial mineral. From like causes what is known as its "dispersion" varies, and its optic axial plane may even be at right angles to its position in muscovite. What the student is now going to observe is the behaviour of a doubly-refracting mineral (*any* such mineral) in parallel and convergent polarized light.

Examination in Parallel Light.—1. The polarizer being in its catch and the analyser in its place, the observer is to turn the disc beneath the stage by one finger of the right and left hand, till the disc is at zero, and the cross-wires in the eye-piece are upright and horizontal. So placed, they are convenient for reference, and the field resembles that of other polarizing microscopes, with which the observer may have some previous acquaintance. They would act equally well in any other position. If the observer cannot see them distinctly, he must adjust the eye-lens of the eye-piece till he can do so with or without the use of spectacles if he is compelled to use them. The cross-wires must be distinctly seen. As the first observations are to be made in parallel light the small lens sliding through the stage must be drawn back, as in the woodcut. For the sake of greater exactness, the lower lens may also be unscrewed from its fitting above the polarizer and the plane mirror turned to the sky. Since, even under these circumstances, the light is not truly parallel, and the field never becomes absolutely dark, it is much more convenient to leave the lens fixed above the polarizer, the difference in the darkness of the field being scarcely appreciable.

The analyser being turned down, and away from the observer, the wedge is placed on the stage parallel to either wire

It is to be focussed by the markings on its surface, or by sundry curves due to "interference" of thin plates of air contained within the mica. The objective to be used should be one of low power—any one from the half inch to the 2 inch will answer. The analyser is then to be raised into its place so that the observer may look through it. If the wedge has been correctly cut, and the instrument accurately adjusted by its maker, the field will remain dark. Any little inaccuracy in the making of the wedge is to be noted by turning the wheels, and reading off the "angle of extinction" on the graduated disc. A small error is not important.

When the wedge is placed at 45° to either cross wire it will be seen at its maximum brightness. This is due to the fact that, being a doubly refracting mineral, it divides the polarized beam into two beams, which, in the language of the undulatory theory, are said to vibrate at right angles to one another. One of these beams is retarded more than the other, and this retardation is proportional to the thickness of the plate. Owing to this retardation what is called "interference" takes place, when the beams, or rather portions of them, have passed through the analyser. That part which affects the eye of the observer is found to have been deprived of certain portions of the spectrum, so that the remaining portion is coloured. To understand this requires the use of a spectroscope, the colours which have "interfered" being represented by dark bands in the spectrum. It is the remaining portions which the observer sees in parallel light.

In the case of the first plate of the step-formed wedge, which the student is supposed to be examining, the colour is a bluish gray, inclining to mere darkness if the plate is rather thinner than to produce a retardation of $1\frac{1}{4}$ of a wave length of the central part of the spectrum; or to mere whiteness if the plate is rather thicker. When the scale is brought back to zero, and the wedge parallel to either wire, it will be found

that by turning the wheels through 45° in either direction, the mineral again attains its utmost brightness between crossed nicols.

Pushing the wedge further into the field, so that a thickness of two plates is looked at, it is found that the colour changes to nearly a pure white. Turning back the scale to zero, the mineral is again seen at its utmost extinction when the longer axis of the wedge is parallel to either cross wire.

When three super-imposed plates are looked at, the step-shaped wedge is still seen to be, as it is said, "extinguished" whilst its longer axis is parallel to either cross-wire, but becomes of a straw colour when the polarizing apparatus is turned through 45° , again "extinguishing" when the scale is brought back to zero.

When the wedge is still further pushed into the field of view till four plates are seen super-imposed, it is found that they still remain dark whilst the longer axis is parallel to either cross wire, but that when the wedge or wheels are turned 45° , the light transmitted is of a reddish colour, inclining to orange or purple according to the thickness of the component plates. These being supposed to be, as nearly as possible, that which gives a retardation of 1-4 wave length, it follows that the thickest combination will give a retardation of one wave length:

Each of the four steps of the wedge shows a different colour, and the colours shown are those of Newton's first order of colours, which he defined as very black, black, beginning of black, blue, white, yellow, orange, and red. The first three do not appear owing to the first plate being too thick to show them. The orange of Newton's scale verges into the yellow or red, according to the thickness of the component plate, as does the red into orange, or into the violet or indigo of the second order.

From these experiments the student will thoroughly realise the fact that the varying thickness of a mineral does not alter its position of extinction between crossed nicols, but that it does alter the colour of the transmitted light.

Examination in Convergent Light.— This is generally done by removing the eye-piece and looking through the analyser down the tube of the microscope. A small interference figure is then seen apparently a little above the back lens of the 1-4 inch or higher power. To observe it thoroughly replace the eye-piece with the analyser over it, then push the lenses G and A' of the woodcut into the axis of vision, and draw the lens G up or down till the rings are in focus. When the instrument is at zero, and the wedge lying, as it were, east and west, one ring is seen on either side the upright cross wire, if the mineral is of the requisite thickness. With increasing thickness more and more polar rings appear. These rings are, as it were, connected together by a dark bar running through the centre of each (parallel to the trace of the optic axial plane), and separated as it were by another dark bar at right angles to the former (optic normal). Around them, if the angle of the objective is high enough, near the margin of the field, will be found another ring, or only part of it may be seen, which encloses the polar rings. With immersion lenses of very high angles another outer ring or two may be seen. These contract or expand as the thickness of the mineral increases or diminishes. A simultaneous movement of expansion and contraction is seen in each of the rings contained within the outer one. The manner in which these two systems of rings coalesce can only be understood by looking at the changes whilst the wedge is passing through the field of vision.

Turning the mineral in its own plane it is seen that the rings turn, and at the same time that the dark bars open at the centre, which then shows the colour seen in parallel light. The dark bars also take the form of curves, one of which passes through each polar ring. If, instead of turning the mineral, the wheels are turned, it is seen that the *rings remain stationary*, but that the dark bars change from straight lines parallel to the cross wires into curves, which turn each as on a

pivot, not far from the centre of each smallest polar ring, but nearer the edge of the field. The point where the dark bars intersect is known as the emergence of the bisectrix. The points where the dark curves turn as on a pivot during the rotation of the nicols are known as the points of emergence of the optic axes, and the line joining them as the trace of the optic axial plane. To determine the direction of this is one of the most important problems which presents itself to the student. It is easy to do so when rings are visible, even when the axes emerge far outside the field, but when the section is too thin to show rings it becomes more difficult. This is especially the case in examining the obtuse bisectrix, to ascertain the direction of the trace of the optic axial plane. The difficulty is further increased when the emergence is very oblique.

The ability to solve the problem is best acquired by fixing a small flake of mica with wax on a needle point and turning the flake in various directions between crossed nicols in convergent light, meanwhile observing the figure. The flakes must be small to be turned sufficiently in such a small space, but it can be increased by dropping a lens of less curvature than A' into the stage aperture shown open in the woodcut in the axes of the instrument. Such a lens, giving with that on the polarizer an angle of about 90° is suitable for use with a stage goniometer for measuring exactly the optic axial angle in air of any crystal. That being known, the value of the degrees on the eye-piece micrometer F is easily observed by comparison. Suppose the rotation in this case of a flake of mica in the forceps of the stage goniometer to be 70° in all (35° on each side the zero mark to bring the point of emergence of each optic axis to the intersection of the cross wires), then it is clear that the value of the graduations on the micrometer can be found. To do so read off the number of graduations between the darkest part of each curve crossing the "eyes" of the figure when the curves are widest apart. Say that it amounts to

24 degrees, as it will do in this instrument when the 1.5 inch objective is in use, then any other mica can be easily dealt with. Suppose the interference figure of the second mica shows 12° , the angle in air will be 35° . Approximately this is true for any other mineral, so long as the observer uses the same objective and *keeps the lens G always at one point, which he should mark on the tube of the instrument.* Using the 1.4 inch objective instead of the 1.5 inch, the number of graduations between the points of emergence of the optic axes will be 30° instead of 24° , in which case the second mica will show 15° instead of 12° . These results are only approximately true, but they suffice for practical purposes. Special investigations of this nature lie outside what is attempted in this pamphlet which is simply to describe the instrument and the methods by which the principal kinds of observations are to be made on sections of minerals with it, and afterwards to give a few practical applications of such observations in the identification of minerals.

These observations may be grouped as under:—

- (1) How to measure angles of extinction.
- (2) How to distinguish between the two directions of extinction in a section of any doubly refracting mineral.
- (3) How to distinguish between what are called positive (+) and negative (—) crystals.
- (4) How to observe the “dispersion” in any mineral.
- (5) How to determine the character of the pleochroism of any mineral.
- (6) How to compare the strength of the refraction and double refraction of different minerals.

HOW TO MEASURE ANGLES OF EXTINCTION.

The expression “angle of extinction” is used with reference to observations on sections or cleavage flakes of any crystal in

parallel polarized light. The boundaries of any section of a perfect crystal are traces of the crystallographic faces, and extinctions may be measured with reference to any one of these traces.

To make an observation of this kind the observer must throw back the analyser and bring one of the cross wires parallel with the trace of a crystal face, or of some other plane with reference to which extinction is to be measured. A reading of the graduated disc beneath the stage is then taken and the analyser raised into position, so that the observer may look through it. If the section is then in the position of maximum obscurity, the extinction is said to be "straight" with reference to the trace of the plane in question. If the mineral is not in maximum extinction, the nicols are to be turned until the position of maximum obscurity is attained. Another reading is then to be taken. The difference between the two readings is the angle of extinction in question. In order that the observation may be of any value, the direction in which the section is taken must be at least approximately known.

Extinction angles may often be measured with reference to the traces of the cleavage planes. These determinations are often of the greatest value.

In measuring extinctions a number of observations are generally made without moving the section and the mean taken. Under favourable circumstances extinctions may be read to about one degree, but in many instances they cannot be read more nearly than to 3 or 4 degrees. It is better, therefore, to say that the extinction angle is about 5° when the readings vary from about 4° to 6° , than to say it is $5^{\circ} 3'$. The latter may be the result of careful readings of the vernier of a graduated disc. It may be the average of many such readings on different crystals. It is nothing more, and such measurements are very puzzling to the beginner, who cannot obtain any approach to them. In zonal crystals there is often a difference of several degrees in the

extinction of the different zones of the same crystal independent of errors of observation.

2. HOW TO DISTINGUISH BETWEEN THE TWO DIRECTIONS OF EXTINCTION IN ANY DOUBLY REFRACTING MINERAL.

Any section of mineral being on the stage of the microscope the nicols must be turned till the section is seen under the maximum extinction using by preference the lower power. A reading of the graduated disc under the stage is then taken and the nicols turned 45° , when the section will transmit the maximum of light. The wheels which rotate the nicols are then to be clamped by the small screw C, so that they may not move when the quartz or mica wedge is thrust into the space between the analyser and eye-piece. It will be found that it can be thrust only in two directions at right angles to one another. One of these directions is through the hinged support of the analyser, which the wedge should fit as nearly as possible. It is pushed through in one direction and the effect on the tint of the section is observed as the wedge passes under the eye of the observer. It is then withdrawn and passed in the other direction at right angles to the first. The effect on the tint is again observed. In one direction the effect will be to raise the tint in Newton's scale—in the other to depress the tint. In the latter case it is easy to find such a position that the wedge counteracts the effect of the section, which then becomes dark. The beginner will not be able perhaps to make up his mind as to whether the tints are rising or falling, but he will have no difficulty in seeing when compensation is attained, because the section will then appear to be in its maximum extinction.

When this is the case the major and minor axes of depolarization in the section correspond respectively with the minor and

major axes in the wedge. The directions of the latter being known (minor axis coincident with length of wedge) those of the former are also known. It is convenient to mark upon the wedge an ellipse as shown at K in the woodcut, and to bear in mind that howsoever it may lie when compensation is attained the ellipse in the section will always have its major and minor axes at right angles to those of the wedge.

3. HOW TO DISTINGUISH BETWEEN POSITIVE (+) AND NEGATIVE (—) MINERALS.

Uniaxial Minerals.—(a) *In Convergent Light.* A section or cleavage flake at right angles to the optic axis, shows the well-known cross and rings if the section is thick enough to show rings. How to see the interference figure has already been explained in the case of a bi-axial mineral. It is seen in the same manner in a uni-axial mineral. When the section is not exactly at right angles to the optic axis the centre of the cross will not correspond with the centre of the field of view.

To ascertain whether the double refraction is + or — use the 1-4 undulation plate shown at K. Thrust the narrow part of the ebonite setting, on which the ellipse is figured, through the hinged support of the analyser so as to look through the 1-4 plate and observe the effect on the black cross. It will resolve itself into two dark spots lying parallel to the major or minor axis of the ellipse. If they lie along the major axis engraved on the $\frac{1}{4}$ plate setting the mineral is positive. If they lie along the minor axis the mineral is negative. This test cannot be applied to very oblique emergencies where the centre of the cross is nearly or wholly outside the field. When that is the case note the direction of the arm when it bisects the field. That shows the direction of the optic axis, though it is not at right angles to the axis of the instrument, in which case proceed to (b.)

(b) *In Parallel Light.* The distinction is easy when the

section is not at right angles to the optic axis, and when the direction of the axis is known or can be found as described in the preceding paragraph. The problem resolves itself into finding the direction of the major and minor axes of depolarization. If the minor axis is found to be coincident, with the optic axis, *in the section*, or with its orthographic projection in the case of an oblique section, the double refraction of the mineral is positive. Conversely if the major axis is found to be coincident the mineral is negative.

Thus to contrast apatite (—) with quartz (+) proceed as follows in parallel light. Suppose a section of each cut parallel, or nearly so, to their optic axes and thin enough to show colour or the gray of the first order between crossed nicols. From the position of extinction turn the nicols 45° , when the sections will attain their maximum illumination. Pass the wedge through the hinged support of the analyser or at right angles thereto till compensation is attained, the section returning to obscurity. In the case of apatite it will happen when the axis of the prism is parallel to the length of the wedge. In the case of quartz when it is at right angles thereto.

Bi-axial Minerals.—(a) *In Convergent Light.* The means to be employed in observing the interference figures of bi-axial minerals has already been explained. There are several methods of ascertaining whether the figure arises from positive or negative double refraction. One only is given here because it suffices for all cases in which the section is thick enough to show rings. Where the section is too thin to do so it is better to employ parallel than convergent light, as will be explained under (b). Assuming the section or cleavage flake to show at least one ring of colour round each axis, or a part of one ring—for the axial emergence in large-angled crystals will be outside the field—proceed as follows. Turn the nicols till one or other cross wire coincides with, or in slightly oblique sections is parallel to, the trace of the optic axial plane (an imaginary line joining the eyes

of the figure). Take a reading and turn the nicols 45° . Pass the wedge, thin end foremost, under the analyser so that its length may pass at right angles to the trace of the optic axial plane. Observe the effect on the circumpolar rings whilst the wedge is passing. If they expand the mineral has negative double refraction; if they contract the mineral has positive double refraction. All this will be reversed if the wedge is passed at right angles to the direction above, or thick end first; strict attention is required to prevent a mistake in this observation. It will be seen that when the circumpolar rings expand, the outer ring which encloses both polar rings also expands.

(b) *In parallel light*.—It is in general much easier for the petrologist to determine the character of the double refraction of a bi-axial mineral in parallel than in convergent light, the sections being generally too thin to show rings. The student during his observation on the mica-wedge will have already made himself familiar with the appearance of sections normal to one or other of the bisectrices of any bi-axial mineral. These two bisectrices are termed positive and negative, also acute and obtuse. When the acute bisectrix is positive the double refraction of the mineral is said to be positive and *vice versâ*. In very wide-angled minerals it is not always possible to tell whether the bisectrix normal to a given section is the acute or obtuse bisectrix. But when both "eyes" are within or on the edge of the field of view of this instrument, the bisectrix normal to the section must be the *acute* bisectrix.

Suppose such a section on the stage of the microscope the student should proceed as follows:—Note the direction of the trace of the optic axial plane and turn from convergent to parallel light by drawing out the two lenses used in convergent light, one on the stage and the other in the tube of the microscope. Ascertain whether the major or minor axis of depolarization in the section coincides with the direction in question. If the minor axis, then the bisectrix normal to the section

is negative; if the major axis it is positive. Two strips of mica cut in the same direction and of the same thickness, or two wedges, worked one on the stage and the other in the eye-piece at 45° to the crossed nicols, and therefore at right angles to one another, will make the matter clear.

Positive and negative bi-axial minerals in which the optic angle is small, as in many micas, are best distinguished in convergent light. On the other hand the student must be on his guard against setting down as bi-axial all sections in which the cross of the interference figure opens a little during the rotation of the nicols. Crystals are not ideally perfect things. Owing to pressure during or after formation, and probably to other causes, uni-axial minerals often show a cross which opens a little at the centre, and a certain amount of caution must be used by the observer in drawing conclusions from very small angled interference figures.

4. HOW TO OBSERVE THE "DISPERSION" IN ANY MINERAL.

Within the limits of this pamphlet it is not possible to treat the whole subject of dispersion, but only how to observe that part of it which is of most practical importance. To do so, place a section of sphenc cut at right angles to the acute bisectrix on the stage of the instrument which has been described. View the interference figure in convergent light, with the use of which the student is familiar. Turn the nicols till the axial curves are at their greatest separation, using the lens G so as to magnify the figure. Push the micrometer marked F in the woodcut through the slot in the instrument at E. For that purpose raise the ring which generally covers the slot. Focus the degrees on the micrometer, if need be, by screwing in or out the eye-lens of the eye-piece. Again, if need be, focus the rings by raising or lowering the lens G till the figure and the

graduations on the scale are seen together. The micrometer should be so set as to enable the degrees to be read which separate the hyperbolic curves when widest apart. For this purpose it is made so that it can be turned in its ebonite setting. It must be borne in mind that the degrees are arbitrary. The reading does not give the angle in air directly. Assume that there are 16° , which will be about the actual number when using the 1.5 inch objective with an angle of 130° . It will be seen that the hyperbolic curves (those crossing the rings) are bordered within by blue and without by red. This is expressed by Greek letters ρ (red) $>$ ν (blue) being apparently the opposite of what one sees. To verify the expression, it is only necessary to view the figure through a piece of red glass, when it will be found that the darkest part of the curves are about 17° apart, whilst in blue light they are only 15° . It thus appears that the expression ρ (red) $>$ ν (blue) is correct, though it seems reversed in white light. What is then seen are the residual colours after interference has abolished their complementaries. Using the 1.4 inch objective of 90° the numbers would be about 20° of the scale in red light, 19° in white, and 18° in blue light or thereabouts.

It is probable that in all minerals the optic angle varies through considerable, often through very wide, limits, so that too much importance must not be attached to these measurements. Perhaps they may acquire more value than they now possess when composition and angle-measurements are more fully known in their relation to one another.

5. HOW TO DISTINGUISH THE CHARACTER OF THE PLEOCHROISM OF ANY MINERAL.

A mineral is said to be pleochroic when it transmits light of different colours in different directions. Coloured varieties of uni-axial and bi-axial minerals show the phenomenon. It is not seen in colourless specimens of the same minerals.

To observe pleochroism turn down the analyser on its hinge, and bear in mind that the vibrations of the light emergent from the polarizer are executed parallel to the marked cross wire.

(a). *Uni-axial Minerals*.—Tourmaline is here selected. The ordinary ray vibrates at right angles to the optic axis in which direction the prism is generally lengthened. The symbol of the ordinary ray is "O." The extraordinary ray vibrating parallel to the axis is known by the symbol "E." When a section of coloured tourmaline, generally brown, green or blue, is viewed under a low power, such as the 1 inch objective, the light is seen to undergo no change during rotation of the polarizer if the section is at right angles to the optic axis of the crystal. But if the section is a longitudinal one a marked change is seen when the polarizer is turned. The colour, when the vibrations are at right angles to the optic axis, remains the same as in the transverse section. When the vibrations take place parallel to the optic axis the light passes through the crystals unchanged, or nearly so. Thus the pleochroism is defined as

O=Brown, green, blue, &c., as the case may be;

E=Colourless or nearly so.

In dark tourmalines the absorption of O is so complete that no light passes when the length of the prism is at right angles to the marked wire.

(b). *Bi-axial Minerals*.—The pleochroism of such minerals is defined by stating the colour for rays vibrating parallel to three directions. These are known as the three axes of elasticity. They are often designated by the old English letters **a b c**. Sometimes the Greek letters $\alpha \beta \gamma$, are used, but as these are also used for the indices of refraction, it is better to avoid confusion, reserving the old English for the axes of elasticity.

Hornblende is here selected. A section normal to the positive bisectrix **c** contains **a** and **b**, the former corresponding to the trace of the optic axial plane, the latter being at right angles thereto. In such sections of glaucophane, one of the

varieties of hornblende, the colour for rays vibrating parallel to the trace of the optic axial plane is pale yellow, whilst for rays vibrating at right angles thereto the colour is violet. Again, a section normal to the negative bisectrix **a** contains **b** and **c**, the latter corresponding to the trace of the optic axial plane. In such a section of glaucophane it will be found that the colour for rays vibrating parallel to the trace of the optic axial plane will be blue, whilst for rays vibrating at right angles thereto, the colour will be, as before, violet. Hence it results that rhombic sections, or sections showing rhombic cracks, are pale yellow when the marked cross-wire is parallel to the shorter diagonal of the rhomb, and violet when the same wire is parallel to the longer diagonal. In longitudinal sections the colour is always blue when the marked cross-wire is parallel to the longer axis, and violet when at right angles thereto if the section is cut parallel to (100); but pale yellow if parallel to (010).

Hence the scheme of pleochroism is defined as—

a = pale yellow.

b = violet.

c = blue.

In green hornblende vibrations parallel to **a** are again pale yellow, parallel to **b** and **c** various shades of green; whilst in basaltic hornblende **a** is once more yellow, and the two latter are various shades of brown. The colour is always deeper for light vibrating parallel to **c**, hence the absorption of hornblende is expressed as $\mathbf{c} > \mathbf{b} > \mathbf{a}$.

In arfvedsonite and riebeckite, other varieties of hornblende, the absorption parallel to **c** is as great as in longitudinal sections of tourmaline, so that the minerals may easily be mistaken at a cursory glance. On more careful observation it is found that whereas the latter is dark when the length of the prism is at right angles to the marked cross wire, the two former in that position, or very nearly so, transmit most light.

6. HOW TO COMPARE THE STRENGTH OF THE REFRACTION AND DOUBLE REFRACTION OF DIFFERENT MINERALS.

This is most easily done comparatively. The student may proceed as follows :—Turn down the analyser on its hinge and withdraw the polarizer from its fitting ; use the one inch or lower power, so as to view anything on the stage by light as nearly as possible “parallel.” Mount a fragment of albite and one of labradorite side by side in Canada balsam, with a fragment of zircon. It will be found that whereas the albite is almost invisible if free from enclosures, the labradorite has its borders so well defined that it can be seen easily without reference to enclosures. This is due to the fact that the refractive index of albite is nearly the same as that of balsam, whilst, on the other hand, that of labradorite is higher. The student must bear in mind that minerals of lower refractive index than balsam such as fluor spar and many zeolites, also show dark borders. All that the dark border indicates is a difference in refractive index between the balsam and the mineral. It can be measured by the method of the Duc de Chaulnes, but the writer has been unable to obtain results of any practical value from the average unpolished thin sections of rocks. Working on thicker sections of minerals which are quite transparent and highly polished, it gives fairly good results. To obtain them requires a graduated scale to be attached to the tube of the instrument.

Further observations on these dark borders should be made before they can be relied on as a step towards the identification of minerals. To do so, replace the polarizer, with its attached lens so as to view the objects in slightly convergent or divergent light, according to the position of the analyser in its fitting. It will be found that the dark border round the labradorite can be, as it were, drowned in light, whilst that of the zircon cannot be abolished, or even materially altered. In ex-

aminating minerals in this relative manner, it is better to use the achromatic condenser if the instrument has been purchased complete, as shown in the woodcut. But without the achromatic condenser excellent comparative results can be got with the polarizer, only they are complicated by its position. It will be found that thin fragments of albite, and other minerals the refractive indices of which are nearly the same as that of balsam, are visible or invisible according to the position of the polarizer. As that is turned they alternately appear and disappear twice in each revolution. It is therefore desirable to withdraw the polarizer, and all lenses beneath the stage, for at least one observation, in every case of comparison where the refractive index of the mineral is nearly the same as that of the balsam. This is known by the borders being only faintly defined. If not done the observer may, for instance, assume that he is looking at flakes from different feldspars, whereas they are flakes of only one feldspar lying in different positions relatively to the direction of vibration of the polarized light. For satisfactory comparisons the fragments must be of about the same thickness.

As an extreme example of these borders, cryolite, though scarcely a rock-forming mineral, should be observed. Viewed in balsam its borders resemble those of zircon, but when viewed in water the cryolite borders nearly disappear, whilst those of zircon are more strongly marked. This is due to the fact that the refractive index of cryolite approaches that of water, and is nearly as much below that of balsam as zircon is above it.

In the case of minerals which differ much in their refractive index from that of the balsam wherein they are mounted, any roughness of surface produced by grinding down the section can be seen, and that fact is often useful in examining a slide of mixed minerals. Unfortunately it prevents the observer from ascertaining, even approximately, whether the apparent roughness is due to higher or lower refractive index than that

of the balsam, and even when the section has been polished the eye has great involuntary power to counteract the effect of any such difference when sections side by side are compared. In these observations the achromatic condenser must be used to focus some distant object as a signal. For that purpose the net-work of any window curtain seen against the sky is suitable. It is to be focussed by moving the condenser up or down in its fitting till the object is distinctly seen, and then closing the iris diaphragm till the sharpest definition is attained. If then the objective must be drawn back to see the object in or through the section as well as it was seen in or through the balsam, the mineral has higher refractive power and *vice versâ*.

It is often of the greatest importance to ascertain approximately the relative strength of the double refraction of any two or more minerals, one of which is known. Suppose the observer has a slide containing uniformly thin sections of apatite, quartz, and muscovite, so cut as to show their strongest double refraction between crossed nicols. That will be when the section is parallel to the optic axis of the two former and at right angles to the basal plane of the latter—its ready cleavage. It will be found that whereas the quartz depolarizes (the word is a bad one, but it is used generally) in, say, the blue of the first order, the apatite will show only the gray of the same. On the other hand, the muscovite will show a tint of a higher order. To observe the facts, proceed as follows. Turn the nicols till the minerals are successively at their maximum obscurity and then 45° further. Pass the quartz wedge first in one direction, and then, if need be, in the other, till compensation is attained, exactly as was done to determine the direction of the major and minor axes of depolarization. Note that if the section originally depolarized in the blue of the first order, it is compensated when crossed by the same blue of the quartz wedge, whilst to eclipse the colour of muscovite it is necessary to push the wedge further into the field.

Compensation is attained in the case of the muscovite only in the second or third order of colours, whereas the thinnest part of the wedge compensates the gray of the apatite. Had there been a section of such a mineral as chlorite, possessing still lower double refraction, the faint light transmitted thereby would not have been within the range of the quartz wedge. So far as the writer's experience goes, a quartz wedge cannot be made much thinner than to produce a retardation of about one quarter of an undulation, because when the quartz gets thinner, its cleavages (only obtained with difficulty) begin to appear, and the edge of the wedge crumbles away. A wedge of mica can easily be constructed as already described, and answers admirably for such minerals as in thin slides lie outside the capabilities of a quartz wedge. When minerals lie in many different directions—as in rock-sections generally—comparison must always be made between such examples of each as show the strongest depolarizing power. Thus a section of quartz cut nearly across its optic axis, must not be compared with a basal section of muscovite. To make these comparisons fairly each mineral should lie in that position in which it shows its strongest double refraction.

HOW TO EXAMINE ANY ROCK-FORMING MINERAL.

A tolerably satisfactory examination of any rock-forming mineral can generally be made through the study of the optical properties of small cleavage flakes of the mineral in question. To obtain and preserve these flakes for future reference proceed as follows.

Select a fragment, which need not be larger than a pea, but may be much smaller, and in doing so give preference to any fragment which shows the best cleavages. Crush it in a steel

mortar or otherwise, but do not grind the flakes. Wash them in water containing two or three drops of strong gum to each ounce of water. The object is to remove dusty matter, leaving only clean cleavage flakes or fragments. Transfer some of them to a glass slide, so that they may lie closely together, but not touching one another. Heat the slides to dry them; the flakes will then adhere sufficiently to the glass. Examine them between crossed nicols to see that they are sufficiently thin to depolarize in colours from the gray of the first order up to colours of the second or third order or even higher. Remove, by the touch of a needle, any needlessly thick fragments. Drop thin Canada balsam upon the flakes and heat the slide, adding more and more balsam till the fragments are submerged in balsam, which will set firmly but not crack when cold. Cover with a thin glass cover and press it down. Having done this with two or three typical varieties (with different colours and cleavages if possible) of each rock-forming mineral, the student will have a collection which will increase in value to him the more he studies it.

Some minerals, such as chlorite and mica, cannot be so mounted, and others, such as rutile, show colour between crossed nicols only when reduced to dust or when the thinnest edges of small fragments are carefully examined. Special slides must be made of such minerals, and the collection will be greatly increased in value by the addition of sections cut parallel to the three pinacoids of one or two representative minerals of each crystalline system.

When the student first looks at a slide prepared in this manner with, say, a 1-inch object glass and between crossed nicols, he sees only what appears to be a wild confusion of depolarizing flakes. After applying to them the principal kinds of observations referred to at page 26 he soon finds that most of the flakes are referable to a few directions more or less parallel to, or across, the axes of the crystal of which the fragment he broke down formed a part. Even in the case of quartz

in which no prism cleavage is developed (for the extinctions are found to be "anyhow"), there is value to be attached to the mere absence of such cleavage. Examined in convergent light a number of the quartz flakes are found to be rudely parallel to a pyramidal face, probably the rhombohedral. They give the oblique emergence of a uni-axial figure, its centre near the edge of the field of an objective with an angle of 130° . Tested by the wedge in parallel polarized light these flakes are found to appertain to a positive mineral. So that even in the case of one of the most characterless of the slides evidence enough is found to establish the identity of some unknown fragment possessing similar properties when so broken up, mounted and examined. Absence of cleavage bearing any definite relation to extinctions oblique emergence of positive uni-axial figure, near approach of refractive index to that of the balsam, shown by faint borders in parallel light, indicate that the unknown mineral is probably quartz. A few subsequent tests such as hardness, insolubility in acids, &c., complete the chain of evidence and establish the identity of the mineral.

The student having prepared for himself a set of test slides from well-authenticated minerals, possesses a "work of reference" of the utmost value. Therein are no mistakes such as the writer of this little pamphlet has possibly made, referring, it may be, to the emergence of an "acute" bisectrix when he meant to say "obtuse," or to some cross wire being parallel to one edge when he meant another. Such mistakes may occur in the best text books, and are very puzzling to a beginner intent on some particular paragraph wherein the mistake occurs.

HOW TO EXAMINE ANY SAND.

Sand consists of a mixture of fragments of minerals in which are generally scattered very small crystals, such as tourmalines, zircons, rutiles, and others originally enclosed in the larger constituents of rocks.

The study of sand forms a good stepping stone for the beginner passing from the test slides he has made of typical rock-forming minerals to the study of the rocks themselves. He may proceed as follows :—Sift the dry sand on a fine muslin or wire sieve. It should have 120 holes per inch. The sifting should not be continued very long. The small crystals pass more easily through the sieve than the fragmentary components of the sand, even when all these are small enough to pass through the sieve. The object of this sifting is to get rid of most of the quartz. Wash that part which has passed through the sieve in a saucer half full of water. Thereby wash away the clay and by a circular movement get the denser minerals to collect as a tail. About half a thimbleful of sand is sufficient, but if it appears to contain little of the denser minerals, as seen by the tail, a second portion of sand may be used, after scraping away the bulk of the quartz grains. Again remove the coarser part and concentrate the tailings till no more is left than can be mounted on a slide, using weak gum water for the last washing. Remove the tailings with a camel's hair brush to a glass slide and heat the slide to dry the preparation quickly, otherwise the grains draw together and adhere one to the other. It is best to have each crystal or fragment detached from its neighbours so that it may be examined under crossed nicols in a dark field. Mount in thin balsam to exclude air bubbles, as in making the set of test slides; heat to thicken the balsam and cover with thin glass. The result will be a slide which may contain about a dozen different minerals. To examine these, turn down the analyser on its hinge and employ the 1-inch or lower power objective so as to use light which is nearly parallel. There will be seen a number of grains and many perfect crystals with more or less strongly defined borders amongst a crowd of ghostly-looking fragments. These latter can scarcely be distinguished owing to their refractive index being about the same as that of the balsam. They consist of quartz and probably some felspar.

Examination of the Denser Minerals. *Tourmalines*.—

Turn the polarizer and observe the tourmalines by their dichroism already alluded to at page 34. They are mostly of a brownish colour, some are yellowish, others light green or blue. Many are perfect doubly terminated crystals, often with different forms at opposite ends, owing to what is called hemimorphism; others are nearly quite round. Amongst the latter can be found some which in convergent light give more or less oblique emergences of a uni-axial interference figure affording excellent practice. Use the small lens H for grains which are too small to fill the field of the 1-4 inch or 1-5 inch objective. To ascertain whether the mineral is + or — in a rounded grain when the centre of the cross emerges far outside the field will require careful observation. It must be done in parallel light with the wedge after having found the direction of the optic axis indicated by the dark bar crossing the centre of the field. Push out the lenses H and A' and swing round the 1-inch or other lower power so as to use parallel light. Turn the nicols 45° and pass the wedge in one or other direction till compensation is attained. Then note the direction of the major and minor axes of elasticity, whereby in uni-axial minerals, as already explained, it becomes known whether the rounded grain is to be referred to a positive or negative mineral. The grains being nearly round do not depolarize in uniform sheets of colour, but in rings which give compensation one after the other as the wedge passes.

Zircons.—These are colourless and occur in much smaller crystals as a rule than the previous mineral. They show darker borders and although thinner depolarize in colours of the higher orders, owing to their high double refraction. Their brilliant colour in the dark field immediately arrests the attention of the observer, though when large they show a colour only on the edges.

These two minerals may be regarded as typical examples of

minerals giving straight extinction. The former being negative and the latter positive, it will be found that whereas the tourmaline gives compensation when its prisms lie with their length parallel to that of the quartz wedge, the zircon does so when at right angles thereto.

Rutiles.—As another example of straight extinction the slide is to be searched for small reddish yellow prisms. They show very dark borders and have such high double refraction that they do not depolarize in brilliant colour, but only in their own reddish yellow colour. To see the coloured depolarization mount a single crystal on a slide and crush it thereon, when its dust and thin splinters will show brilliant colours between crossed nicols. Occasionally kite-shaped twin crystals of rutile are to be seen. Those occurring in clay are often thin enough to depolarize in colours which can be compensated by the quartz wedge. They give a positive reaction.

Kyanite.—As an example of a mineral giving oblique extinctions the slide may be further searched for colourless cleavage flakes showing dark borders and depolarizing in the bluish grey or white of the first order. These flakes are generally traversed by cleavages nearly at right angles to their length. The extinction angle is about 30° on M measured from the edge (100:010). They generally lie on the M face (100) and show in convergent light the emergence of a negative bisectrix. The optic angle is very large, both poles being outside the field. Occasionally a cleavage flake lying on the face T (010) may be met with; such flakes have an extinction angle of about 8° . Compare one of the test slides. To see the interference figure in the flakes from the sand the small lens H in the woodcut must be used as they are too small to fill the field of the 1.4 inch or 1.5 inch objective. The lens G may be used with the test slide which will contain larger flakes of kyanite.

Garnet.—As an example of an isotropic mineral the slide is

to be further searched for fragments of garnet. They show dark borders in the balsam, and remain dark during the rotation of the nicols. They are generally of a reddish tint, but so faint sometimes as to seem nearly, if not quite, colourless.

Ilmenite.—This mineral is widely distributed in sands and clays, and must not be confounded with titaniferous iron ore. The brilliant surfaces it shows by reflected light may lead to its being confounded with magnetite, but it is not attracted by a small magnet. The grains transmit a faint green light at the edges, best seen by crushing a single grain on a glass slide under a thick cover glass. When a quantity of it, got from sand, is decomposed by cold hydrofluoric acid, which requires about twenty-four hours, it generally leaves a few grains and crystals of chromite, and some dark spinels. The chromite may be distinguished by the red light it transmits when a grain is crushed on a glass slide. The spinels when crushed transmit bluish or greenish coloured light.

The finer grained Bagshot sands are good sands to examine, particularly those occurring at Hampstead. In some of the large deposits the grains of sand do not exceed the 1-200 of an inch in diameter. It is in such sands that the minute dense minerals once forming "enclosures" in the larger constituents of rocks are found most abundantly. The coarser grained sands contain but few minerals. In the Hampstead sand all "iron ores," such as pyrites, hematite, magnetite, titaniferous iron and specular iron, if ever present, have been removed by water percolating through the sand. Sundry other minerals may be occasionally met with, but are not generally to be found in any one slide; such are topaz and anatase.

HOW TO EXAMINE ANY ROCK.

If coarse-grained, break it up in a steel mortar reducing it to the condition of sand. Then examine it as though it were

a natural sand. In addition to the minerals already enumerated, all of which may reasonably be expected, others, such as hornblende and augite, will easily be identified amongst the larger constituents of the rock. Coarse-grained rocks may be expected to yield crystals of apatite, sphene, pyrites, specular iron or other "enclosures." It will probably astonish the beginner to find how perfect many of these remain after being broken out in such a rough manner. Doubly terminated crystals of apatite with complex terminal facets and very perfect crystals of sphene will be observed, as though there had never been any true junction of the enclosed minerals, and the minerals enclosing them. After the optical examination of the fragmentary minerals, such tests as hardness, action of acids, and others outside the scope of this pamphlet, may be used. Selecting any granite containing hornblende such as the well-known granite from Dalbeattie, Scotland, it will be found to give beautiful crystals of apatite and sphene (the latter may be absent in other granites), whilst amongst the coarser constituents quartz, felspar, hornblende and mica can easily be seen with a hand lens. With the exception of the hornblende, a single fragment of each of these, if crushed, will give flakes yielding interference figures, from which, with other links of evidence, the identity of the mineral may be established. It may be noted that the hornblende cleavage fragments show little or no dichroism, because they are all prismatic cleavage flakes, which in that variety of hornblende show scarcely any dichroism. Sections cut in other directions shew the well-marked dichroism of green hornblende, as will be seen when the student advances to the examination of "rock sections."

These are thin slices of rock cut by a lapidary's wheel, and ground down on a piece of glass with emery powder till they are transparent. They should, as a rule, be of such thickness that the quartz they may contain may depolarize in the yellow or red of the first order, where the section of the quartz is parallel, or

nearly parallel, with the axis of the crystal. So cut, the quartz shows its greatest double refraction. It would be well if in the preparation of all sections three or four small slices of quartz so cut were ground down with the section, and mounted with it for comparison of tints. This is done, the writer understands, by some petrologists, and it seems an excellent practice. A few thicker sections for the beginner are useful because they give one or two rings, or parts thereof, in the interference figures, in addition to the black cross or hyperbolic curves, on which the advanced petrologist principally relies. The cross or hyperbolic curves are the only parts of the interference figure which the majority of the minerals in ordinary rock-sections afford, and they suffice; but for the beginner to fully understand them, one or two rings, or parts of rings, are very useful. It must be borne in mind that in the instrument described in this pamphlet, the rings do not move, as in an ordinary polarizing microscope, during rotation of the section. They always remain stationary; only the dark shadows move. In many respects this is an advantage, though it gives a feeling of strangeness to an observer accustomed to the ordinary polarizing microscope. Very quickly the sense of strangeness passes away, and the advantage of being able to turn rapidly from parallel to convergent polarized light, with perfect centering, is experienced. This is especially the case in examining the smaller crystals in rock sections.

It may be noted that during the preparation of any rock section, the traces of cleavage planes appear in many of the constituent minerals. These apparent cracks are of great value in aiding the observer to identify a mineral, as it is on them that he must often rely in the measurement of extinctions and observations on pleochroism. They are developed at different thicknesses during the grinding down of the section; thus in basal sections or sections nearly parallel to the basal planes, of hornblende, augite, and hypersthene, the cracks appear when

the section is still almost too thick to be transparent. In felspar they do not appear as a rule till the section is thin enough for the felspars to depolarize in the gray of the first order. In quartz they do not appear at all, or only very rarely. The grinding down of the section is stopped, when the cleavage marks are developing in the felspars, and before they have appeared in the quartz; the section crumbling away if the grinding be continued.

These rock sections show the manner in which the rocks have been, so to speak, built up, as the observer can see how the minerals enclose each other. They are also the only means of optically examining the finer grained rocks and the ground-mass of porphyrites, &c. The observer distinguishes the minerals in such sections by applying to them those kinds of observations described on page 26. Thus, suppose a section of Dalbeattie granite on the stage of the microscope. Viewed under the low power without the use of the analyser, the section is found to consist of opaque, coloured, and colourless minerals. The first must be got out for examination, chemically or otherwise, by breaking up the rock as previously described.

Turning to the coloured minerals, which in the case supposed are hornblende, black mica, and sphene, and taking them in that order, note in the hornblende its typical dichroism. In sections showing the rhombic cracks (traces of the prism cleavages), the mineral is brownish green when the marked cross wire is parallel to the longer diagonal of the rhombs, and yellow when it is at right angles thereto. In sections parallel to the prism, or approximately so (known by parallel cracks), the colours are green when the marked wire is nearly parallel to the cracks, and yellowish when nearly at right angles thereto. Turning from parallel to convergent light, note the emergence of one "eye" of the interference figure in basal sections, and of the other eye in sections parallel to the face (100). Probably

only sections approximately parallel to the different faces will be found, but they will generally be sufficiently so to enable the observer to know how the section is cut.

In the mica the basal sections show no dichroism, or if slightly inclined as they probably will be, only slight changes of depth of tint. In sections at right angles thereto, or nearly so, the pleochroism is so marked that "absorption" seems a better word to use. When the traces of the basal cleavage are practically parallel to the marked wire, there is complete absorption of all colours, whilst at right angles thereto the mineral transmits yellow light. If the observer has before him, in default of a section of Dalbeattie granite, one of some other granite, it may prove that black mica is not present, but only white mica, or both may be present. The white mica (muscovite) will easily be recognised by its high double refraction, its extinction, practically straight in sections, showing basal cleavage cracks, and by the absence of dichroism. The interference figures in convergent light are best seen in flakes broken out of the rock, but generally sections can be found which are so nearly parallel to the basal plane, that they may be used for observations in convergent light.

In the sphene, known by its dark borders, rough surface and yellowish colour, there are no typical cleavage cracks developed during the grinding. The crystals are generally small, and present more or less rhomboidal sections showing little or no dichroism. They are too thick to show interference colours, if they are as thick as the section, though if small enough to be regarded as "enclosures" they may be thin enough to show brilliant colour. Generally sphene is too sparsely distributed to enable the observer to see an interference figure, the chances being against his finding a suitable section. To identify the mineral it must be got out by breaking up a bit of rock as previously described, and looking for the sphene in the tailings. A crystal or fragment crushed on a glass slide, and viewed between

crossed nicols under a low power, shows depolarizing colours on its thin edges, and here and there a flake shows a uniform shimmering light. These shimmering flakes give in convergent light the oblique emergence of the positive interference figure with characteristic dispersion $\rho > v$. In many rocks sphene occurs only in irregular grains.

Quartz.—The quartz is distinguished by the total absence of cleavage cracks, depolarizing in sheets of very uniform colour, and showing, when examined by a high power, numerous cavities containing liquid, and a gas bubble which in many cases shows spontaneous movement; on the other hand quartz in many rocks is free from enclosures, and it may show undulose extinctions. Sections at right angles to the optic axes remain dark during rotation of the nicols, and give in convergent light a positive uni-axial figure. Slightly oblique to the axis, the quartz depolarizes in the cold gray of the first order in sections of average thickness, and may then easily be mistaken for felspar. Its enclosures, generally differing from those of the felspar, and the oblique emergence of a uni-axial figure in convergent light, suffice to distinguish the minerals.

Felspar.—The interference figures of this mineral are always bi-axial or parts of bi-axial figures. As a rule also its enclosures differ greatly from those of the quartz. They very frequently mark the lines of accretion of the felspar crystal. What are known as “undulose extinctions” are common. Twinning, best seen in polarized light, forms a marked feature in many felspars in granite and other rocks, but it must be borne in mind that it is often absent, and that the enclosures in the felspars of one rock frequently resemble those in the quartz in some other rock. The comparison to be of any value must be made upon the felspars and quartz occurring together in the sections of any one rock. To recognise the felspars in a section is easy, but to ascertain to which of the different felspars the mineral is to be referred is one of the most difficult problems which the

petrological student has to solve. He must as a rule get the felspar out of the rock by breaking it up and picking out the felspar-fragments, or separating them by dense solutions from the accompanying minerals. The fragments must be further broken up, if need be, till they depolarize in the colours of the first order. Owing to the frequent twining the thinnest, from which wedge-shaped flakes should be excluded, are generally the best for optical investigations. The cleavages of felspar in such thin flakes are numerous. It seems that each principal face has a cleavage parallel to it, and that there are others parallel to the secondary prism faces, rarely obtained, but very puzzling when met with. In moonstone a common cleavage is a prism face near K, another is nearly or quite parallel to the face K, and another much less frequently met with gives the acute bisectrix in the centre of the field. These different cleavages seem to exist in all the felspars, and it is their number which makes the identification of the felspars so difficult.

The method of identification generally employed is that known as Max Schuster's. It is an excellent method, but requires the observer to get an M flake into the proper conventional position, or turned through 180° in its own plane. To find an M flake and put it in position for determining whether the extinction is + or — in the conventional sense in which these signs are used in the recognition of felspars, search the slide for a flake giving the emergence of a positive bisectrix, and bounded by traces of the basal plane and prism or K cleavages. The felspars rarely cleave true to the prism cleavage. There is a common cleavage inclined a few degrees to the prism cleavage often marked as in microcline by striæ, so that the rhombic M flakes rarely show the true angles. Set the instrument at zero and turn the slide till the trace of the basal cleavage in the M flake under investigation is parallel with the marked cross wire. The traces of the K or prism cleavage must then lie nearly *north east by north*, and *south west by south*, when the field is

regarded as a map. If they are not so the flake is on its wrong side. Turn it over, or if the flake is in balsam turn the slide over, but in that case the glass must be thin or the objective will not focus through it. Having placed the flake in position so far as it is possible to do so (in the writer's experience it is not possible to say whether it is in its right position or turned 180° in its own plane), view it between crossed nicols in parallel light. In rare cases, such as the sunstone from Twedestrand, the extinction is straight in reference to the basal cleavage of the M flake; perhaps it may not always be so even in that felspar, but in other feldspars, as a rule, it is not straight. Suppose a flake of albite on the field in conventional position, or turned 180° in its own plane, it will be found that extinction is not attained till the zero has been turned about 20° towards the observer's right—towards the E in the field regarded as a map. That was what Max Schuster called a $+$ extinction. To attain extinction in a similarly placed flake of labradorite by the smallest movement of the nicols they must be turned about 16° in the opposite direction, which Max Schuster called a $-$ extinction. For reasons, which are connected with the position of the optic axial plane in different feldspars, the reader is referred to the original memoir or text books on petrology. In actual work it is not necessary to set the instrument at zero, that was done only to simplify the description of the mode of procedure. It is enough to observe how the marked cross wire crosses the trace of the basal and prism cleavages when the flake is at its maximum extinction.

M. Schuster's mode of procedure may be combined with one founded more entirely on the use of convergent light, though that is at first rather puzzling, since each interference figure may present itself in four different positions. These depend upon how the flake lies, whether in the conventional position, or turned 180° in its own plane; or turned over, and

again turned 180° in its own plane. In hopes of simplifying this matter, and for general measurements, a cross ruled eyepiece micrometer has been added to this instrument. To use the micrometer with these interference figures set the instrument at zero, and observe that the marked cross wire forms the equator, whilst the upright wire occupies the position of the first meridian of longitude. Insert the micrometer through the slot E, push the lens G into the axis of the instrument, and draw it up or down till it shows nine lines on either side of each cross wire. The 1-5 inch objective being in use the interference figure will then be seen projected on a field which may be regarded as a map, each line representing 10° , whilst the intersections of the cross lines at the margin give very nearly the points of the compass. Absolute exactness is not required.

Such a field is a great assistance to the beginner, working as he ought to work on large flakes or sections specially prepared, though it is not of much use to the advanced student, and it cannot be used with the smaller lens H in general work. But when the idea of exactly locating the point of emergence of any part of an interference figure, and noting the position of any hyperbolic curve, has got possession of the student's mind, he can do without lines to represent degrees on the field, though at first they are an undoubted assistance. He should mark with ink the N. S. E. and W. points of the compass on the field, so that whilst it goes round with the nicols he never loses his bearings. With or without lines on the field one of three appearances presents itself, when the M flake of any felspar is viewed between crossed nicols in convergent light, the trace of the basal cleavage being parallel to the marked cross wire.

1. No axial bar is seen whether the 1-4 inch of 90° or the 1-5 inch of 130° is used. On turning the nicols a few degrees two hyperbolic curves appear simultaneously, the axes of which are outside the field, close to the ends of the marked cross-wire, with the bisectrix in or near the centre (see 3a); or the bisectrix

may emerge more obliquely, the axial curves having appeared one after the other (in some albites almost simultaneously), in which case pass to the next paragraph—the mineral must be either albite or labradorite.

2. One axial bar is seen emerging close to the east or to the west end of the equator and turning sharply to the N. or S., but wholly within its own quarter of the field. Turn the nicols; if no bisectrix appears the mineral is anorthite; the axis is within the field. If a second axial bar appears the felspar is either albite or labradorite. Sharp attention is now required to note whether the trace of the optic axial plane crosses the traces of the prism cleavage nearly at right angles (about 80°); if so the mineral is albite. If it crosses the prism cleavage very obliquely (about 35°), and slopes with it, the mineral is labradorite. A comparison of the interference figures of the two minerals will make the distinction so clear that the student cannot mistake them; no actual measurements are required, though they may be made. The general direction is enough. The real difficulty is to find the flake and then to determine the direction of the trace of the optic axial plane without rings and sometimes emerging very obliquely. When the traces of the prism or K cleavage are not developed recourse must be had to the refractive index. Albite immersed in balsam shows scarcely any borders, whilst labradorite shows them distinctly. In some varieties of albite the bisectrix emerges nearly perpendicularly, but the trace of the optic axial plane crossing the prism cleavage so much more nearly at a right angle than it does in other felspars there is no fear of a mistake. Labradorite sometimes shows an “eye” in the field of 130° as well as the bisectrix, the optic angle being under the average.

3. Two axial bars are seen. They are nearly straight, and nearly parallel with the basal cleavage. The axis of one emerges close to either end of the marked cross wire (depending on the position of the flake) and just outside the field of 130° , whilst

the bar itself passes into the adjoining quarter whence the bisectrix emerges, in some cases more perpendicularly than in others. The mineral is microcline. It may be further identified by the cross hatching on basal flakes, though that is sometimes almost entirely absent, in which case the extinction relatively to the trace of the M cleavage being about 15° or 16° distinguishes it from all other feldspars. The writer has met with only one such microcline. It occurs in Madagascar, is apple green, and shows unusually good cleavages. Other microclines of that kind have been described.

3 (a). Two axial bars are seen. They may be so nearly out of the field that only a faint darkening is perceptible on the margin in two opposite directions (moonstone of Ceylon and the chatoyant feldspar of Friedrichvarn), or they may be distinctly seen each in its own quarter (many varieties of orthoclase and oligoclase), or they may have met in the centre so that the field is dark, as in the sunstone of Twedestrand. In all these cases the emergence of the bisectrix is either perpendicular, or so nearly so that no distinction can be founded on the optical properties of thin cleavage flakes even with the aid of basal flakes. In these the traces of the transverse cleavage are often very imperfectly developed, and the lines or edges not truly parallel, so that the observer is in doubt whether the extinction is straight or not, and it may vary, as seen in the undulose extinctions so common in feldspars.

On the whole it may be said that whilst anorthite, labradorite albite and microcline may be distinguished from one another and from all other feldspars, in thin flakes it is requisite to have recourse to the twining in rock sections or to flame reactions, specific gravity, or chemical analysis for the identification of the remaining feldspars.

Of andesine giving minus extinctions the writer can say nothing from his own experience, as he has been unable to meet with any examples of that class of feldspar. The nearly

perpendicular emergence of the bisectrix from the M face will, he supposes, bring it into the group of feldspars described under 3 (a), from which however it must be easily distinguished by the — extinction.

HOW TO VERIFY THE INSTRUMENT.

Set the disc at zero and observe the interference figure of a perfect basal flake of topaz showing two or three rings round each axis. In default of topaz a flake of muscovite may be used, though that theoretically is not so suitable as topaz. Magnify the image by the lens H, and turn the flake till the trace of the optic axial plane is parallel with the upright cross wire. If it is a little on one side try the objective on the other limb of the nose-piece. If that does not answer unscrew the objective a little, watching the figure till a point is reached at which the cross wire is coincident with the trace of the optic axial plane. Fix the objective in that position by a washer of paper or a thin sheet of metal. Absolute correctness does not seem to be attainable, for if the wire is truly coincident with the dark bar of one set of rings it seems always to be a little out of coincidence with the other. Turn the nicols 90° to see that the wires are at right angles to one another and turn correctly. There are three things to be dealt with, viz., the mineral, the instrument, and the observer, all of which may be very good, but none of which are perfect. Fortunately in such studies absolute accuracy is not required, conclusions being drawn from the correlation of the results of a number of different kinds of observations such as have been described in the preceding pages, and which generally suffice for the identification of any rock-forming mineral.

