

POLARIZATION FIGURES AS AN AID TO IDENTIFICATION OF POLISHED ISOTROPIC MINERALS

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ABSTRACT

The azimuth of vibration of plane-polarized light falling obliquely on a polished surface is rotated on reflection. This rotation can be measured with a conventional ore microscope calibrated for the purpose, giving the refractive index of transparent isotropic minerals within 0.05. Use of a compensator for measuring the ellipticity of the reflected light in the polarization figure yields a rapid method for approximate determination of the absorption and refractive indices of opaque minerals. These data may aid mineral identification during routine examination of polished ores.

INTRODUCTION

At normal incidence plane-polarized light is reflected unchanged from a polished isotropic surface and there is no rotation of the plane of vibration. At inclined incidence, however, the azimuth of vibration is unchanged only if it lies in or normal to the plane of incidence. If ψ_E be the angle which the vibration direction of the incident light makes with the normal to the plane of incidence (E_s) and ψ_R be the corresponding angle between the normal and the vibration direction of the reflected light, then, for an isotropic, transparent surface (Jenkins and White, 1957, p. 516):

$$\frac{\tan \psi_R}{\tan \psi_E} = \frac{\cos (i + r)}{\cos (i - r)}$$

where i is the angle of incidence and r the angle of refraction. It is thus possible to calculate the rotation due to reflection if the refractive index and angle of incidence are known. Conversely, the refractive index may be calculated from the rotation.

For minerals with appreciable absorption the reflected light is elliptically polarized unless the incident vibration is parallel or perpendicular to E_s . The ellipticity results from a phase difference between R_s and R_p , the two components respectively perpendicular and parallel to the plane of incidence, into which the reflected vibration may be resolved. For transparent minerals this phase difference is 180° for all angles of incidence less than the Brewster angle and the reflected light is thus plane polarized. For opaque minerals the phase difference decreases from 180° to 90° for angles of incidence up to the Brewster angle and the reflected light is thus elliptically polarized. Fuller discussions may be found in Wood (1934), Jenkins and White (1957) and Cameron (1961).

There are thus two values which may conveniently be determined in reflected light and which may be of assistance in mineral identification.

The first is the rotation of the plane of vibration and the second is the degree of ellipticity, from which the phase difference between R_s and R_p may be calculated.

Refractive and absorption indices are normally determined by analysis of light reflected at the Brewster angle, when the phase difference imparted is 90° . The following rapid method may, however, be employed to give approximate results during the course of routine examination of polished surfaces. Use is made of the polarization figure, the properties of which Cameron (1961) has described. With the Bertrand lens inserted and the nicols accurately crossed, a black cross is seen in the back of the objective. On rotation of the analyzer the cross splits into two brushes resembling a centred biaxial interference figure. The degree of separation of the brushes depends on the rotation of the analyzer. The rotation of the plane of vibration due to oblique reflection can thus be measured for any point in the field by rotation of the analyzer. The degree of ellipticity, which causes faintness or coloration of the brushes, is determined by using a rotary elliptical compensator. The angle of incidence i , at which rotation and ellipticity are measured, is fixed by confining observation to a point in the field after determination of Mallard's constant for the apparatus.

CALIBRATION OF MICROSCOPE

A conventional ore microscope with rotating analyzer and polarizer is used with a rotary elliptical compensator (retardation $0.1-0.05\lambda$) inserted, when required, above the objective. A short-mount 50/0.65 objective gives good results. The instrument is adjusted to ensure accurate crossing of the nicols, correct orientation of the reflector and reduction to a minimum of the anomaly in the objective (Hallimond, 1953, p. 94; Cameron, 1961, p. 30). A reflecting prism of Berek type is used in preference to the coated plane glass reflector since the added complication of increased ellipticity and rotation due to return of light through the reflecting plate is thereby obviated.

Mallard's constant for the instrument is determined (Wahlstrom, 1948, p. 154) using standards such as barite and aragonite. A micrometer eyepiece with a graduated linear scale oriented accurately at 45 degrees to the analyzer is used and points in the back of the objective at half-conoscopic angles of 30° and 20° located. The orientation of the scale thus fixes the plane of incidence while the positions of the previously determined points fix the angles of incidence for subsequent measurements.

All microscope objectives rotate the plane of vibration of plane-polarized light slightly (Cameron, 1961, p. 158). Determination of the amount of rotation is essential and this may be done by the following method. A

polarizing film is taped to the glass platform of a universal stage (with hemispheres removed) mounted on the microscope stage, and the microscope, with sub-stage condenser and polarizer removed, is set for transmitted light. With the polarizing film normal to the microscope axis, it is accurately crossed with the analyzer. Appropriate tilts are then made with the universal stage so as to tilt the polarizing film 30° about the normal to the plane of incidence, as defined by the linear scale in the ocular. Light falling normally on the polarizing film will then be incident on the front element of the objective at 30° to the microscope axis. The angle between the plane of vibration of light leaving the polarizing film, and the normal to the plane of incidence (angle ψ_R) is readily calculated from stereographic projection. By subsequent rotation of the polarizing film about the A_1 axis of the stage, the angle ψ_R can be varied. The analyzer settings which produce a black brush passing through the 30° -point in the polarization figure for various ψ_R values are recorded. Readings are then repeated for the point at 20° to the microscope axis, the universal stage being adjusted accordingly. Table I shows readings taken with a Leitz 'Dialux' microscope, using a 50/0.65 objective. Dispersion of rotation is so slight that white light is entirely satisfactory. As predicted by theory (Cameron, 1961, p. 161) the rotation is towards the plane of incidence and it is greatest when ψ_R is 45° (Table I). It is convenient to plot the data graphically so that the angle ψ_R can be read off for any analyzer setting.

MEASUREMENTS WITH TRANSPARENT MINERALS

The microscope is set for examination by reflected light. With the graduated linear scale defining the plane of incidence and the polarizer

TABLE I. ROTATION OF PLANE OF VIBRATION OF LIGHT BY THE OBJECTIVE

Angle ψ_R^1	$i=20^\circ$		$i=30^\circ$	
	Anal. ²	Rot. ³	Anal. ²	Rot. ³
0.0°	0.0°	0.0°	0.0°	0.0°
10.0	10.1	0.1	10.1	0.1
20.0	20.2	0.2	20.3	0.3
35.0	35.2	0.2	35.5	0.5
45.0	45.3	0.3	45.6	0.6
55.0	55.2	0.2	55.5	0.5
70.0	70.2	0.2	70.3	0.3
90.0	90.0	0.0	90.0	0.0

¹ Angle given by setting of universal stage.

² Rotation of analyzer from 45° -position.

³ Rotation of plane of vibration after passage through objective.

TABLE II. DETERMINATION OF ANGLE ψ_E USING STANDARDS OF KNOWN REFRACTIVE INDEX

Standard	Ref. Ind. ³	$\frac{\cos (i+r)^2}{\cos (i-r)}$	ψ_R measured	ψ_E calculated
Fluorite	1.434	0.647	33.1°	45.2°
Quartz ¹	1.544	0.670	34.0	45.2
Glass	1.659	0.691	34.8	45.2
Corundum ¹	1.768	0.709	35.4	45.1
Zircon ¹	1.930	0.732	36.3	45.1
Cassiterite ¹	2.000	0.740	36.6	45.1
Sphalerite	2.369	0.779	38.0	45.1
Diamond	2.420	0.783	38.2	45.1
Rutile ¹	2.614	0.802	38.8	45.1

¹ Accurately oriented basal section.

² Angle of incidence, i , is 30°.

³ All data for wavelength 588 m μ .

accurately set east-west, the angle ψ_E is 45°. A slight difference may occur between the centre of the field and the margins of the polarization figure. The setting and calibration may be checked by using reflecting surfaces of low absorption index. Table II shows measurements made with polished surfaces of materials whose refractive indices were accurately known. The procedure consists of bringing the brush of the polarization figure over the previously selected points in the back of the objective, by rotation of the analyzer. The corresponding angle ψ_R is then read from the calibration curve previously set up and the angle ψ_E calculated from the refractive indices of the standard.

Values shown in Table II are averages of 10 readings made with each standard, read to 0.1°. The average value of ψ_E is 45.1°; a series of readings repeated over the point at 20° from the microscope axis gave the same average value. Close to the centre of the field the angle ψ_E is 45.0°. From this it is clear that the rotation of the plane of vibration of light travelling downward through the objective is very small away from the centre of the field.

A curve may be drawn by plotting the rotation of the analyzer against refractive indices (Fig. 1), and this can be used for subsequent rapid determination of refractive indices of isotropic minerals of low absorption index. The slight degree of ellipticity exhibited by sphalerite and rutile does not affect the accuracy.

The standard deviation for the analyzer settings is normally below 0.15° and refringence is thus determinable within 0.02 up to a value of 1.7. The accuracy falls off with increasing refringence to 0.05 at 2.6. These measurements may assist identification. The refractive indices of

minerals like magnetite and chromite with relatively low absorption indices are, for example, readily determinable by this method.

Preliminary tests with oriented sections of uniaxial minerals suggest that, in certain cases, the optic sign may be determined. Cassiterite and rutile consistently show a smaller rotation of the plane of vibration of incident light parallel to the optic axis than normal to it, indicating positive optic sign. Hematite, which is optically negative, shows the reverse relationship. Accurate setting of the mineral in the extinction position is essential in order to avoid rotation of the plane of vibration due to anisotropy.

REFLECTION BY OPAQUE MINERALS

With increasing absorption index the brushes of the polarization figure become less distinct when the analyzer is rotated from the crossed posi-

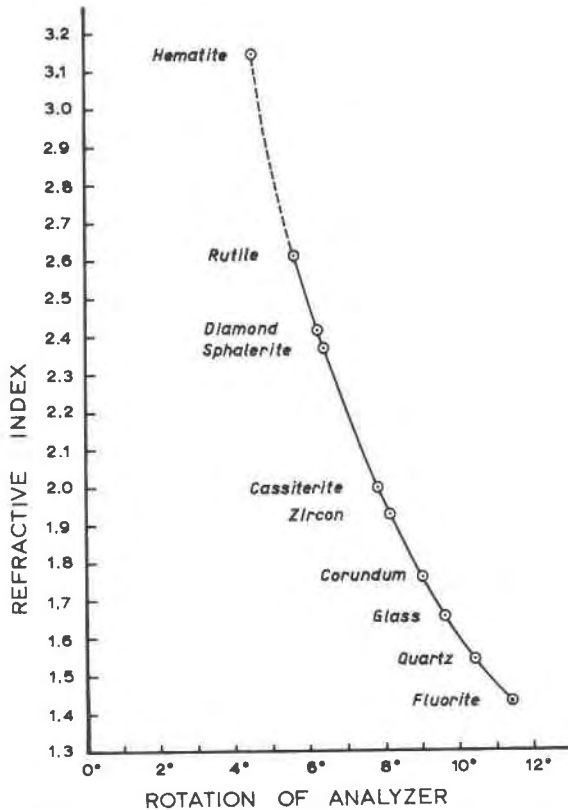


FIG. 1. Refractive indices of standard minerals plotted against rotation of analyzer required to produce extinction at point in polarization figure at 30° to microscope axis. The ellipticity shown by hematite is appreciable and the upper part of the curve is therefore less reliable.

tion, due to increasing degrees of elliptical polarization of the reflected light. No significant loss of definition occurs with minerals such as sphalerite. Silver, with a very high value of the absorption index κ is an extreme case in which an analyzer rotation of only 3° is sufficient to cause the brushes to vanish. With a rotary elliptical compensator inserted above the objective, the phase difference between R_s and R_p can be compensated and the brush restored. Since the dispersion of ellipticity may be strong with some minerals, the restored brush may be strongly coloured and monochromatic light should therefore be used.

In practice a standard deviation of less than 0.15° for the setting of the analyzer is not difficult to attain for successive readings on different parts of the polished section, provided that the surface is uniform. The standard deviation of the compensator setting is liable to be slightly higher. The method entails the following steps:

1. *Determination of the zero reading of the compensator.* The analyzer is first accurately crossed with the polarizer by producing a black cross in the back of the objective. Silver is to be preferred as the reflecting surface. The compensator is then inserted and rotated to produce zero phase difference. This is its zero position.

2. *Adjusting to extinction.* With the mineral under investigation on the stage, maximum density of the brush over the 30° -point is produced by alternate slight adjustments of the analyzer and compensator. Readings should be repeated on different parts of the surface and mean values for the rotations of the analyzer and compensator determined. If the relations are as indicated in Fig. 2, a clockwise rotation of the compensator is regarded as negative.

3. *Calculation of ellipticity.* The difference between the respective rotations of the analyzer and compensator, designated β (Fig. 2), yields the ellipticity of the reflected light. Calculation may be made either by using Poincaré's spherical projection (Shurcliff, 1962) or by direct substitution in the expression:

$$\sin 2\vartheta = \sin 2\beta \cdot \sin \Delta_{x,y}$$

where

2ϑ = phase difference at 45° to the axes of the ellipse of vibration of the reflected light

and

$\Delta_{x,y}$ = angular retardation of compensator.

Similarly,

$$\tan 2\alpha = \tan 2\beta \cdot \cos \Delta_{x,y}$$

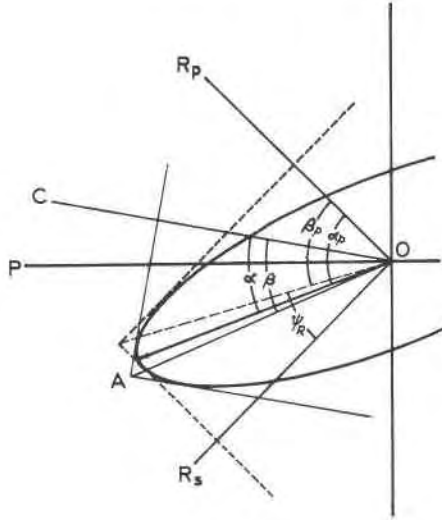


FIG. 2. Conditions at extinction when ellipse of vibration is converted to plane-polarized light along OA. OP—plane of vibration of incident light; OA—normal to plane of analyzer; OC—fast vibration direction of compensator; R_p —plane of incidence; R_s —normal to plane of incidence. Broken lines show circumscribed rectangle and its diagonal for compensation of phase difference between components along R_s and R_p .

where

α = angle between fast vibration of compensator and semimajor axis of ellipse.

It is convenient to prepare a graph by plotting 2ϑ and α against values of β within the range encountered (Fig. 3), thus eliminating calculation.

4. *Calculation of phase difference.* The phase difference Δ_R between R_s and R_p is given by:

$$\tan \Delta_R = \frac{\tan 2\vartheta}{\sin 2\alpha_p}$$

where

α_p = angle between semimajor axis of ellipse and R_p
 = $45^\circ + \alpha$ + rotation of compensator

In practice, since either α_p is close to 45° or 2ϑ is small, no significant error is introduced by writing $\Delta_R = 2\vartheta$.

5. *Calculation of ψ_R .* The angle β_p represents the angle between R_p and the azimuth of vibration for 180° phase difference between R_p and R_s (see Fig. 2), and $\psi_R = 90^\circ - \beta_p$. In practice, if 2ϑ is small or α_p is close to

45° , no significant error is introduced by writing $\psi_R = 90^\circ - \alpha_p$. Finally, ψ_R must be corrected for exaggeration by the objective, according to the values shown in Table I.

6. *Calculation of κ and n .* The absorption index is given by the expression:

$$\kappa = \sin \Delta_R \cdot \tan 2\psi_R$$

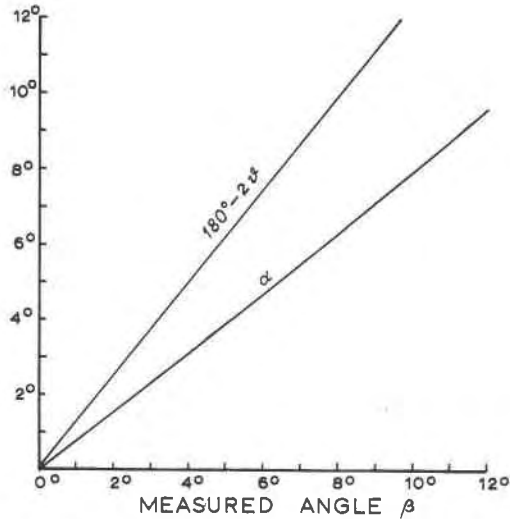


FIG. 3. Graph used for conversion of measured values of β to 2ψ and α .

and the refractive index by the expression:

$$n = \sin i \cdot \tan i \cdot \frac{\cos 2\psi_R}{1 + \cos \Delta_R \cdot \sin 2\psi_R} \quad (\text{Wood, 1934, p. 554})$$

Ten readings can be taken on different parts of the polished section in less than five minutes, while calculation requires but a few extra minutes. An example is shown below and in Table III are shown determined values of n and κ for some common metals and minerals. Figure 4 illustrates the settings of the compensator and analyzer for minerals of respectively high and low absorption index.

Example. Native antimony, cleaved parallel to (0001)

$$\left. \begin{array}{l} \text{Rotation of analyzer} \quad : \quad 1.4^\circ \\ \text{Rotation of compensator} : \quad -2.1^\circ \end{array} \right\} \beta = 3.5^\circ$$

1. From Fig. 3, $2\psi = 175.65^\circ$

$$\therefore \Delta_R = 175.65^\circ \text{ (approx.)}$$

2. From Fig. 3, $\alpha = 2.7^\circ$

3. $\alpha_p = 45^\circ + 2.7^\circ - 2.1^\circ = 45.6^\circ$

$$= \beta_p \text{ (approx.)}$$

$$4. \psi_R \text{ uncorrected} = 90^\circ - \beta_p = 44.4^\circ$$

$$\psi_R \text{ corrected} = 43.8^\circ \text{ (from Table I)}$$

$$5. \kappa = \sin 175.65^\circ \cdot \tan 87.6^\circ$$

$$= 1.8$$

$$6. n = \sin 30^\circ \cdot \tan 30^\circ \cdot \frac{\cos 87.6^\circ}{1 + \cos 175.65^\circ \cdot \sin 87.6^\circ}$$

$$= 3.1$$

DISCUSSION

As a means of determining accurately the optical constants the method is of little value, but it is useful as a supplementary aid to mineral identification. In particular, quantitative measurements can be made to supplement the descriptions of polarization figures of isotropic minerals (Cameron and Green, 1950).

It is not necessary to calculate the optical constants if all that is required is a comparison of an unidentified mineral with a known standard from a reference collection. In this case the respective analyzer and compensator readings may simply be compared, since they are characteristic values fixed by the apparatus used and the mineral under examination. For the determination of refractive indices of isotropic minerals with low absorption, direct reading from the graph (Fig. 1) is more rapid. The re-

TABLE III. DETERMINED ABSORPTION AND REFRACTIVE INDICES OF SOME COMMON METALS AND MINERALS

Specimen	Determined Values				Published Values	
	${}^1\Delta_R$	$2\psi_R$	n	κ	n	κ
Quartz ²	179.90°	68.0°	1.5	0.004	1.54	—
Sphalerite	179.20	76.0	2.4	0.06	2.37	³ 0.05
Hematite ²	178.60	80.2	3.3	0.14	⁴ 3.15	⁴ 0.13
Galena	176.75	83.1	3.9	0.47	⁵ 4.30	⁵ 0.40
Antimony ²	175.65	87.6	3.1	1.8	⁶ 3.04	⁶ 1.63
Mercury	173.85	87.9	1.7	2.9	⁶ 1.73	⁶ 2.87
Copper	167.85	87.3	0.57	4.5	⁷ 0.62	⁷ 4.26
Gold	167.80	88.4	0.35	7.6	⁶ 0.36	⁶ 7.70
Silver	170.05	89.5	0.17	19.8	⁶ 0.18	⁶ 20.2

¹ Averages taken to nearest 0.05°.

² Basal section.

³ According to Wooster (Hallimond, 1953, p. 111).

⁴ According to Berek (Hallimond, 1953, p. 111).

⁵ According to Drude (Hallimond, 1953, p. 111).

⁶ According to Drude (Wood, 1934, p. 558).

⁷ According to Minor (Jenkins and White, 1957, p. 524).

sult is also more accurate since the method does not rely on the determination of rotation caused by the objective or the use of a rotary compensator.

For consistent results certain precautions are necessary. Polished surfaces should always be prepared in the same way. Although polished and

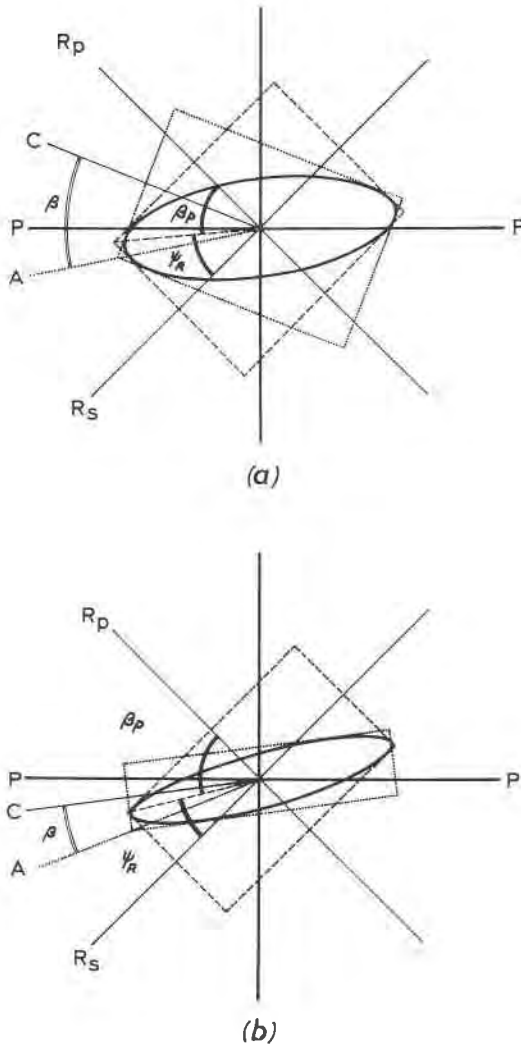


FIG. 4. Conditions at extinction for (a) minerals of high absorption and (b) minerals of low absorption. Analyzer readings are always regarded as positive while clockwise rotation of the compensator from its zero position is regarded as negative.

natural cleaved surfaces of native antimony have been found to give identical results, highly polished surfaces of purchased glass standards have been found to cause rotations which differ slightly from those given by surfaces of the same material repolished by the writer. The latter uses diamond grit for initial lead lapping and rouge for a final brief burnishing. Soft minerals such as galena and silver require particular care and may appear to be anisotropic unless the final burnishing produces a flat, unpitted surface with a non-directional polish. Minerals which are difficult to polish, such as bismuth, give inconsistent results, in which case cleavage flakes may be used. Sections which are badly scoured by polishing are troublesome since the surface being examined may not be uniformly perpendicular to the microscope axis and the angle i thus not constant on rotation of the stage. Surfaces should always be fresh (free from oxidation or tarnish) and thoroughly clean. The field diaphragm of the incident illuminator should be closed to restrict observation to a small, perfectly polished area. An area measuring 0.05 mm across is then adequate for purposes of measurement.

The effects of surface film produced by polishing have not been fully investigated. However, accordant results given by polished and natural cleaved surfaces, as in the case of native antimony, and the general correspondence of results with those achieved by more precise methods (Table III) suggest that the inherent limitations of the method are likely to introduce greater error than the effects of surface film.

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