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I.—THE PRESIDENT'S ADDRESS: THE DESIGN OF THE PETROLOGICAL MICROSCOPE.

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(*Read January* 16, 1924.)

SIX TEXT-FIGURES.

TWELVE months ago, I had the honour of addressing the Society on the subject of "The early history of the Polariscope and the Polarizing Microscope." In that address I traced the history of the Polarizing Microscope down to near the end of the last century.

My address to-night deals with the general principles which should be considered in the design of the petrological microscope, and has been written as a sequel to the first address, with which it should be read.

In the early days of the polariscope, as we have seen, it was an instrument *sui generis*, but later, when its aid was called upon for petrological work, the demand was met by fitting an ordinary microscope with polarizing adjuncts, and this fact appears to have determined the lines upon which the subsequent development of the petrological microscope has proceeded. Some time ago I was discussing the question of instrument designing with a well-known engineer, and he illustrated this tendency on the part of inventors, to confine their work unconsciously within the limits originally laid down—to improve existing designs, rather than invent new ones—by referring to the evolution of the gun-lock. In the first fire-arms the powder was ignited by a lighted match, or string, applied by hand to a primed vent, placed on one side of the barrel to allow of the harmless escape of the gas blown through it. The next inventor improved upon this arrangement by fitting a mechanical finger to apply the lighted match. Then came the flint-lock, in which the match was, in effect, simultaneously lighted and applied. Later the flint-lock was modified for the use of the percussion-cap, and later still when the breech-loader was introduced, with its ready-made cartridge, a lateral pin, struck by a hammer, was still used to detonate the charge.

Thus the trend of invention in the case of the gun-lock has probably been determined for centuries by the fact that in the original fire-arm the powder was ignited by a hand-applied match. It will be interesting to enquire whether the evolution of the petrological microscope has been influenced in a similar way. The demands of the early petrographer, as judged by what can be met to-day, were not great, but as time passed, these demands grew, until, to-day, the utmost skill of the optician and instrument maker are taxed to meet the needs of a worker in the front rank. Clear evidence of this is given in the articles which have been contributed from time to time, during the last twenty years, by Mr. F. E. Wright to the " American Journal of Science." In the words of this worker: "Minerals in thin sections are determined and recognized chiefly by the effects they produce on transmitted light, and the relation of these effects to observed crystallographic effects such as cleavage, crystal form, etc. The usual optical properties which are thus made use of in determinative work are—crystal habit, cleavage, character of elongation, colour, pleochroism and absorption, refractive indices, bi-refringences, extinction angles, optical axial angles, optical character, and rarely dispersion of the optical axes." *

It will be convenient for our purpose to-night to consider the subject of the design of the petrological microscope under the three following heads, namely :—

1. The optical elements of the imaging system, including the condenser, objective, eye-piece, and auxiliary lenses and systems.
2. The polarizing elements, including the polarizer and analyser.
3. The mechanical design.

OPTICAL IMAGING ELEMENTS.

Broadly speaking there can be no doubt but that so far as the optical system is concerned, which is responsible for the presentation to the eye of a magnified image of the rock section, optical science has been equal to the demand; indeed in some respects the optical requirements of the petrological microscope are not of quite such a difficult order as in the case of the microscope *per se*; on the other hand, however, there are certain requirements of a more exacting nature. It simplifies the problem to remember that generally speaking low and medium power objectives are

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* " American Journal of Science," xxix, 1910, p. 415.

almost entirely relied upon. This is a fortunate circumstance because, as we shall see later, it is of some importance that the lower focal plane of the condenser be in air, and accessible, as is the case in the simple two-lens Abbe condenser. In the three-lens form of this condenser and the achromatic varieties of the same, which, if not necessary, are desirable when high powers are used, this focal plane is inside the system, and not so accessible for our purpose. A desirable property of the objective is that its upper focal plane should be accessible, but this I am afraid is not likely to be realized. Possibly, however, something might be done in the case of the lower powers, but that is a question for the lens designer. The question as to whether the eye-piece should not be of a type which gives, for a given power, a greater distance between the last lens vertex and the Ramsden circle than the Huygenian eye-piece does, is one of some importance because, as we shall see later, this distance determines the efficiency with which the analyser can be used in certain types of instruments.

POLARIZING ELEMENTS.

Analysers and their Mounting.—A bi-refractive substance, like Iceland Spar, acts as though it possesses what may, by analogy, be called optical grain, by virtue of which light waves pass through it in different directions with different speeds, just as sound waves do through a piece of wood by virtue of its grain. The direction of the optical axis in the case of spar is the direction of this grain. Now in the case of an analyser transmitting a parallel beam, all the vibrations in the various elements of the plane wave-front take place parallel to one another, and at right angles to the direction of propagation. These vibrations, however, can only occur in one of two rectangular directions—the first in the plane, or in planes parallel thereto, containing the axis of the beam and the axis of the crystal; and the second, normal to this plane. In either case all the vibrations take place at the same inclination to the direction of the grain, and are consequently transmitted with the same speed. The plane wave-surface remains plane, and is consequently transmitted without deformation. In the case of spherical wave-surfaces, however, this condition of equal inclination to the grain cannot be satisfied, because the direction of propagation is different for the different elements of the spherical wave-surface, with the result that the wave is broken up and deformed, so that incident homocentric pencils emerge as highly astigmatic pencils. Experimentally the results can be shown as follows:—Take a petrological microscope and throw the polarizer and analyser out of action. Then place a grating, ruled in squares, upon the stage, and focus it under a magnification of about 100, using a $\frac{2}{3}$-in. objective, with the lines of the grating vertical and horizontal respectively in the field of view. Now push the analyser into position immediately above the objective. Both sets of lines will now be out of focus, and the astigmatism of the image is so great that when one set of lines is brought into focus, the other set practically disappears from view, and this, too, with an analyser of the best design and manufacture. Now repeat the experiment with the analyser above the eye-piece. No re-focussing is required: both sets of lines remain sharply defined. The above considerations show conclusively that to obtain the best definition, it is imperative that the analyser be mounted in such a position that the imaging beams pass through it with their rays parallel to one another, and, unfortunately, this can only be done by mounting the analyser between the last lens vertex of the eye-piece and the Ramsden circle. This difficulty is further increased by the fact that in the common type of eye-piece employed—the Huygenian—this distance is small, especially in the case of high powers. With the ordinary spar analyser in this position, the Ramsden circle is no longer accessible, except in the case of low-power eye-pieces,* and the field of view is seriously cut down; but in spite of all objections, the advantages derived from this place of mounting the analyser are very great, and it is still the mounting perhaps most favoured by professional workers. Should a colourless substitute for tourmaline ever be discovered all the difficulties mentioned will disappear. Quite recently, I believe, the analyser above the objective has been fitted satisfactorily with a correcting lens, but I have not had an opportunity of testing the device. Another way of increasing the effective field of view would be to combine an analyser with an eye-piece of a type giving a greater distance for the same power between the last lens vertex and the Ramsden circle. The demands for angular aperture should not be forgotten. For an analyser above the eye-piece a field of about 30° at least is required, whereas for an analyser above the objective not more than half this angle is required, so that in the latter case the prism can be reduced in length.

The polarized field of view should also be symmetrical about the axis of the microscope. A lop-sided field, and it is common, of say 35° in all, but of which the limits are between 20° to the axis, on one side, to 15°, on the other, is only effective over the symmetrical angular field of $2 \times 15 = 30°$. The limitation thus imposed is often serious.

Another important practical matter is the order of flatness of the prism faces. Spar, unfortunately, can only be polished on pitch with great difficulty, and cloth polishing often results in the turning over of the edges, and with such prisms, of course, good definition is impossible for any position of the prism.

In the Abbe analyser an achromatized double-image prism of

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* To get the maximum field of view an eye-piece analyser should always, if possible, be used with a low-power eye-piece.

glass and spar is mounted between the stop and the eye-lens of an ordinary Huygenian eye-piece. This prism gives two Ramsden circles, i.e. two images of the stop in the upper focal plane of the objective. One of these is stopped out mechanically, so that a single polarized beam only is transmitted to the eye. The use of a double-image prism in this way was not due originally to Abbe; Amici used a prism in a similar way about the year 1830.

Polarizers.—For simple microscopes, and especially for low-power work in which a large field of view is required to be illuminated, the reflecting blackened-glass polarizer is much more effective and satisfactory than the ordinary small Nicol. A single plate with one reflecting surface gives ample light for most work; if more is wanted it can be obtained quite easily by superposing a plate of glass on the blackened-glass so as to obtain three effective reflecting surfaces. In an emergency 3 × 1 in. slips may be used, secured by wax to the ordinary silvered reflector and tilted to the polarizing angle. The equivalent of a rotary polarizer can be obtained by mounting, to rotate between the polarizer and the condenser, a mica $\lambda/_2$ retardation plate.

Polarization by a Pile of Glass Plates.—When a parallel beam of ordinary light falls upon a pile of parallel reflecting glass plates at the polarizing angle, (1) part of the light is reflected, (2) part is absorbed, and (3) part is transmitted. Practically all the light reflected (1), is polarized with its vibrations parallel to the reflecting surfaces, and normal to the plane of reflection; whilst that transmitted (3), is polarized, partly with its vibrations parallel to those in the reflected light, and partly with its vibrations at right angles to this direction, i.e. in the plane of reflection. Some years ago Stokes calculated the percentages of the light in each of these parts, and these are given in fig. 1* and plotted in fig. 2.

No. of Plates.	Reflected (A) Percentage.	Transmitted (B)	(C)	(B–C)	$\frac{100\,(B-C)}{(B+C)}$
		Percentages.			
1.	13·3	48·8	35·6	13·2	15·5
2.	20·5	47·7	27·2	20·5	27·3
4.	27·8	45·4	17·8	27·6	43·5
8.	32·8	41·2	9·1	32·1	63·5
16.	34·8	34·0	2·9	31·1	84·0
32.	35·0	23·1	0·3	22·8	97·5
∞	35·0	0	0	0	100·0

FIG. 1.—Reflected and transmitted polarized components of a beam of light incident at the polarizing angle on a pile of glass plates. (Stokes.)

In this table, column A (curve A, fig. 2) gives the percentages of polarized light reflected, and with vibrations normal to the

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* Proc. Roy. Soc., xi, 1860–2, pp. 545–57.

plane of reflection for the numbers of plates set out in the first column. Column B, (curve B, fig. 2), gives the percentages of transmitted light with vibrations in the plane of reflection, whilst in column C, (curve C, fig. 2), are given the percentages of transmitted polarized light with vibrations parallel to those in the reflected beam. In the fifth column are given the differences between the two components of the transmitted light, whilst in the last column the ratio is given between the balance of the polarized light in the transmitted beam, and the total quantity transmitted. In other words, the numbers give the effective polarization of the transmitted light. It will be noticed, however, that the more pure this becomes, the smaller is the quantity of light transmitted. Each plate is assumed to absorb 2 p.c. of the light entering it and to have an index of 1·52.

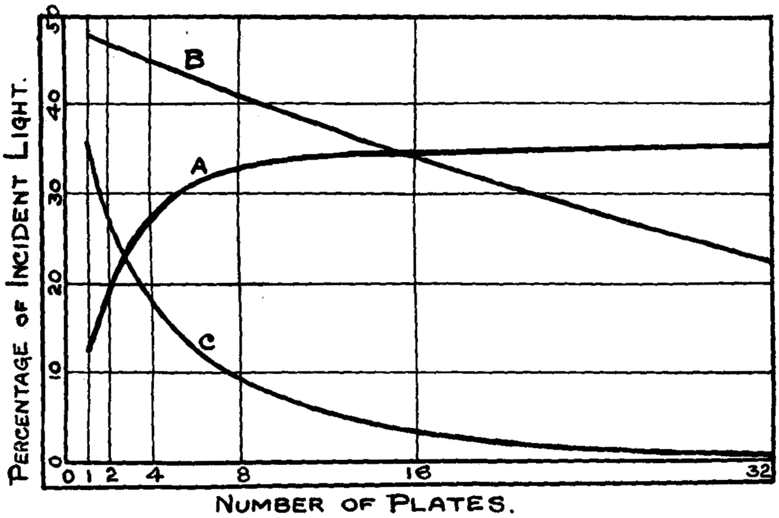

FIG. 2.—Polarization by reflection by glass plates (Stokes). The figures given by Stokes in fig. 1 are plotted in fig. 2.

From this diagram it will be seen that one sheet of glass (two surfaces) reflects about 13 p.c. of the incident light in the completely polarized condition, whilst in the transmitted beam, 36 p.c. is similarly polarized, i.e. with its vibrations parallel to the reflected surfaces; but this 36 p.c. is mixed with 49 p.c. of transmitted light, which is polarized with its vibrations in the plane of reflection. Thus in effect 36 p.c. of white light is transmitted mixed with 13 p.c. of polarized light.

Iceland Spar Prisms.—Many polarizers fitted to-day are not the best for the particular work required of them. They are frequently too small in diameter to give the full field of view with low powers, and, on the other hand, the angular aperture is larger than is necessary, and the cost is increased without compensating advantages by the use of the square-ended type. A shortened Nicol with an aperture of about 20° is probably the best, taking all requirements into consideration.

Some years ago, Halle, who has had great experience as a maker of all kinds of polarizing prisms, published an account of these,* from which I have taken the table, fig. 3, and the diagrams of the prisms referred to (fig. 4).

Name.	Section.	Medium.	Used of 125 c.cm.	Side.	Length.	Waste.	Field.
			c.cm.	mm.	mm.	c.cm.	
(*a*) Foucault	Diamond	Air . .	120	45	61	5	7°
(*b*) Nicol .	Diamond	Balsam	110	35	92	15	24°
(*c*) Halle .	Octagonal	Linseed Oil	68	37*	67	57	19° unsym. field 17° sym. field
(*d*) Halle .	Square	Balsam	59	29	72	66	25°
(*e*) Hartnack-mowsky-Praz	Square	Linseed Oil	29	22	60	96	32°
(*f*) Glan .	Square	Air . .	27	30	30	98	8°
(*g*) Glan-Thompson	Octagonal	Linseed Oil	23	27*	43	102	32° unsym. field 18° sym. field
(*h*) Glan-Thompson	Square	Linseed Oil	20	20	50	105	34°
(*i*) Ahrens .	Square	Ditto .	20	24	34	105	26°
(*k*) Ahrens .	Square	Balsam	19	22	39	106	24°
(*l*) Grosse .	Square	Air . .	19	33	17	106	6°

* These are the diameters of the round end faces.

FIG. 3.—Polarizing prisms (Halle).

In the case of each of the prisms referred to in column 1 of the table it is assumed that a rhomb of spar of the most favourable dimensions, with the cubic content of 125 c.cm. is used; column 4 gives the volume of the finished prism, and the difference between this and the original volume of the rhomb is given as waste in column 7. From the figures given it will be seen that in the making of an ordinary Nicol prism with an angular field of view of 24°, a waste of 12 p.c. occurs, whilst in the case of the Glan-Thompson prism the waste rises to 84 p.c., but the field rises at the same time to 34°.

The design of polarizing prisms was dealt with very fully in a lecture given by the late Professor S. P. Thompson at the Optical Convention, London, in 1905.

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* Deutsche Mechaniker Zeitung (1908), pp. 6 and 16.

With a small and sharply defined source of light, such as is now commonly employed, and which can be made at any time by placing a flat flame behind a round hole in a sheet of metal, a short double-image prism of spar and glass can be used as a polarizer. Such a prism produces two images of the source of light in the plane of the object, one on the axis and the other to one side of it. If the separating power of the prism is sufficient for the size of light source employed, then the two images are sharply separated, and one only is used for illuminating the part of the object which it is desired to observe. I have not yet been able to complete the experiments with this arrangement, but so far as I have gone the results are satisfactory with the higher powers.

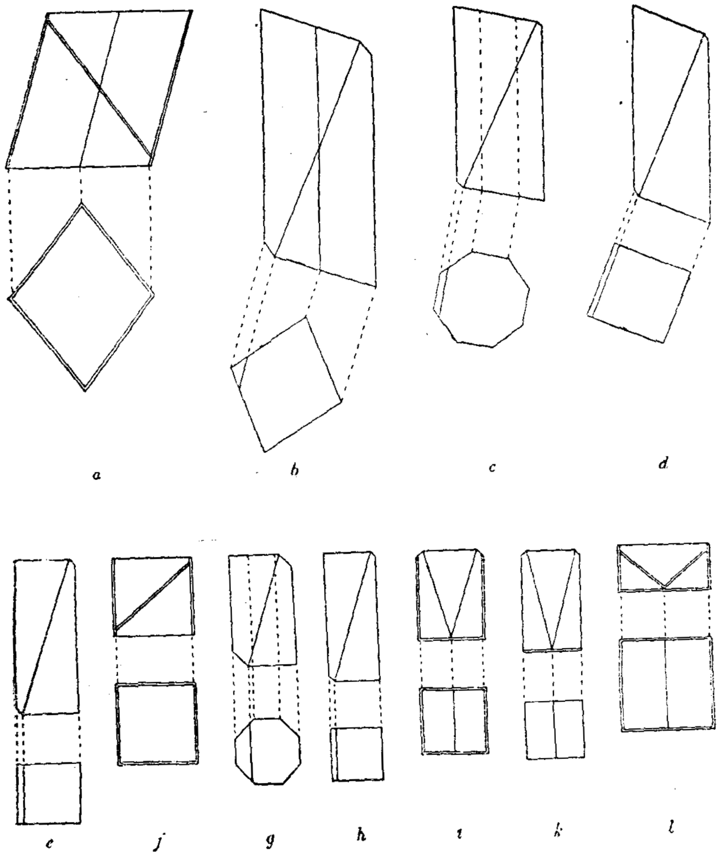

Fig. 4.—Prisms referred to in Fig. 3.

The Use of Monochromatic Light.—Up to the present time monochromatic light appears to have been but little used with the petrological microscope. Its systematic use, especially for work with convergent light, would undoubtedly result in a considerable simplification, and the attainment at the same time of a higher standard of accuracy. Excellent sodium lamps are now available, and with these tourmalines can advantageously be employed, because it so happens that yellowish-brown tourmalines, of great transparency for sodium light, are amongst the commonest, and least expensive, of these crystals. Such an analyser placed immediately above the eye lens of the eye-piece does not reduce the effective angular aperture of the latter.

THE MECHANICAL DESIGN OF THE PETROLOGICAL MICROSCOPE.

Having come to a conclusion as to the number and disposition of the optical and polarizing elements, there only remains the question of mounting them, and the provision of certain mechanical accessories such as goniometers, etc. Now, in the microscope system five focal planes are available, if accessible: the lower focal plane of the condenser, conjugate images of which appear in the upper focal plane of the objective, and in the plane of the Ramsden circle, so that an object, placed in the first of these planes, can be seen in each of the other two; whilst an object (or image) in the upper focal plane of the objective is seen also in the Ramsden circle. In addition to these planes there are two others—that of the object and its conjugate in the focal plane of the eye-piece. Of the first three planes mentioned above, only one is readily accessible in the ordinary petrological microscope—that of the Ramsden circle; whilst of the second two, the object plane only is available, and this to a very limited extent because of the short distance between the front lens of the objective and its lower focus. For petrological work of an advanced character, however, the ready accessibility of these five planes is very desirable.

Were the sections of crystals in rock sections sufficiently large, much of the petrographer's work could be done with a simple microscope of the dissecting type; the accessibility of the object enabling retardation plates, wedges, etc., to be placed directly upon the section under examination. This advantage, however, has been surrendered in the petrological microscope, and the use of several valuable adjuncts, such as the step wedge, made difficult. Again, in examinations in convergent light, the stauroscopic figures are projected into the upper focal plane of the objective, where the necessary measurements could be made with a mm. scale, were the plane accessible. Another point to be remembered is that the introduction of auxiliary transparent elements, between the object on the stage and its image in the focal plane of the eye-piece, should be avoided as much as possible, because of the deterioration of the image usually produced. This difficulty could be avoided by making the lower focal plane of the condenser accessible for slides, scales, etc. A mm. scale, for example, would project into the upper focal plane of the objective for the measuring of angles, etc., and this, incidentally, would meet another difficulty arising from the fact that in modern microscope objectives of all but the lower powers, the upper focal plane is inside the lens and not therefore directly accessible.

The stage of the petrological microscope could, I think, be improved. The petrographer requires a table on which he can place his section and tilt the normal to that section through an angle up to 90°, and in any direction. This could be done with a simple attachment to the present rotating stage giving a rotation about a transverse axis, but the design would be severely hampered by the necessity for providing for the usual English 3 × 1 slip. Most workers agree, I think, that this size should be replaced by the small size used on the Continent for rock sections.

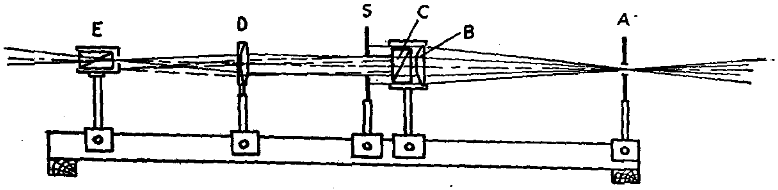

Fig. 5.—Projection microscope—parallel light.

Fig. 5 shows a simple form of projecting apparatus which lends itself admirably to the experimental demonstration of what has been said. The light from an arc, in an ordinary projecting lantern body, is focussed by the condenser in an aperture, with a diameter of about 0·4 in., in a brass plate *A*. This circular aperture when filled with light may be looked upon as the source of light. The light passing through the aperture is collimated by a lens *B*, with a focal length of 10 in., and then, passing through a double-image prism *C*, is split up into two beams, one passing along the axis of the instrument, whilst the second beam is deflected to one side through an angle of about 3·5°. The compound double-image prism, itself, is made up of two equal rectangular prisms, one of glass and the other of spar; the face of each prism is about 1·5 in. square, whilst the axial thickness of the compound prism is about 0·75 in. The weight of the spar used does not exceed 2 oz. The projecting lens *D*, with a focal length of 6 in., throws the two images of the aperture in *A* on to the entrance face of the analysing prism *E*, which is fitted with a diaphragm to stop all the light in the deflected beam. With the apparatus thus adjusted any polarizing object which does not exceed 1·3 in. in diameter may be placed on the stage *S* and projected as a whole on to the screen.

Fig. 6 shows the same apparatus as adapted for the examination of crystals, etc., in so-called convergent light. Between the projecting lens *D* and the double-image prism *C*, after the stage *S* has been removed, a pair of equal lenses *F* and *G* are placed with a separation equal to the sum of their focal lengths. The crystal to be examined is placed in the common focal plane of these lenses. The stauroscopic figures are then found in the focal plane *H* of the lens *G*, and these figures are projected on to the screen in the usual way by the projection lens *D*. It is to this form of the apparatus that I wish to draw particular attention, because it is that which, in my opinion, is best adapted for the purpose of carrying out investigations concerned with the optical and mechanical design of the petrological microscope. The apparatus described is essentially a projecting microscope. The prism *C* acts as the usual polarizer found below the sub-stage condenser *F*; whilst the lens *G* acts as the usual objective, in the upper plane *H*, of which the stauroscopic figures are to be seen; the lens *D* acting as the eye of the observer, looking directly down the tube of the microscope, after removing the eye-piece; whilst the projection screen corresponds to the retina of the eye. In the microscope, however, the object stage only is accessible for slides, whilst the lower focal plane of the condenser, the upper focal plane of the objective, and the focal plane of the eye-lens are scarcely accessible at all. In the apparatus, however (fig. 6), the lower focal plane of the condenser, the object plane, and the upper focal plane of the objective, are freely accessible, so that with this apparatus we can perform a number of experiments which we can scarcely do with the ordinary microscope, adapted for projection purposes.

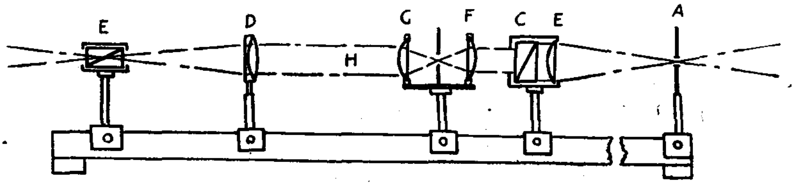

Fig. 6.—Projection microscope—convergent light.

Finally, to sum up briefly, I have tried to-night to show that:—

1. More use should be made of the reflecting polarizer, especially in the case of the simpler types of instruments and for low-power work.

2. The fitting of the analyser in the upper focal plane of the objective is radically wrong. If retained in this position it should

be compensated to avoid the necessity for refocussing, and to correct the inevitable astigmatism imposed upon a convergent beam upon passing through Iceland spar.

3. The advanced petrographic worker needs an instrument better adapted for his work than the present type of petrological microscope. These needs would be substantially met by an instrument embodying the optical system of the microscope, but in which the five primary focal planes were made readily accessible for the introduction and withdrawal of the polarizing adjuncts.