

OPTICAL FIGURES OBTAINED WITH THE REFLECTING MICROSCOPE

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CONTENTS

Abstract.....	527
Introduction.....	528
Techniques and Equipment.....	529
Nature of the Surfaces Examined.....	531
Definitions of Terms.....	531
Descriptions of Types of Optical Figures.....	532
Type I.....	532
Type II.....	533
Type III.....	535
Type IV.....	536
Effects Due to Test Plates.....	537
"Dispersion" and Color Phenomena.....	537
Relations to Luster and Degree of Opacity.....	540
Effects Due to Rotation of the Polarizer.....	541
Effects Due to Polishing.....	542
Conclusions.....	542
Appendix.....	544
Table 1. Figures Yielded by Natural Surfaces.....	544
Table 2. Figures Yielded by Polished Surfaces.....	546

ABSTRACT

Optical figures, obtained with a petrographic microscope converted to a reflecting microscope, are described. Four types of optical figures were seen. These are: (1) type I, which resembles a uniaxial cross, but differs in being centered in all orientations; (2) type II, which resembles a centered acute bisectrix interference figure, differing in being centered for all orientations, although the size of the optic angle shows a relation to orientation; (3) type III, which resembles a centered acute bisectrix interference figure fixed in the 45° position, and which is the same for all orientations; and (4) type IV, which is like type III, except that the isogyres move from a minimum to a maximum optic angle on rotation of the stage. Nothing is known concerning the relation of type IV to different orientations. Type I is subdivided into four subtypes, three of which are based on the width of the isogyres, the fourth subtype differing also in having color bands. Type II is subdivided into two subtypes, subtype II*a* being seen only on natural surfaces and subtype II*b* only on polished surfaces.

A large part of this investigation has been limited to natural surfaces, because of modifying effects produced by polishing. Other than this effect, the nature of the surface examined governs only the quality of the figure. The test plates, used in petrography, have no effect on the figures. The optical figures from a few minerals show color phenomena and color patterns, some of which phenomena are likened to "dispersion." Rotation of the polarizer affects differently the figures from different minerals. The best figures are ob-

tained from the opaque minerals of metallic luster. Nonmetallic minerals of dark color also yield optical figures, but light colored, nonopaque minerals yield no figures.

A tabular summary of the results obtained from the minerals examined is added at the end of this report.

INTRODUCTION

Optical figures on polished sections of opaque minerals were first noticed by the author when he was studying mineralogy, under Dr. Joseph Murdoch of the department of geology at the University of California at Los Angeles. While studying the anisotropism of covellite under a 4 mm. objective on a petrographic microscope modified to a reflecting microscope, the author inserted the Bertrand ocular for the sake of curiosity. A figure, analogous to a centered acute biaxial interference figure was seen. Superficial examination of other minerals showed similar figures. A study of these figures was undertaken as a research problem in the department of geology at the University of California at Los Angeles, in the Spring of 1946.

The original object of this investigation was to determine whether the figures obtained from opaque minerals could be used in the determination of minerals in polished section. This question has not been completely answered, but, because of the apparent complexity, the indication is that these figures will be of only limited use in this connection. It was necessary in attempting to answer this question to determine the number of types of figures, their relations to crystallography, and to compare them with true interference figures obtained from the nonopaque minerals with transmitted polarized light.

The purpose of this report is threefold. It is intended (1) to show the general nature of the optical figures seen in this investigation, (2) to demonstrate the desirability of further study, and (3) to form a basis for further investigations of these phenomena. No attempt is made to explain the observed phenomena, this report being solely a consideration of the observations made; however, some inferences are made with respect to expected behaviors of the figures in a few cases.

No previous literature mentioning optical figures from opaque surfaces was found, although no exhaustive search of the literature was attempted. That these figures are not entirely unknown is apparent from the fact that Dr. R. W. Webb informed the author that he and others had noticed the figures and recognized them to be some type of optical figure, but had not investigated them.

The author gratefully acknowledges the guiding influences and many valuable discussions offered by Dr. Joseph Murdoch and Dr. Cordell Durrell, of the department of geology at the University of California at Los Angeles. Thanks are due Dr. Durrell for critically reading

this manuscript. The author also wishes to express his appreciation for the interest shown in this work by Dr. George Tunell, of the Geophysical Laboratory and for his encouragement in presenting this report for publication. This investigation was carried out under the supervision of Dr. Murdoch.

TECHNIQUES AND EQUIPMENT

The microscope employed was a Spencer petrographic microscope, model 42A. This was converted into a reflecting microscope by installing a Bausch & Lomb vertical illuminator. As shown in Fig. 2 the illuminator is of the transparent disk rather than the prism type. A 4 mm. short-mounted objective was used. The lamp employed was a Bausch & Lomb projection type, water cooled incandescent lamp, using a ribbon filament,

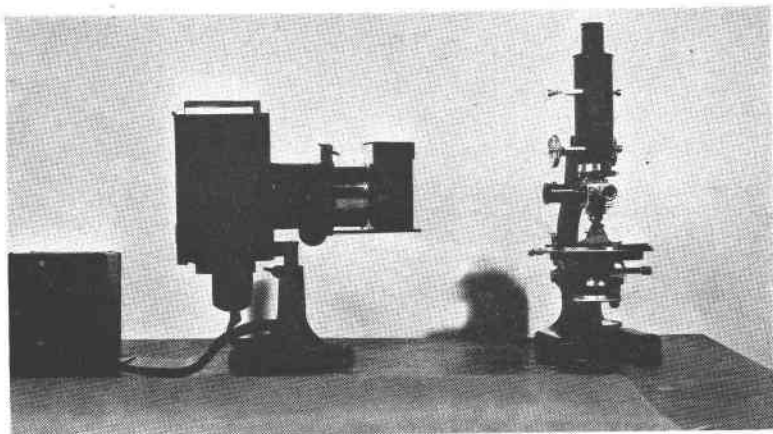


FIG. 1. The equipment as used in this investigation. A crystal of rutile, with (100) in reflecting position, mounted in plasticene, is seen on the stage of the microscope.

projection type bulb; in two cases a coil filament bulb was used. The mirror used was an optically-parallel-ground piece of glass. The equipment is shown in Fig. 1.

The importance of a strong source of illumination can hardly be over-emphasized, for otherwise the figures are visible only on a few minerals of very strong anisotropism, such as covellite. Strongest illumination is obtained by setting the polarizer so as to bring the light in from the side of the microscope as shown in Fig. 1. In this position the vibration direction of the polarized light is set parallel to the mirror. This is diagrammatically shown in Fig. 2, in comparison with what is apparently the usual setup. By this means the amount of light reflected from the plane

glass surface is much greater in comparison to that passing through, than is the case with the usual setup.

The lens system in the equipment employed was not very satisfactory, for reflections from surfaces in the system produced blind spots in the field. This was partly obviated by increasing the distance between the light source and the polarizer, but beyond a certain distance this causes a decrease in the area of light on the field of view.

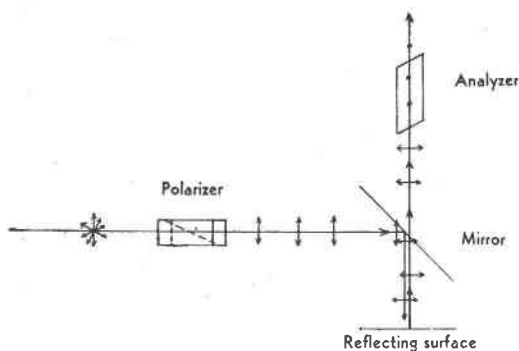


FIG. 2a. The relation between the vibration direction and the mirror in the usual setup.

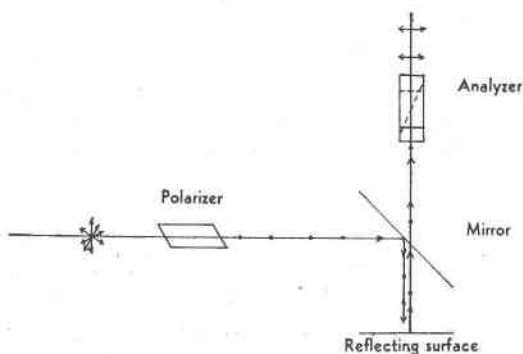


FIG. 2b. The relation between the vibration direction and the mirror in the setup used in this investigation.

The techniques and mounts used with polished surfaces are the same as described by Murdoch (*Econ. Geol.*, **33**, 542, 1938). Crystals and cleavage fragments are mounted in plasticene, in such a way that the base of the mount and the surface being examined are optically parallel. This is often difficult to accomplish because of irregularities in the surface or

because of the small area of a surface in relation to the rest of the grain. There is a very definite limit of about 3 mm. diameter below which the fragment or crystal could not be mounted by this method.

In examining a mineral surface, the mounted specimen is first placed on the stage of the microscope, the 4 mm. objective is brought into focus, and the Bertrand ocular is inserted. It is necessary, with the equipment employed, at this stage to adjust the position of the lamp in order to eliminate or decrease the size of the blind spots in the field due to the optical system. The type of figure, the effects due to the nature of the surface, rotation of the stage, effects due to test plates, and other phenomena, such as "dispersion" are then noted. The optic angle, where there is one, is estimated on the basis of the field diameter being equivalent to a 60° optic axial angle. As many orientations as possible from the available material for each mineral are investigated.

NATURE OF THE SURFACES EXAMINED

Two general types of surfaces were examined: polished and natural. The polished surfaces are generally highly polished and mirror-like; the only marring feature was the presence of small scratches in some specimens.

The crystal surfaces examined showed the usual imperfections, including symmetry pits and ridges, small cracks and steps. Small cracks on minerals which are not truly opaque are very disturbing, as they give intense internal reflections in certain positions between crossed nicols, which seriously interfered with the quality of the figures. Cleavage surfaces are generally not satisfactory, as they are stepped and show other breakage phenomena. It was usually difficult to find a single area on cleavage surfaces large enough to yield a figure. It is necessary to have an area at least about one-fourth the area of the field when viewed without the Bertrand lens.

DEFINITIONS OF TERMS

The quadrants in the field of view, the optic angle, the crossed and the 45° positions, the vibration directions of the polarizer and analyzer, and the diameter of the field of view of the microscope used are diagrammatically shown in Fig. 3. The positive and negative directions of measurement of angles on rotation of the stage are also shown.

The use of the terms optic angle, optical figure, and dispersion may not be merited as the optics involved in these figures are not known, but the terms are used here because of the close similarity of these optical figures to interference figures obtained with transmitted light.

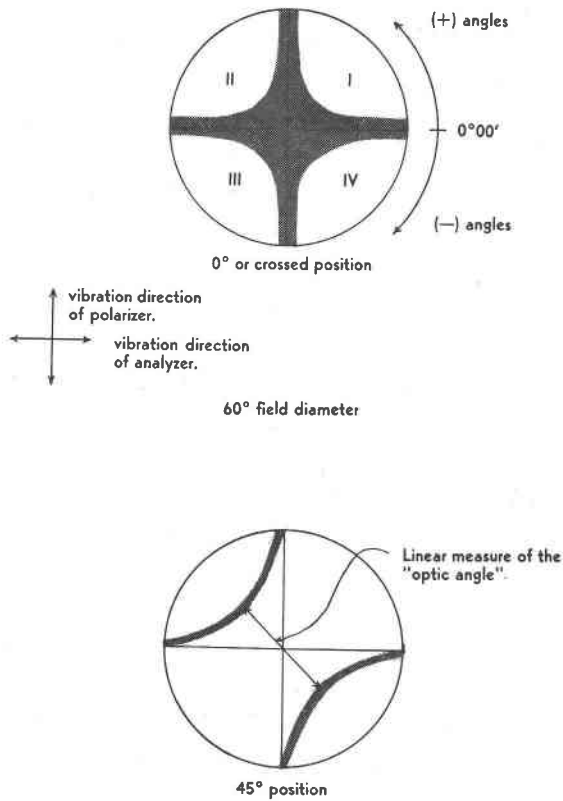


FIG. 3. Diagrammatic definition of some terms.

DESCRIPTIONS OF TYPES OF OPTICAL FIGURES

TYPE I. Type I in general form is like the centered uniaxial optic axis interference figure, but it is centered in all orientations. Type I is subdivided into four subtypes (Fig. 4). Three of the subdivisions are based on the width of the isogyres; they grade into one another. The fourth subtype differs from the others in having color bands. The width of the isogyres is perhaps related to optical constants in much the same way that the width of the isogyres in the uniaxial interference figure is related to birefringence. It appears that one mineral species may show more than one of these subtypes.

Subtype Ia has thin isogyres. It has been seen only on polished surfaces of minerals. This figure has been found on a fine-grained aggregate of breithauptite and niccolite, and on chalcopyrite, cuprite, and pyrite.

Subtype Ib has isogyres of medium thickness, about like that of the

centered obtuse bisectrix figure in the crossed position. It was the commonest subtype noted and was found on both natural and polished surfaces. It is perhaps the most characteristic figure obtained from dark-colored nonmetallic minerals, and has been found on crystal faces of andradite, augite, diopside, grossularite, magnetite, and sphalerite. It was also found on polished surfaces of boulangerite, bournonite, chalcocite, cosalite, gratonite, magnetite, and polybasite (?).

Subtype Ic has very broad isogyres, which closely resemble the optic normal interference figure. It was found on crystal faces of boléite and sphalerite, and on polished surfaces of pyrrhotite and sphalerite.

Subtype Id is like subtype Ia, with respect to the width of the isogyres, but it differs in being the only subtype of type I showing any color pattern. This pattern consists of color bands at 0° and 180° which are convex toward the center of the field. The colors range from second order blue green to second order red in Newton's series of colors (see Fig. 4). This subtype was seen only on one grain of pyrite in a polished section from the Kelly Gold and Silver Mine, Randsburg, California.

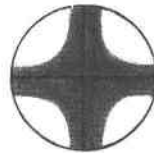
TYPE II. The general form of type II is like a centered acute bisectrix interference figure. It shows a 90° phase relation, being in the crossed position four times and in the 45° position four times through 360° of rotation. In the crossed position the figure resembles subtype Ib.

This type is subdivided into two subtypes (see Fig. 5) based on the different behaviors on polished surfaces versus natural surfaces. On polished surfaces the analogy of the optical figure to the centered acute bisectrix interference figure is not so close, for the optic angle in adjacent 45° positions is, in most cases, not the same. The figures of subtype IIa are from natural surfaces and those of subtype IIb from polished surfaces.

Subtype IIa shows a general relation of the size of the optic angle to orientation. The optic angle is largest in the prism zone and becomes smaller as the section approaches perpendicularity to the base and on the base the optic angle is 0° . There are exceptions to this general rule as is shown by epidote (see appendix). The exceptions may perhaps be explained in the same way as is the occurrence of the acute bisectrix interference figure being in different positions, with respect to the crystallographic axes, on different biaxial minerals. On hexagonal and tetragonal minerals the optic angle is the same for all faces in the prism zone, whereas in minerals of lower symmetry, such as wolframite, the optic angle is at a maximum on one pinacoid in the prism zone and at a minimum value in a direction at right angles (?) to it. This is perhaps one of the most valuable observations from this study, for it gives a means of determining whether a given opaque mineral is tetragonal or hexagonal on the one hand, or orthorhombic, monoclinic or triclinic on the other,



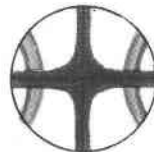
Subtype 1a.



Subtype 1b.



Subtype 1c.

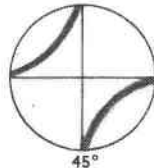


Subtype 1d.

FIG. 4. Type I.



0°

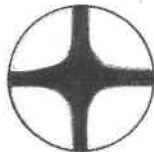


45°

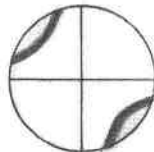
Type IIa.



(-) 45°



0°



(+) 45°

Type IIb.

FIG. 5. Type II.

as, with one other possible exception, the type of figure does not seem to indicate the crystal symmetry. Whether this observation will hold for polished sections is not known. The crystals showing subtype IIa and their estimated optic angles are azurite (10°), brookite (5°), cassiterite (7°), chalcopyrite (10°), covellite (65°), epidote (5°), hematite (45°), ilvaite (5°), marcasite (10°), rutile (20°), stephanite (?), and wolframite (15°). Many of these angles are probably not the maximum values, for only one orientation or an insufficient number of orientations were available in examination of many of the minerals. It is tentatively concluded on the basis of these few observations that those minerals with the most marked anisotropism, such as covellite and hematite have the largest optic angles.

Subtype IIb, seen only on polished sections, appears to be related to subtype IIa by some modifying effect induced by polishing. The main difference between subtypes IIa and IIb is the marked asymmetry of the optic angle in subtype IIb, wherein it may be greater in quadrants I and III, than in quadrants II and IV, or the reverse. The asymmetry of the optic angle is not seen in all sections, as shown by enargite. It is not known whether the asymmetry of the optic angle bears any definite relation to the orientation of the surface. This subtype apparently shows the same relation of the size of the optic angle to orientation as does subtype IIa.

Figures of subtype IIb were found on polished surfaces of arsenopyrite, covellite, enargite, löllingite, miargyrite, specularite, and stephanite. (See appendix for the values of the optic angles.)

TYPE III. Type III has been noted only on natural surfaces, and, with two exceptions, only on isometric minerals. It is like the centered acute bisectrix interference figure in the 45° position, but differs in that the isogyres do not move from this position throughout 360° of rotation. The isogyres were found only in quadrants I and III in all cases examined (see Fig. 6). The figure is the same for all orientations.

Type III appears to be fundamentally related to isometric symmetry, although limited to metallic opaque or near-opaque minerals, regardless of the two exceptions. It has been found on a specimen labeled glaucodot, and on molybdenite. The glaucodot may, however, be replaced by pyrite, the figure being very much like that of pyrite. The figure from molybdenite is not so easily explained.

Type III is seen on cuprite (15°), franklinite (20°), galena (15°), pyrite (25°), tetrahedrite (5°), and the two non-isometric minerals glaucodot (20°) and on a (0001) cleavage surface of molybdenite. No other orientations of molybdenite were available.

Although magnetite shows an optical figure of type I, it may conceiv-

ably be type III in which the optic angle is 0° , for it is the only metallic isometric mineral examined that did not show a type III figure on a natural surface.

TYPE IV. Type IV has been noted only on natural surfaces. It consists of two isogyres in quadrants I and III that are convex toward the center of the field; the isogyres move from a minimum to a maximum optic angle on rotation of the stage (see Fig. 7). Presumably this minimum angle may be as low as 0° , although it was not noticed on the minerals showing this type. The most startling fact which was observed in connection with this type is that, totally unlike biaxial interference figures and type II figures, the figure returns to the same position only every

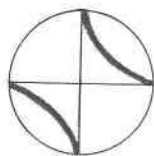


FIG. 6. Type III.

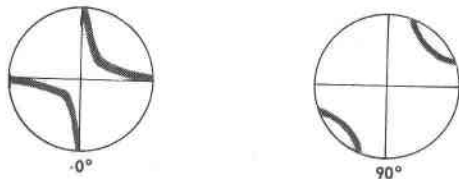


FIG. 7. Type IV.

180° of rotation. On each of the minerals examined, only one orientation was available so that no information concerning a relation to orientation could be ascertained. This type was seen only on arsenopyrite and stibnite in which the minimum and maximum angles are respectively 5° and 25° , and 15° and 50° .

At this point it should be noted that type IIIb, at least in the case of arsenopyrite, is derived by the effects of polishing not only from subtype IIIa, but also from type IV.

In a speculative mood, it might be supposed that type III and type IV show a fundamental relation to each other, similar to that which types I and II show. That is, type IV may in certain orientations take on the form of type III, as type II does with respect to type I. If this were true, it might well explain the two apparent exceptions to the statement that type III is characteristic only of the metallic isometric minerals.

EFFECTS DUE TO TEST PLATES

The mica plate and the quartz wedge produce only a uniform color over the field, dependent on their thickness and double refraction. The gypsum plate produces a constant color pattern for all minerals, except diopside and epidote. The color pattern (Fig. 8) remains the same throughout 360° of rotation. For diopside and epidote the gypsum plate produces only a sensitive tint uniform over the whole field.

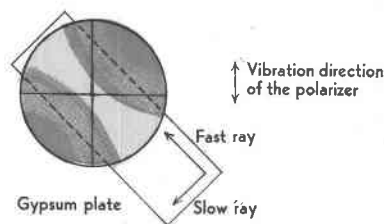


FIG. 8. Effect of the gypsum test plate.

"DISPERSION" AND COLOR PHENOMENA

The term "dispersion" is used here, as that is the nearest thing known to the author with which the phenomena under consideration may be compared. Three general phenomena are considered here.

The most interesting and striking of these phenomena are the color patterns observed on a few minerals. Rather than attempting to describe these color patterns, they are shown diagrammatically in Figs. 9, 10, 11, and 12; it was found impossible to reproduce accurately the actual colors. The color patterns show a definite, regular relation to the isogyres and to rotation of the stage, Hematite appears to have a different color pattern on different faces, whereas the color pattern on covellite is the same for all orientations. Color patterns are apparently not affected by polishing. The color bands on pyrite, showing the subtype *Id* figure, may perhaps logically be included in this group of color pattern phenomena. Type III figures show no color patterns on any of the minerals examined. It is of interest to note that the salmon pink in the color pattern of covellite is precisely the same shade seen as one of the rotation colors between crossed nicols.

On certain minerals of types II, III IV, a color phenomenon was noticed that resembles the dispersion of the optic angle in biaxial interference figures. The colors involved are a dirty red-brown and blue-gray. The red band is very narrow and on the concave side of the isogyres, whereas the blue-gray fills the area between the isogyres (Fig. 13).

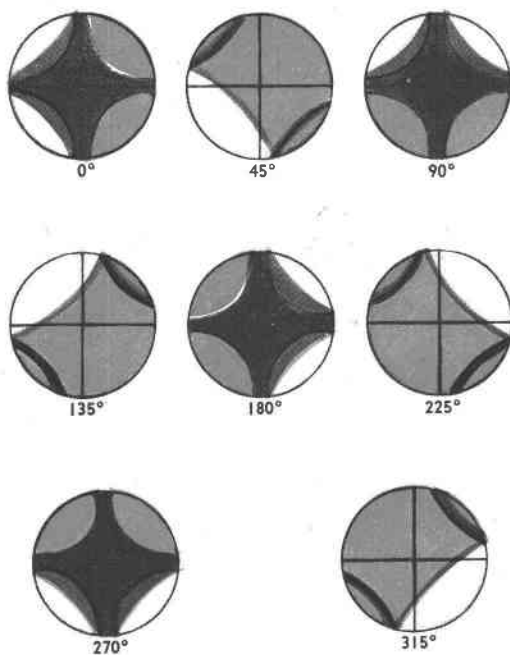


FIG. 9

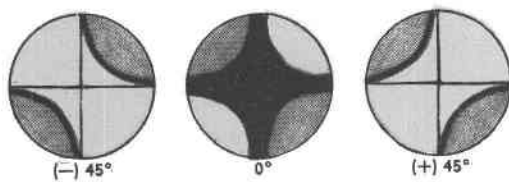


FIG. 10

FIG. 9. Color pattern on covellite; "optic angle" as on an assumed $(k0\bar{h}l)$ face.

FIG. 10. Color pattern on enargite; "optic angle" as on an $(hk0)$ face.

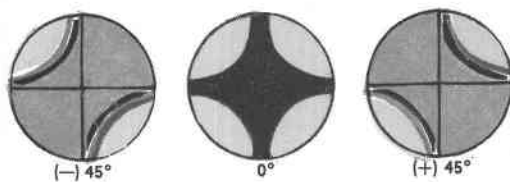
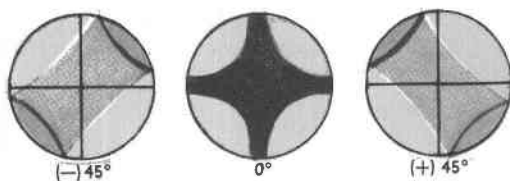
FIG. 11a. Color pattern on hematite on $r(10\bar{1}1)$.FIG. 11b. Color pattern on hematite on a steep $(h0\bar{h}l)$ face.

FIG. 12. Color pattern on stibnite.

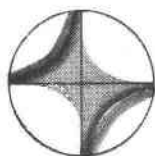


FIG. 13. "Dispersion" of the optic angle.

In all types the isogyres are subject to variations in intensity of darkness only in certain positions during rotation of the stage. This effect consists of an extreme lightening of the color of the isogyres at this point to a very light gray; not uncommonly this is limited to the center portion of the isogyres (Fig. 14). For the sake of brevity, this effect is termed "dispersion of the isogyres" in the tables in the appendix. This phenomenon appears to be a property of the mineral. Perhaps related to this is the



FIG. 14a. "Dispersion of the isogyres" in the crossed position.

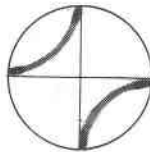


FIG. 14b. "Dispersion of the isogyres" in the 45° position.

phenomenon in type IV, where, at the minimum angle position, the isogyres may be a very dark shade of a certain color, and at the maximum angle position they may be a very dark shade of a different color. This is well shown by stibnite, whose isogyres are broad and very dark red brown at the minimum angle position and thin and very dark blue at the maximum angle position (see Fig. 12).

RELATIONS TO LUSTER AND DEGREE OF OPACITY

Minerals of metallic luster and a high degree of opacity give the best and most varied figures, and this study is primarily based on such minerals. The smoothest surfaces give the clearest figure so that the best figures are obtained from polished surfaces, but because of the effects of polishing most of the investigation was limited of necessity to natural surfaces.

With respect to the truly nonmetallic minerals, the best and most varied figures are obtained from those minerals with the highest luster and the darkest color. It is interesting to note that with few exceptions dark-colored minerals, with vitreous or slightly higher luster, seem to give subtype *Ib* or *Ic* figures. The exceptions gave subtype *IIa* figures in which

the optic angle was 10° or less. Light colored minerals of any degree of luster give no figure. This is perhaps due to a high degree of internal reflection, which gives only a hazy field of a paler shade of the same color as the mineral.

EFFECTS DUE TO ROTATION OF THE POLARIZER

Rotation of the polarizer, with the stage at a set position, causes either of two effects depending on the mineral. On some minerals the only effect is to cause the intensity of the color of the isogyres to fade with continued rotation, and eventually to cause the isogyres to disappear. The positions of the isogyres during rotation of the polarizer do not change.

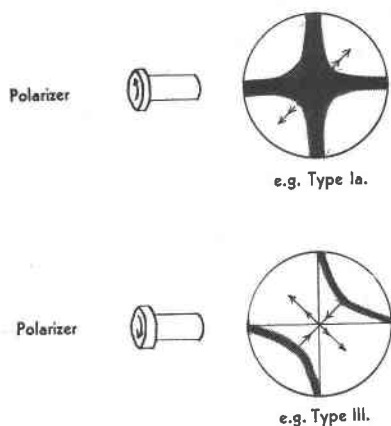


FIG. 15. Directions of movements of isogyres on rotation of the polarizer.

On other minerals the effect is to cause what basically can be assumed to be a change of type in the cases of types I and III. During rotation of the polarizer, the isogyres move in directions controlled by the direction of rotation of the polarizer as shown in Fig. 15. On type III, the isogyres may enter quadrants II and IV, where they were not seen to occur otherwise. Continued rotation of the polarizer not only causes further movement of the isogyres, but causes the isogyres to disappear in the same manner as in the first effect, usually before they have passed out of the field. These effects were investigated only on a few of the minerals examined.

During the early part of the investigation the minerals were examined with the nicols set at the crossed position by judgement of the eye, which is not very accurate, but no other way was at hand at the time. Once

the polarizer had been set in position, it was not disturbed. Later the effect of rotation of the polarizer was investigated at Dr. Murdoch's suggestion. It was found then that magnetite gave a figure of type I while at the most accurate position obtained by judgement of eye. The figure changed to type III on rotation of the polarizer. For the rest of the investigation, magnetite in the position where it gives a type I figure was used as a means of adjusting the nicols in the crossed position. Thus magnetite is the standard for determining the type and optic angle of most of the minerals.

It has been noted that subtype II*b* may be derived not only from subtype II, but also from type IV. The known effects of rotation of the polarizer suggest the possibility that type IV is derived from type II*a* by rotation of the polarizer. However, as a standard setting of the polarizer is chosen, which is believed as near at 90° to the analyzer as possible with the present equipment, this is considered to be a valid type.

EFFECTS DUE TO POLISHING

It was recognized early that polishing causes a change in the figures obtained from various minerals. At the beginning of this study, the investigation was limited to polished surfaces, until an unusually excellent crystal of rutile was examined out of curiosity. It was noted on this crystal that the type II figure was not asymmetric with respect to the optic angle, whereas all the type II figures which had been seen previously were. This was investigated further, and found to be invariably true; therefore all subsequent work was limited to natural surfaces, it being felt that this was necessary before any attempt at a systematic study of the polished surface figures could be started. Much more work in this direction is yet to be done before such a study can be attempted.

With respect to the change of type, which polishing seems to produce, all type III figures are changed to type I, and types II*a* and IV figures to subtype II*b*. The asymmetry of the optic angle seen in subtype II*b* is apparently caused by polishing as it has never been observed on natural surfaces.

The most striking effect produced by polishing consists of an aggregate effect, wherein a very fine-grained aggregate of one or more minerals, any individual of which is too small to give a figure, yields a figure of either type I or subtype II*b*.

CONCLUSIONS

1. Opaque minerals yield figures by reflected polarized light that are analogous to interference figures obtained by transmitted polarized light in nonopaque minerals.

2. The figures obtained may be classified into four principle types and into six subtypes.

3. The four subtypes of type I are based on the width of the isogyres and on the presence of color bands. The two subtypes of type II are based on the difference in configuration on natural surfaces and polished surfaces.

4. Figures obtained from polished surfaces are different from those obtained from crystal faces of the same mineral, and this is believed due to the mechanical effects of polishing.

5. Other than the effects due to polishing, the nature of the surfaces governs only the quality of the figure.

6. The test plates produce no changes that might be of value in identifying the mineral.

7. Certain minerals show color patterns having definite relations to the figure and to rotation of the stage, which are totally unlike the interference colors obtained in interference figures from nonopaque minerals by transmitted polarized light.

8. Some minerals show a color pattern like the dispersion of the optic angle in interference figures from nonopaque minerals.

9. On some figures the isogyres are subject to variations in intensity of darkness only in certain positions during rotation of the stage.

10. Minerals of a high degree of opacity and luster with smooth faces give the best figures. Some nonopaque minerals of dark color yield figures.

11. Rotation of the polarizer affects the figures from different minerals differently.

In conclusion, the author believes that this subject offers a very fruitful line of investigation.

APPENDIX

TABLE 1. FIGURES YIELDED BY NATURAL SURFACES
OF THE MINERALS EXAMINED

Note: This table is arranged with respect to types of figures and according to the crystal symmetry within the types.

TYPE I			
Mineral	Crystal System	Subtype	Remarks
Andradite	Isometric	Ia	On (110)
Grossularite	Isometric	Ib	On (110)
Magnetite	Isometric	Ib	On faces (100) and (111) and on parting (111). "Change of type" on rotation of the polarizer. The standard for setting the polarizer at 90° to the analyzer.
Sphalerite	Isometric	Ib	On rounded (111) face.
Sphalerite	Isometric	Ic	On (110) cleavage.
Boléite	Tetragonal	Ic	On (001)?
Augite	Monoclinic	Ib	On several faces: (110), (100), (010), (111), and (111).
Diopside	Monoclinic	Ib	No effect with the gypsum plate. Several orientations.
TYPE IIa			
Mineral	Crystal System	Optic Angle	Remarks
Cassiterite	Tetragonal	(110) 7° (hkl) 1-2°	Internal-reflecting cracks cause much interference.
Chalcopyrite	Tetragonal	(hkl) 10°	Hazy figure. Suggestion of a color pattern, which could not be resolved.
Rutile	Tetragonal	(hkl) zone 20° flat (hkl) 0° (111) 5°	"Dispersion of the isogyres" in the crossed position.
Covellite	Hexagonal	(0001) cl. 5° (1010) cl. 65°+	Color pattern (see Fig. 9).
Hematite	Hexagonal	(0001) 0° (1011) 10° steep (h0hl) 45°	No color pattern. Color pattern (Fig. 11a). Color pattern (Fig. 11b)
Brookite	Orthorhombic	(122) 5° (110) 0°	"Dispersion of the isogyres" in the crossed position and in the 45° position in quadrants II and IV.
Ilvaite	Orthorhombic	(110) 5°	"Change of type" with rotation of polarizer.
Marcasite	Orthorhombic	(hkl) 10°	
Azurite	Monoclinic	(101) 10° (001) 5°	Strong blue tint on the isogyres.
Epidote	Monoclinic	(101) 5° (011), (010) 0°	No effect on the gypsum plate.
Wolframite	Monoclinic	(110) 5° (010) cl. 15°	"Dispersion of the isogyres" in the crossed position.

TYPE III. (This type is seen only on natural surfaces.)

Mineral	Crystal System	Optic Angle	Remarks
Cuprite	Isometric	(111) 15°	"Dispersion of the isogyres."
Franklinite	Isometric	(111) 20°	Isogyres wide. "Dispersion" of the optic angle strong.
Galena	Isometric	(111) 15° (001) 15°	
Pyrite	Isometric	(001) 25° (110) 25° (111) 25°	No "change of type" on rotation of the polarizer.
Tetrahedrite	Isometric	(111) 5°	"Change of type" on rotation of the polarizer.
Molybdenite	Hexagonal	(0001) 17°	"Dispersion" of the optic angle strong.
Glaucodot	Orthorhombic?	(110) 20°	Replaced by pyrite? "Dispersion of the isogyres." No "change of type" on rotation of the polarizer.

TYPE IV

Mineral	Crystal System	Optic Angle		Remarks
		Min.	Max.	
Stibnite	Orthorhombic (010) cl.	15°	50°	Color pattern (Fig. 12); the blue color disappears rather sharply at 45°. At 45° the optic angle is 40°. "Change in type" with rotation of the polarizer.
Arsenopyrite	Triclinic?	(110) (110)	5° 5°	25° 25° "Dispersion of the isogyres" in the 90° position.

The following light-colored, nonopaque minerals, which yielded no figures, were examined: calcite (suggestion of a uniaxial interference figure on a cleavage fragment), pyromorphite, quartz, siderite, titanite, vanadinite (suggestion of a uniaxial figure on (001)), wulfenite, and zircon.

TABLE 2. FIGURES YIELDED BY POLISHED SURFACES OF THE MINERALS EXAMINED

<i>TYPE I</i>			
Mineral	Crystal System	Sub-type	Remarks
Cuprite	Isometric	<i>Ia</i>	Red isogyres because of strong red internal reflections?
Magnetite	Isometric	<i>Ib</i>	
Pyrite	Isometric	<i>Ia</i>	
Pyrite	Isometric	<i>Id</i>	A coil filament lamp was used in this case.
Sphalerite	Isometric	<i>Ic</i>	
Chalcopyrite	Tetragonal	<i>Ia</i>	
Breithauptite and niccolite	Hexagonal	<i>Ia</i>	A fine granular aggregate. This is an aggregate effect.
Gratonite	Hexagonal	<i>Ib</i>	On (0001), (10 $\bar{1}$ 0), and (11 $\bar{2}$ 0).
Pyrrhotite	Hexagonal	<i>Ic</i>	A coil filament lamp was used in this case.
Boulangerite	Orthorhombic	<i>Ib?</i>	Grains too small.
Bournonite?	Orthorhombic	<i>Ib</i>	
Chalcocite	Orthorhombic	<i>Ib</i>	A fine-grained aggregate of granular chalcocite and feathery covellite. An aggregate effect?
Cosalite	Orthorhombic	<i>Ib</i>	
Polybasite?	Monoclinic	<i>Ib</i>	
<i>TYPE IIb</i>			
Mineral	Crystal System	Optic Angle	Remarks
Covellite	Hexagonal	30° and 40° 40° and 65° 40° and 45°	Several random sections. Color pattern (see Fig. 9).
Hematite var. specularite	Hexagonal	20° symmetrical	A multitude of plates of varying orientations; an aggregate effect.
Enargite	Orthorhombic	5° and 25° 20° symmetrical 5° symmetrical	Several sections. Color pattern (see Fig. 10).
Löllingite	Orthorhombic?	10° and 20°	"Dispersion" of the optic angle.
Stephanite	Orthorhombic	0° symmetrical 5° symmetrical	Reddish isogyres; strong red internal reflections.
Miargyrite	[Monoclinic	5° and 10° 0° symmetrical	Random sections. "Dispersion of the isogyres" on the grain where the optic angle is 0°.
Arsenopyrite	Triclinic?	5° and 10°	Wide isogyres.