THE DESIGN, CONSTRUCTION, AND TESTING OF A LOW MAGNIFICATION CAMERA TO PHOTOGRAPH POLISHED ORE SPECIMENS

Thesis by

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The investigations were carried out in the Arms Laboratory of Geological Sciences and frequent use was made of the shop and darkroom facilities offered by the department. The investigation was initiated in September 1951 and terminated in May 1952.

Abstract

The color photography on "Bantam" film of polished ore specimens is the subject of this research. Preliminary tests showed that a diffused light source of large area (6 inch diameter) is necessary for even illumination of the subject which is up to 1 3/4 inches in diameter. An enlarging lens, designed to function best at low image magnifications, is used on the camera. Focusing and framing is done on a ground glass.

A special camera was designed which has a magnification range of 1 to 4 3/4 times. Further testing with type A Kodachrome film showed that acceptable results can be achieved using for illumination either a #1 Photoflood bulb (color temp. 3400°K) giving bluish colors or a PS-25 lamp (color temp. 3200°K) giving reddish colors. If pictures are taken using nearly crossed polarized light: (1) the intensity of reflected light drops from 20 to 100 times depending on the minerals, and the intensity will vary with the orientation of the minerals and the degree of extinction of the polarized light; (2) the extinction color of the polaroid filters is not gray but blue-violet, and for some pictures an orange correction filter may be necessary.

A study of the sharpness of the pictures indicates that the resolution of the lens, limited by aberrations and diffraction, is below that of the film. Kodachrome film is better than Ektachrome for miniature transparencies.

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Introduction

There has been little study of the techniques and problems of the photography of polished ore specimens on a macro scale; that is, utilizing ordinary camera lenses for objectives and working in the general magnification range of equal object and image size. On the other hand, much work has been done with the true photomicrography of polished ore specimens, and of course, rock thin sections. There is a need for photographs in the form of colored transparencies of polished sections at magnifications lower than can be achieved with a microscope, for in many sections there are structures in the mineral assemblages that are too large to be seen clearly even with the lowest power objectives of a microscope.

The purpose of this investigation is first to make a study of the problems of this kind of photography; to name a few: problems of vertical illumination, focusing, exposure determination, and the reactions to polarized light. The photographs must be in color as well as black and white, and it was decided that color transparency films, suitable for projection, would be the most desirable type of color films to use. The common "miniature" size film, either double frame 35 mm size (24 by 36 mm) or "Bantam" size (28 by 40 mm), was selected as the most useful at minimum cost. After the primary investigations, the second purpose is to design and build a suitable camera to take consistantly good color photographs of polished ore specimens at low magnifications.

I

Investigations Concerning the Photography of Polished Ore Specimens

Purpose - The purpose of the investigation is to develop a method to photograph polished ore specimens at a magnification of about 1:1 using color transparency film of the popular miniature size. To achieve this end tests were made specifically (1) to obtain even illumination of the object, (2) to determine the correct exposure and color temperature of the light source to be used, and (3) to find the limits of resolution of the films and lenses used in a qualitative sense. The first two of these tests were made simultaneously.

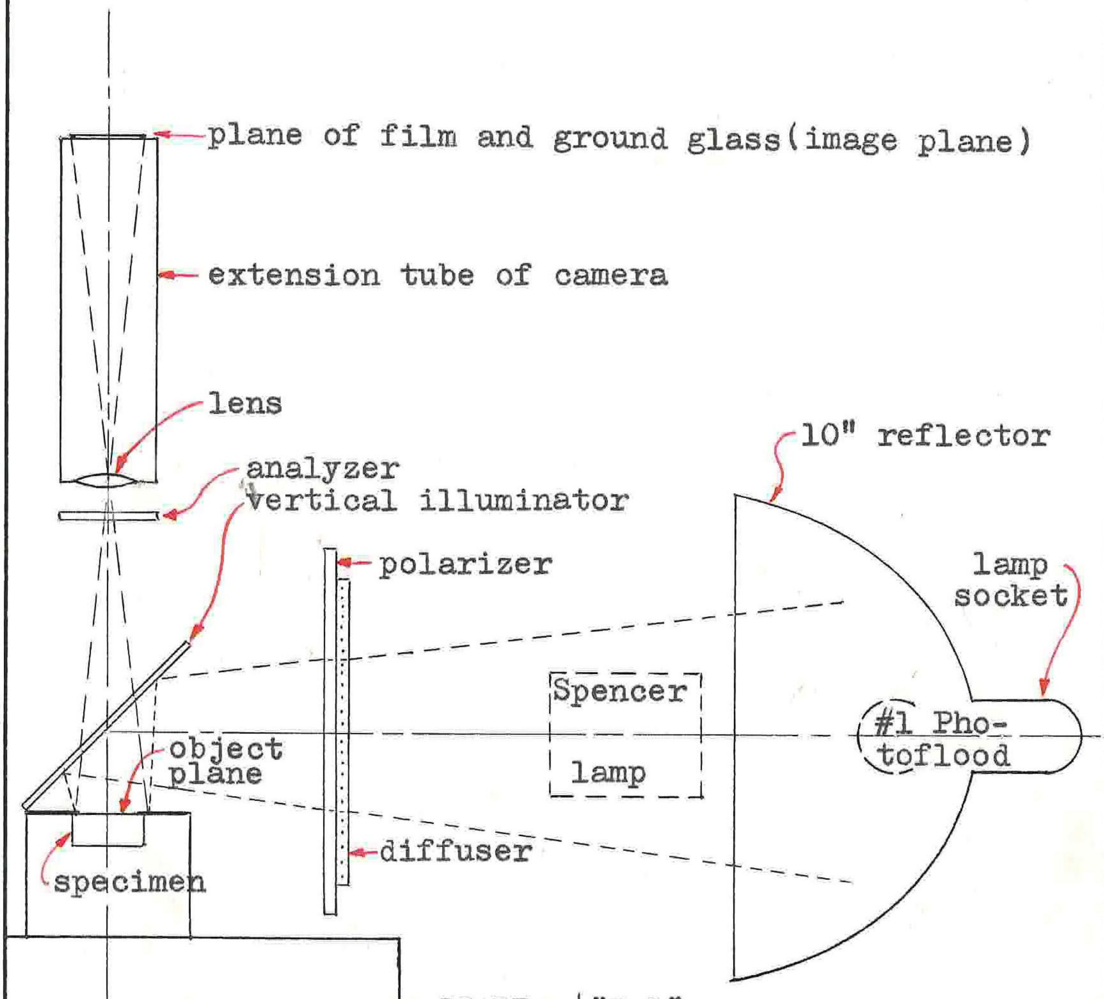
Results of previous experiments - Experiments made by Rudolf von Huene indicated that uneven illumination of the object caused pictures to be unsatisfactory. The intensity of illumination in these pictures dropped off very rapidly at the edges and only about half of the picture was usable. The cause of this uneven lighting was not known at the time. The light source used was a standard Spencer microscope lamp with an area of illumination several inches in diameter, much larger than the area of the object. The glass plate of the vertical illuminator was slightly larger than the object to be photographed.

Present experiments - Using available photographic equipment, belonging to Rudolf von Huene, a simple camera, vertical illuminator, and light source were assembled; equipment of rather unrefined appearance but most adequate for the job of testing. The first tests concerning illumination were made using a mirror surface in focus for an object. Visual study of the image on a ground glass made several factors apparent.

First, it was found that the vertical illuminator could be placed between the camera lens and the object, a desirable location from the viewpoint of construction and the adjustment of the illumination system (fig. 1). The vertical illuminator in metallographic microscopes is placed between the microscope objective and the eyepiece; in this system the objective serves as a condensing lens for the illuminating light rays.

Second, it was found that the light source must be large enough to fill completely and evenly the cone of rays coming into the camera lens (dotted lines, fig. 1). A ground glass diffuser should be placed in the light path to help make the illumination even over the whole object area. If the light source does not fill the cone of rays, as was the case when a Spencer microscope lamp was used, the intensity of illumination will fall off rapidly from the center. If the Spencer lamp was used for illumination the bright central portion of the image became more sharply defined and decreased in apparent size as the aperture of the camera lens was stopped down until the depth of focus of the

Fig. 1



SCALE: $\frac{1}{4}$" = 1"

Figure 1 - Geometric vertical section of the test apparatus.

- - - - - light path of illumination system

— — — light path of camera optic system

Note: The test apparatus was adjusted to photograph the polished sections at a magnification of 1:1, the object-to-image distance is 14 inches.

lens was great enough to reveal an image of the light source in the plane of the mirror-surfaced object. An adequate light source is a #1 Photoflood lamp in a standard 10 or 12 inch reflector. If this larger light source is used with a proper diffuser even illumination is achieved on the object even if the camera lens is stopped down to the smallest aperture. The diffuser should have a fine grain and be placed as far as possible from the vertical illuminator to prevent the image of a coarse diffuser being superimposed on the object image if the camera lens is stopped down.

Test exposures - Test exposures were made with the camera after the illumination system was constructed to give even coverage. The first exposures were made on Panatomic X black and white film. After the correct exposure was determined by trial the evenness of illumination was studied on the negatives. Film A (see table A) showed a slight unevenness of illumination on two sides of the pictures so opaque light guards were placed in positions to prevent undiffused light from striking the object at a low angle. A sheet of polaroid 6 inches square (larger than necessary) was placed between the diffuser and the vertical illuminator to act as a polarizer. A 2 inch square of polaroid was placed between the vertical illuminator and the camera lens to act as an analyzer (fig. 1). Film A and film B contain pictures taken in nearly crossed polarized light (see table

A and B). Experiment showed that nearly crossed polarization cut the light intensity to less than 20 times that of plain light. Additional work with color film showed that this ratio could be as large as 100 times. In all cases the polarizer was left in the illumination system oriented in a vertical position, parallel to the direction of polarization of light caused by reflection from the vertical illuminator.

Test exposures in color - The exposure values obtained with black and white films A and B served as a guide for the color exposures which followed. The first color work was done with Kodak Ektachrome transparency film because this film could be developed in two hours in the department darkroom and because consistent development is possible. The exposures on color film showed the characteristic narrow latitude of color films and it was found that for consistent results an exposure latitude of plus-minus $\frac{1}{4}$ of a stop is a maximum. This latitude is less than that assumed for "normal" color work.

Reflectivity variations - Reflectivity measurements for different minerals in polished sections vary from as low as 10% from gangue minerals up to 90% reflectivity from native silver (see Short, 1940, pp.294-296). Limited experience thus far has shown that a parallel range in exposure values, especially for sections with mixed mineral assemblages, probably need not be made. In most specimens one or more of the common opaque minerals such as pyrite, galena, sphalerite, or chalcopyrite are present in abundance, and the exposure should be used that will show these minerals in their most natural color and brilliance. The more uncommon minerals will be represented in tones relative to the common sulphides. A visual classification of a polished specimen into a dark, medium, or light category, with each category separated by one exposure stop will probably compensate for the variations in reflectivity encountered. The range of dark to light tones in color films is about 1 to 16, that of the human eye about 1 to 500, so color films must be viewed with this limitation in mind.

Color tests - The first two sets of color pictures taken, films C and D, served to help determinethe correct exposure and also to check the color temperature of the illumination system. A photoflood bulb, with a color temperature of 3400° Kelvin, was first used for a source of light. The type B Ektachrome film used for these pictures is balanced for a color temperature of 3200° Kelvin. As was expected, films C and D appeared abnormally blue (see tables C and D). A 3200° Kelvin lamp was procured and film E was taken using this lamp for illumination. The pictures in film E were superior in the color rendition of the different minerals photographed. For all pictures the polarizer, which was a 6 inch square sheet of type J polaroid, remained in the illumination system. The polaroid is gray but with a noticeable brownish cast, but this brown color did not seem to be intense enough to alter the color balance of the transparency. Even when the analyzer was introduced into the system in a parallel orientation the color balance of the transparency remained, by visual comparison, unchanged. Pictures taken in nearly crossed polarized light showed good color balance.

Comparison of color films and camera lenses - The next step in the investigation was to compare visually the "grain" of type B Ektachrome with that of type A Kodachrome, and to compare the resolving power of a 5 inch f 6.3 camera lens with a 4 inch f 4.5 Elgeet "Apos Colorstigmat" enlarging lens. Four texture specimens were obtained to best show the effects of film grain and the degree of image sharpness. Film F and film H were taken using type B Ektachrome and 3400° and 3200° Kelvin illumination respectively (see tables F and H, etc.). Film G was taken using type A Kodachrome, which is balanced to a color temperature of 3400° Kelvin, a photoflood bulb (3400°) was used for illumination. For film G the four texture specimens and the three original test specimens were photographed. The 5 inch f 6.3 lens was used for all pictures for films A through H inclusive. The seven specimens in film G were again photographed on film I, using type A Kodachrome and 3400° illumination but this time using the 4 inch f 4.5 Elgeet enlarger lens. This lens was probably designed for use at magnification ratios of from 1:1 to approximately 10:1 and should be sharp enough, that is, have sufficient resolving power, for the type of work intended. The results of the film and lens comparisons are given below.

Results of comparisons - It was found that the "grain" of Ektachrome film is too coarse for clear projection of the miniature size transparencies. This does not mean that this film is not adequate for larger sized transparencies. Kodachrome film, on the other hand, seems to be quite adequate for the small transparencies. "The resolving power* of Ektachrome film is 45 lines per millimeter, which compares somewhat unfavorably with Kodachrome's '55 lines'"(Crandall & Lavell, 1951, p.59).

A comparison of films G and I shows a marked superiority of image sharpness in film I, the photographs of which were taken using the Elgeet enlarging lens. The lens resolves the finest scratches visible with a 5 power magnifier on the air image in the plane of focus. Although the Elgeet lens does not resolve as high as possible with Kodachrome film, transparencies appear sharp when viewed by projection (The human eye can resolve a maximum of 10 lines per millimeter at a distance of 10 inches). Further tests using a lens of better optical quality, e.g. a 4 inch Kodak Enlarging Ektar or an apochromatic process lens, could be made.

* see p.46 for a discussion of resolving power

No tests at higher magnifications were made with the test apparatus but the author believes that the Elgeet lens is quite adequate for photographs taken at a magnification ratio of about 1:1.

Table A

Film: Panatomic X (black & white), speed: ASA 16

Light: #1 Photoflood in reflector

Lens: surplus f 6.3 10/11/51

light: pp - plane polarized, xp - nearly crossed polarized

Specimen	Exp. No.	light	exposure		Remarks
			sec.	f	
Miargyrite*	1	pp	1	11	best exposure
	2	pp	2	11	dense
	3	pp	4	11	dense
	4	xp	16	11	best exposure
	5	xp	32	11	dense
Bornite**	6	pp	1	16	best exposure
	7	pp	2	16	dense
	8	pp	8	16	dense
	9	pp	16	16	dense
Covellite**	10	pp	2	11	best but dense
	11	pp	4	11	dense
	12	pp	16	11	very dense
	13	xp	4	11	thin negative
	14	xp	8	11	good exposure
	15	xp	16	11	" "
	16	xp	32	11	dense negative

General Remarks: Slight unevenness of illumination on lamp side of specimen.

* from "Work Suite - 'Internal Reflection'"
** from "Work Suite - 'Color'"

Table B

Film: Panatomic X, film speed: ASA 16 Light: #1 Photoflood in reflector Lens: surplus f 6.3 10/17/51					
Specimen	Exp. No.	light	exposure		Remarks
			sec.	f	
Covellite	1	pp	1	11	all
	2	xp	12	11	exposures
Bornite	3	pp	1	16	good
Miargyrite	4	pp	1	13	"
	5	xp	16	11	"
General Remarks: Shadow cast by edge of specimen holder, must be some oblique light.					

Table C

Film: Ektachrome, type B, balanced to 3200° K speed: ASA 10 Light: #1 Photoflood, color temperature 3400° K Lens: surplus f 6.3 10/20/51					
Specimen	Exp. No.	light	exposure		Remarks
			sec.	f	
Miargyrite	1	pp	1,3	22	3 sec. exp. best
Bornite	2	pp	2,3	22	both exp. dense
Covellite	3	pp	2,3	16	lost
Covellite	4	xp	24 48	16	both exp. dense
General Remarks: For all Ektachrome photographs an Erb and Gray single exposure film holder was used. Transparencies too blue.					

Table D

Film: Ektachrome, type B, balanced to 3200° K
speed: ASA 10

Light: #1 Photoflood, color temperature 3400° K

Lens: surplus f 6.3 10/22/51

Specimen	light	exposure		Remarks
		sec.	f	
Covellite	pp	1	11	illumination uneven
Covellite	xp	24 48	11	both overexposed
Bornite	pp	1	11	good
Miargyrite	pp	1½	16	good, but too blue

General Remarks: Transparencies too blue

Table E

Film: Ektachrome, type B, balanced to 3200° K
speed: ASA 10

Light: PS-25 lamp, color temperature 3200° K

Lens: surplus f 6.3 10/27/51

Specimen	light	exposure		Remarks
		sec.	f	
Miargyrite	pp	1	11	good, light edge
Bornite	pp	1½	11	good
Covellite	pp	1½	11	good
Covellite	xp	30	11	uneven polarization

General Remarks: Color balance is excellent

Table F

Film: Ektachrome, type B, balanced to 3200° K
speed: ASA 10

Light: #1 Photoflood, color temperature 3400° K

Lens: surplus f 6.3 — 11/1/51

Specimen	light	exposure		Remarks
		sec.	f	
Texture 12	pp	2	16	one edge light
CE 1 (A?)	pp	2	16	slightly underexposed
Texture 9	pp	2	16	one edge light
Texture 8	pp	2	16	compare sharpness with likeness on film G

General Remarks: All pictures too blue, 3200 K illumination should be used.

Table H (see p. 16 for Table G)

Film: Ektachrome, type B, balanced to 3200° K
speed: ASA 10

Light: PS-25 lamp, color temperature 3200° K

Lens: surplus f 6.3 — 11/2/51

Specimen	light	exposure		Remarks
		sec.	f	
Texture 12	pp	2	16	all good exposures
Texture 9	pp	2	16	" " "
Texture 8	pp	2	16	" " "

General Remarks: Correct color balance, not as sharp as same specimens in film G on Kodachrome.

Table G

Film: Kodachrome, type A, balanced to 3400° K
speed: ASA 16

Light: #1 Photoflood, color temperature 3400° K

Lens: surplus f 6.3 11/1/51

Specimen	Exp. No.	light	exposure sec.	exposure f	Remarks
Texture 8	1	pp	2	16	good exposure color balance good
CE 1 (A?)	2	pp	2	16	light edge good exposure
Texture 9	3	pp	2	16	good exposure
Texture 12	4	pp	2	16	good exposure
Miargyrite	5	pp	2	16	light edge good exposure
Bornite	6	pp	3	16	good exposure
Covellite	7	pp	3	16	good exposure light edge
Covellite	8	xp	60	16	underexposed

General Remarks: Kodachrome gives finer detail than Ektachrome.

Table I

Film: Kodachrome, type A, balanced to 3400° K
speed: ASA 16 11/14/51
Light: #1 Photoflood, color temperature 3400° K
Lens: 105 mm f 4.5 Elgeet "Apos Colorstigmat"

Specimen	Exp. No.	light	exposure		Remarks
			sec.	f	
Texture 9	1	pp	2	13	light edge good exposure
Texture 12	2	pp	2	13	good exposure
Texture 8	4	pp	1	10	light edge good exposure
CE 1 (A?)	3	pp	2	13	good exposure
Miargyrite	5	pp	2	13	good exposure
Bornite	6	pp	2	11	good exposure light edge
Covellite	7	pp	2	11	slightly overexp.
Covellite	8	xp	60	11	slightly underexposed

General Remarks: Fine scratches and detail visible on specimens recognized in transparencies. Sharpness is adequate, color balance is good.

II

Design, Construction, and Testing of a Camera to Photograph Polished Ore Specimens

After the investigation and testing program had been completed the author felt enough was known of the characteristic features and problems of this type of photography that a special camera could be intelligently designed and constructed. The magnification range of the test equipment was limited to 1:1 $\pm\frac{1}{2}$. For practical use the design of the camera was extended to include a magnification range of from 1:1 to about 5 times. Many polished specimens are much smaller than the 1 by 1$\frac{1}{4}$ inch maxium size, and to avoid wasting film area and to achieve better resolution of smaller specimen areas it is necessary to fill the picture area with the image of the specimen. Also, in many cases, only a part of a specimen may be of interest; or two pictures, one covering the whole specimen and the other showing detail of a part may be desirable. Calculations were made to determine the lens to image and lens to object distances at several image magnifications and various lens focal lengths. Table I-2 contains the pertinent data.

<u>Camera body</u> - An Elgeet 105 mm lens (about 4 1/8 inches) was selected as adequate for the purpose of the camera and was procured for a nominal sum ($20.). Referring to table I-2 one finds that with a 4 inch lens a two foot bellows extension is needed for a 5X magnifi-

Table I-2

O=object

O-L = object to lens distance

L=lens

L-I = lens to image distance

I=image

(all measurements in inches)

Mag.-	7/8		1		2		5		10	
Focal length	O-L	L-I	O-L	L-I	O-L	L-I	O-L	L-I	O-L	L-I
4	8.5	7.5	8.0	8.0	6.0	12	4.8	24	4.4	44
5	10.7	9.4	10	10	7.5	15	6.0	30	5.5	55
6	12.9	11.2	12	12	9.0	18	7.2	36	6.6	66
8	17.1	15	16	16	12	24	9.6	48	8.8	88

The following equations were used for the calculations:

let: magnification = m, let: Focal length = f
let: O-L = s and L-I = s'

then:

$$m = s'/s$$

$$1/s + 1/s' = 1/f$$

by substitution:

$$s = f + f/m$$

$$s' = ms$$

cation. A 5 by 7 view camera (stock no. 631) with a 22 inch bellows extension and a revolving back was found in the department and was procured for this project. Utilizing the maximum bellows extension and using the 105 mm lens a magnification of 4 3/4X may be achieved. The rising front on the camera body gives a useful adjustment in selecting the specimen area to be photographed. Although the camera body is old it is quite solid enough for use.

Selection of film size - There is a choice of two sizes of film in the miniature types: either the 24 X 36 mm "double frame" which is available in 20 or 36 exposure rolls or Bantam size (28 X 40 mm) in 8 exposure rolls. Because of the larger film area and the more convenient number of exposures per roll the Bantam size of film was selected for use.

Film holder and focusing mechanism - A "Bantam Kodachrome Adapter A", made by Eastman Kodak Co. (cost: about $38.), was obtained to hold the film and for focusing control. On the Bantam back a 28 by 40 mm ground glass is mounted next to a roll film holder. Either may be centered, by means of a sliding mount, for focusing or photographing. A semi-automatic film advance mechanism as well as a "window" to view the frame number is provided on the roll film holder (fig. 2). The Bantam adapter is mounted on a plywood fitting designed to be interchangeable with the 5 by 7 plate holder on the ca-

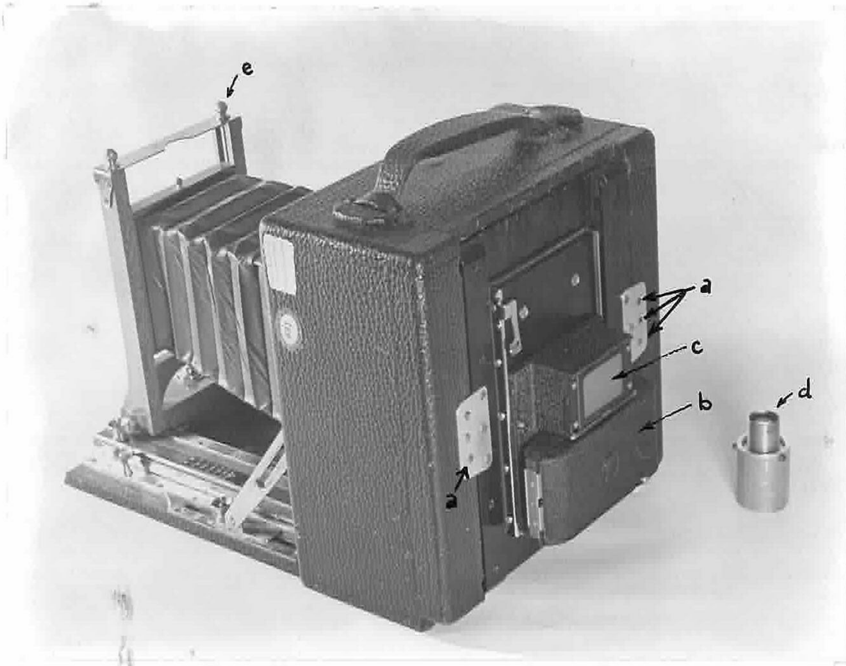


Figure 2 - Bantam back on 5 by 7 camera

(a) interchange screws for normal film holder
(b) roll film holder
(c) ground glass
(d) magnifier for viewing ground glass
(e) screw adjustment for rise and fall of lens board

Fig. 2a - Ground glass in position for focusing

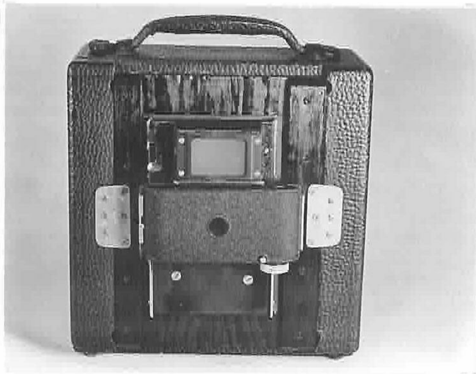


Fig. 2b - Roll film holder in exposure position

Figure 2 - Bantam back on 5 by 7 camera

mera body. Interchange of the plate holder and the Bantam back is made easily by removal of six screws (a, fig. 2).

Camera support - For ease of operation it was decided that the optic axis of the camera and the axis of illumination should lie in a horizontal plane. Most elongate optical instruments are designed in this manner (Graton, 1937, p.358). A steel support, designed and built for the camera, allows linear changes of camera position for focusing adjustments at various magnifications. Two opposed lengths of 1½ inch right angle stock provide vertical support and linear horizontal freedom (fig.3). These two supports are spaced with 2 inch channel stock, and a rider of the same stock between them provides keyway control of the linear movement. This rider is bolted to a wooden bed (fig. 4) which rests on the angle-iron channel supports. Two shorter lengths of 2 inch right angle stock are bolted to the ends of the channel and serve as supports for the 4 iron legs. A strip of ½ inch brass right angle stock, spanning two of the legs lengthwise, serves as a guide for the magnification and exposures factors calculated for use with a 105 mm lens on the camera (fig. 3). The exposure factors are calculated as shown in table I-3.

Specimen support - The mount is built to hold the polished ore specimens in a vertical plane and it will accomodate either the cylindrical mounts 1½ inches

Fig. 3

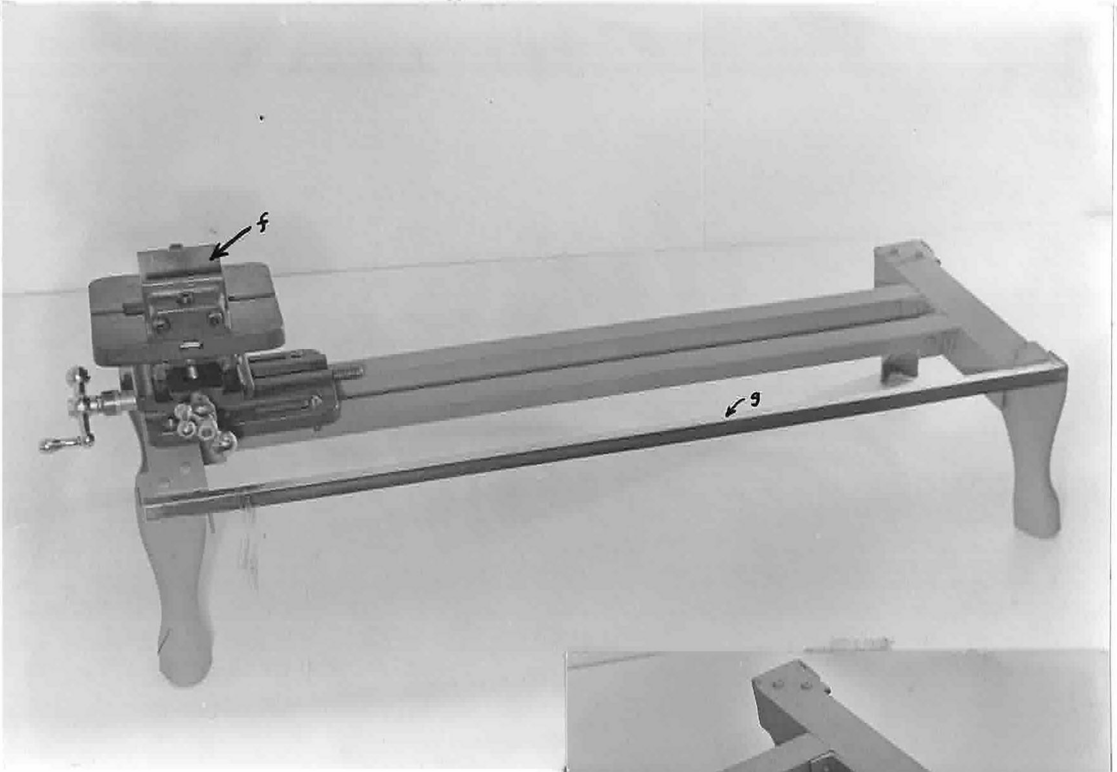


Figure 3 - Steel support for camera

(f) mill vise to hold specimen support
(g) brass angle bar with exposure factor and magnification data engraved on it

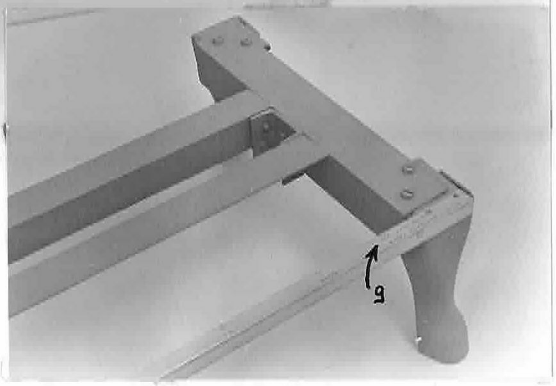


Fig. 3a - Detail of end of camera support

Fig. 4

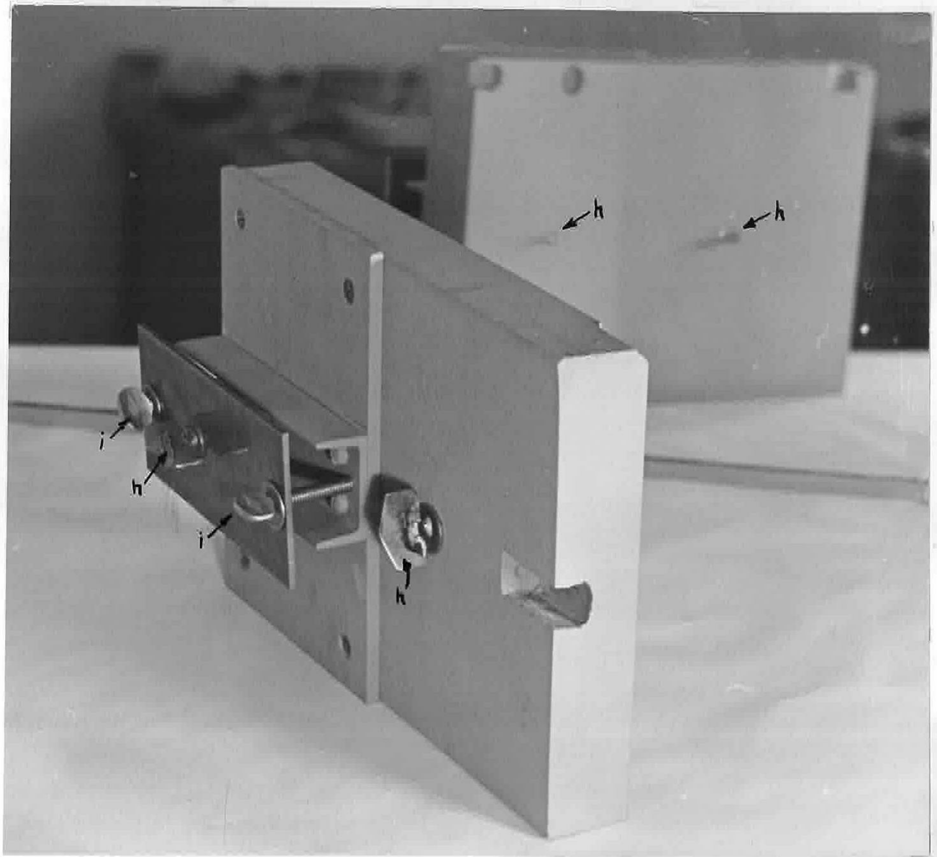


Figure 4 - Camera bed, bottom view, top view is reflected in the mirror. The six inch segment of channel stock keys into the ways of the steel support.

(h) thumb screws to hold camera in place, tightening the central one also serves to clamp the camera bed to the steel support
(i) thumb screws to hold clamping plate in alignment

Table I-3

The formula for calculating the exposure factor (exf) for photography of close objects is as follows:

let: f = focal length of lens

let: s' = total distance from lens to image

let: x = exposure factor (exf)

then $x = \left[\frac{s'^2}{f^2}\right]$ (Morgan, 1947, p.232)

This formula is based on the inverse square law of the intensity of light.

from Table I-2: s = f + f/m , s' = ms

then s'/m = f + f/m

s' = mf + f = f(m + 1)

substituting: $x = \left[\frac{f(m+1)}{f}\right]^2 = (m+1)^2$

The magnification range of the camera is from 1:1 to X4 3/4, and if one plots the exposure factors for this range:

m	1	2	3	4	4 3/4
x	4	9	16	25	33

Reducing a 1:1 magnification to a X1 factor:

m	1	2	3	4	4 3/4
x	1	2 1/4	4	6 1/4	8 1/4*

* Changed to 8½ on the camera factor scale to allow for reciprocity loss of film speed on long exposures.

in diameter and up to 1 inch thick or the 1 by $1\frac{1}{4}$ inch rectangular mounts. The polished surface of the specimen rests against a narrow flange at the extreme edges of the mount and a thumb screw from the rear holds the specimen mount in place. Regardless of the thickness of the specimen mount, the front polished surface is always held in the same plane. This is convenient if several specimens are to be photographed at the same magnification, for in this case focusing would need to be done only on the first specimen. Since the specimen support is circular, the specimen may be rotated about an axis parallel to the optic axis of the camera (fig. 5). This flexibility, coupled with the revolving back on the camera, enables one to obtain any orientation of the specimen with respect to the polariser and analyzer, and hence obtain the best orientation for maximum polarization colors.

Vertical illuminator - The vertical illuminator is made of a 3 by 4 inch sheet of 1/8 inch "water white" plate glass mounted in a vertical plane 45 to the plane of the polished specimen. This sheet of glass is considerably larger than necessary so that even coverage of illumination is assured. The polarizer, a 4 inch circular glass-mounted sheet of type J "polaroid", is mounted $2\frac{1}{2}$ inches from the optic axis of the camera. It is mounted so that it may be set easily at any orientation throughout 360 degrees. A ground glass diffuser, 6

Fig. 5

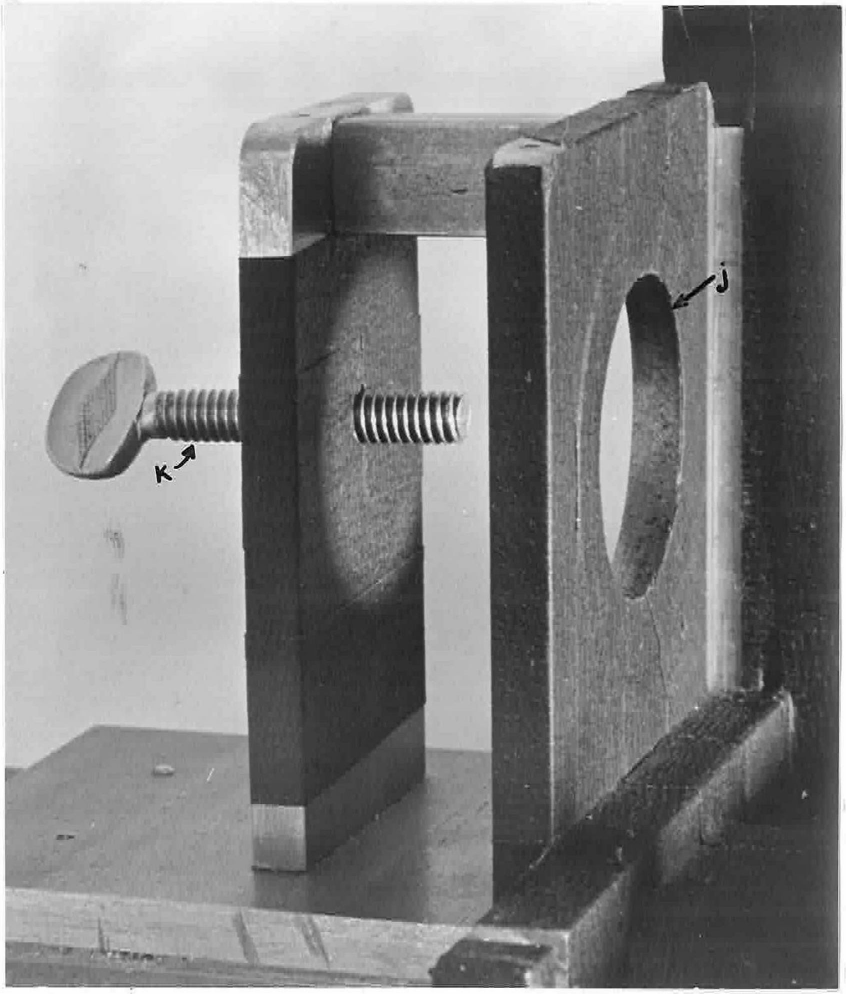


Figure 5 - Specimen support, about natural size

(j) collar flange, against which the specimen is held by pressure from the thumbscrew
(k) thumbscrew, adjustable to accommodate specimens of different thickness

Note: the face of the support toward the camera is coated with black tape to minimize oblique reflection of light inches in diameter, is mounted $1\frac{1}{2}$ inches from the polaroid. This whole assembly is an integral part of the specimen support (fig. 6a). Since the vertical illuminator tends to polarize light in a vertical direction, due to the reflection phenomena, maximum transmission of light will be achieved if the polarizer is in a similar orientation. This position giving maximum brightness has been used at all times for pictures in both parallel and nearly crossed polarized light and all standard exposures are given in terms of this lighting convention. The polarizer is left in the illumination system at all times.

<u>Light source</u> - Either a #1 Photoflood (500 watts, color temperature 3400° Kelvin) or a PS-25 (500 watts, color temperature 3200° Kelvin) can be used, depending on the nature of the work (see discussion of film N, p.35). Either lamp screws into the socket provided. A 10 inch aluminum reflector is attached to this socket and reflects the stray light toward the diffuser. The lamp socket is attached to a horizontal rod which can be clamped at any point on its length to the specimen support (see insert, fig. 6). Two lines are scribed on this rod: one for the #1 Photoflood and the other for the PS-25 lamp. The latter is used at the closer position. The lamps are hot and should not remain lighted longer than necessary. An automatic electric timer is introduced into the lighting circut to control the

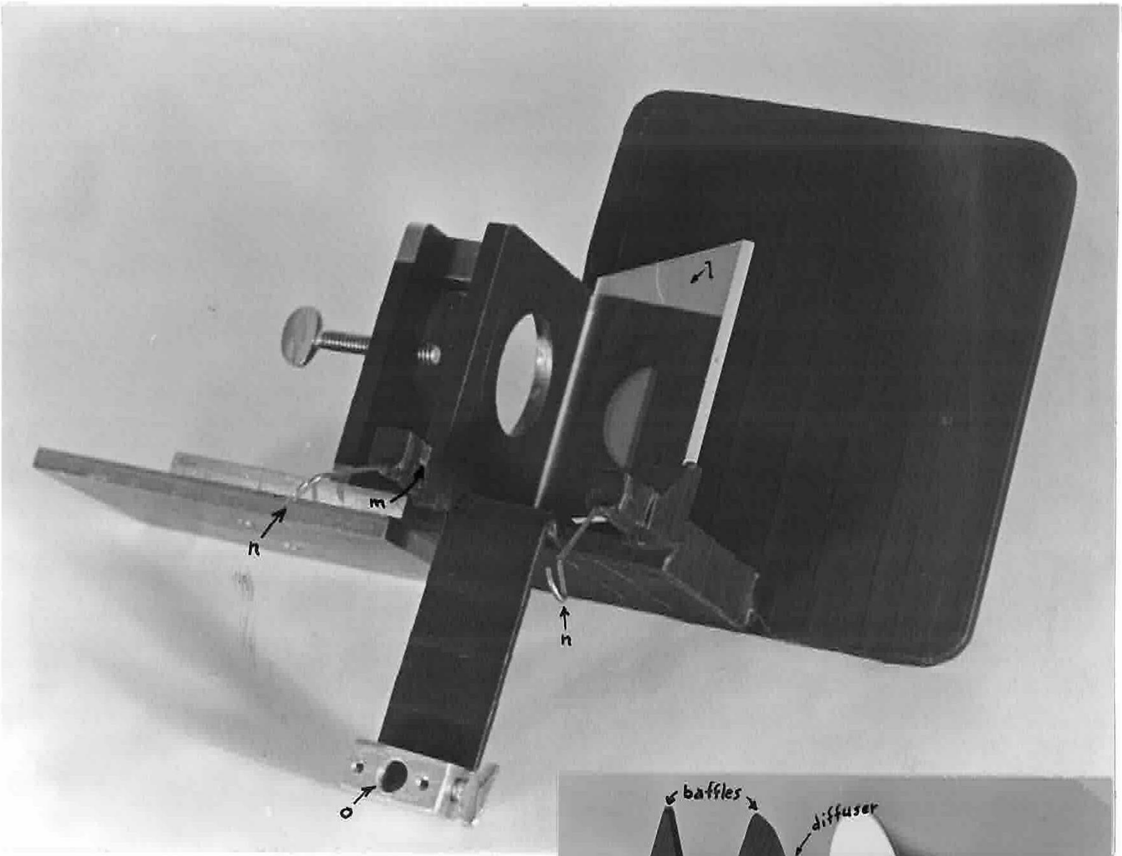


Figure 6 - Vertical illuminator on specimen support

(l) plate glass set at 45 degrees to optic axis
(m) keyway to hold polarizer
(n) hooks to hold diffuser
(o) clamp for light reflector rod, notches on rod should be aligned with the face of this clamp

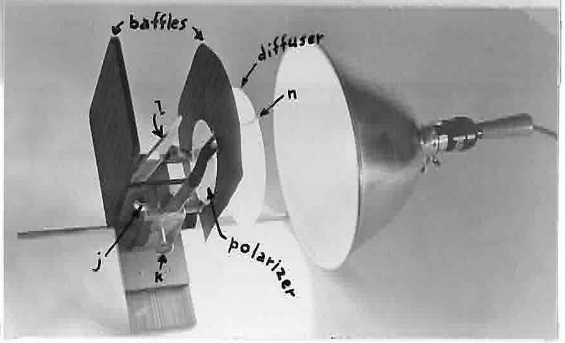


Fig. 6a - Complete unit of the specimen support, vertical illuminator, polarizer, diffuser, and lamp with reflector, all this is held in the mill vise.

Note the two blackened light baffles in position in Fig. 6a.

length of exposure. This method of turning the light on and off is superior to having a shutter on the camera.

The one unit comprising the specimen support, the vertical illuminator-polarizer-diffuser, and the light source is clamped in a mill vise which is bolted to the steel camera support. This vise has a two way adjustment. The cross feed gives linear adjustment of the position of the specimen, so that any tranverse part of the specimen,may be selected for photographing. This adjustment, coupled with the rise and fall on the lens board of the camera gives all the freedom of movement that a mechanical stage gives on a microscope. Furthermore, the freedom of rotation of the polished specimen in its support corresponds to the rotational movement of the stage of a petrographic microscope. The longitudinal feed on the mill vise serves as a fine focus mechanism.

<u>The analyzer</u> - The analyzer is a Kodak "Polascreen" mounted in a standard removable filter holder on the lens of the camera. A small arm projecting outward from this polaroid filter is aligned parallel to the polarization direction of the filter, and serves as a convenient handle for close adjustment of the analyzer (fig. 7). The filter may be rotated freely through 360° of arc. A sunshade attached either to the filter or to the lens if the analyzer is not needed.

Two views of the complete camera are shown in (fig. 8).

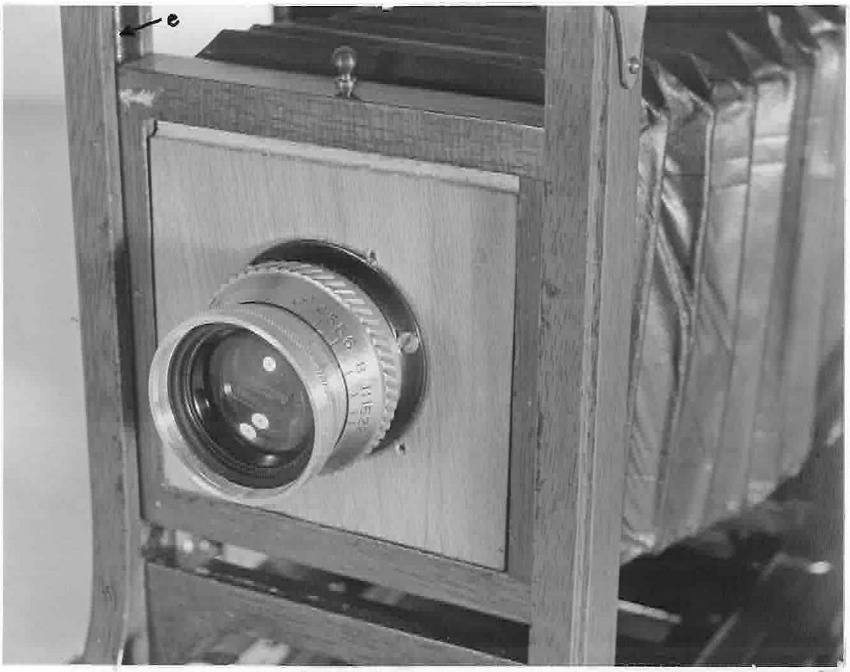


Figure 7 - Elgeet lens, 105 mm focal length, f 4.5, a series V adapter ring is attached to the rim of the lens. The f stop figures can be seen in the picture. Note the threads of the rise and fall screw (e).

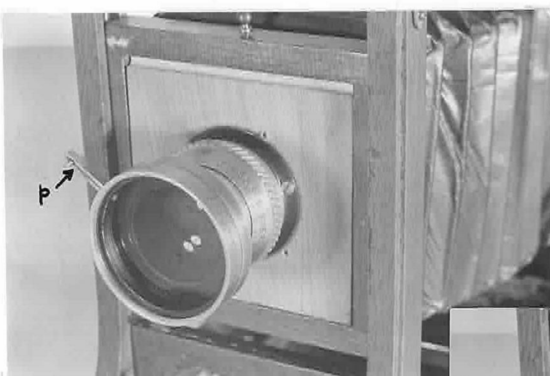


Fig. 7a - The analyzer, a Kodak "Pola Screen" is attached to the lens.

(p) handle on analyzer, oriented with polarization

Fig. 7b - A sunshade is attached to the analyzer. The sunshade may be attached to the lens without the analyzer between.

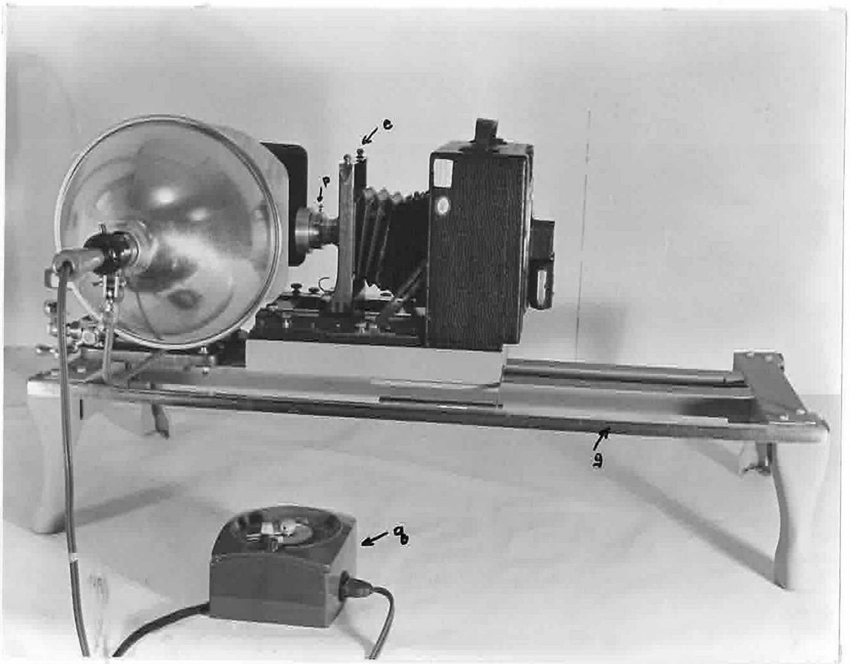


Fig. 8a - The camera, focused for a magnification of $1\frac{1}{2}$ times.

(q) electric timer to control the light

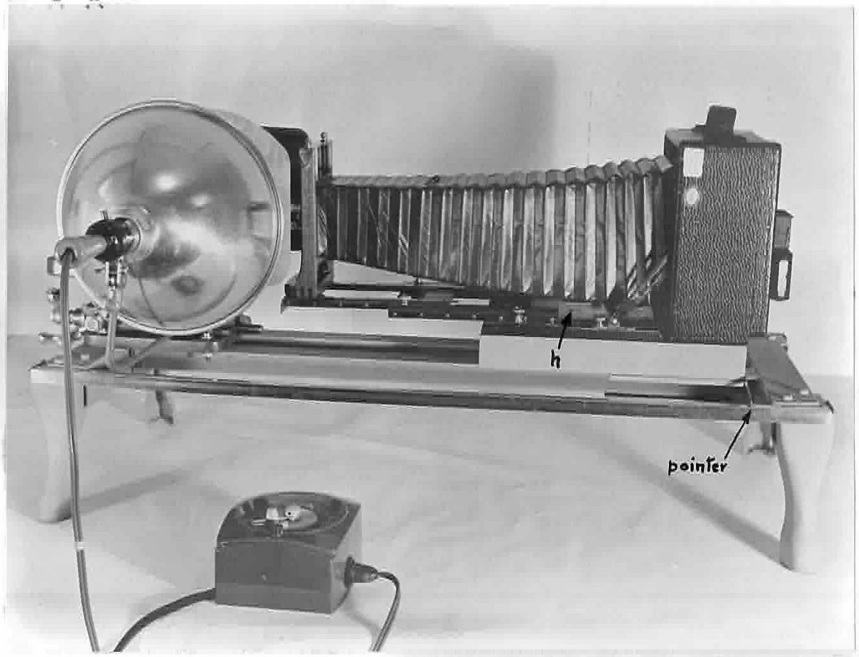


Fig. 8b - The camera, focused for the maximum magnification of 4 3/4 times.

Figure 8 - The camera

Thin section photography - If a suitable mount were made to hold thin sections and to support a polarizer, diffuser, and light source for transverse illumination the camera could be used to photograph thin sections. As with the polished specimen mount, a thin section mount could be clamped in the mill vise on the camera support.

Testing the camera - The first test film put through the camera gave discouraging results. Table J gives the data for this film number J. All of the pictures were overexposed and this was due to the fact that the diffuser on the camera does not absorb as much light as that used on the test apparatus. Focusing is very easy and great depth of focus was found at magnifications less than 1½. Beyond this magnification the depth of focus seems to decrease and at the maximum magnification of 4 3/4 sharp focus can not be observed on the ground glass at lens apertures larger (in diameter) than f 11. Some minor mechanical difficulties were encountered, such as the failure of the semi-automatic film stop to function and the tendency of the film to wind loosely on the take up spool. These difficulties have largely been resolved.

Close observation of the pictures in film J indicates that the sharpness of even the low magnification exposures is much less than that obtained on film I with the test apparatus. Since the lens used for both films is the same the accuracy focusing with the Bantam back was questioned. A check with a depth gauge indicated that the plane of the film in the roll film holder did not correspond with the plane of the ground glass. The film holder was removed from the Bantam back and the soft felt "shim" was replaced with one made from thin sheets of brass and aluminum. Film K, taken with black and white film, showed a definite improvement in sharpness.

The exposures in film K were adjusted to be in balance with the brighter illumination, and negatives of acceptable density were obtained in this film (see table K). Two exposures on film K were made with the Photoflood lamp off but with the room lights first on (exposure 6) and then off (exposure 7). These exposures were made at f 16 for a period of 10 seconds. The exposure with the room lights on contains an objectionable density of fog. However, for a normal exposure, the time lag before the main light source is turned on and the emplacement of the film in the plane of focus is only about one second. A similar time elapses after the main light source is extinguished and before the film can be moved out of the plane of focus. With color or slow pancromatic films one may safely operate the camera in any dimly lighted room withour worry of fogging the film.

The first practical test of the camera was with film L. Eight black and white pictures of polished specimens from the Cactus Queen mine (Mojave district, Kern Co., Calif.) were photographed for illustrations in a report. The eight pictures were taken in about $\frac{1}{2}$ hour. The prints were enlarged to 8 by 10 inches and have acceptable sharpness.

Enough testing and adjustment had been done to warrant the further investigation with color film. The accuracy of focusing is improved by the use of a 6 power magnifier especially adapted for use on the 28 by 40 mm ground glass. By using this magnifier the need for refocusing the camera when the analyzer is introduced into the optical system was recognized, verifying the effect predicted by application of the theory of geometric optics. The 5 exposures using parallel light are of good density and sharpness (table M) but appear to have abnormally pale shades of yellow in the minerals like pyrite and chalcopyrite. This indicates that the light source was too dominant in blue light. In film N a bulb with a lower color temperature (i.e. redder light, a 3200° instead of a 3400° Kelvin color temperature) was used for some of the exposures. The three exposures in film M taken in nearly crossed polarized light are disappointing. The previous test work indicates that the drop in light intensity with crossed polarization is variable but in a range of from 20 to 40 times less. The factor used in film M is 40 times and the results are ambiguous, two pictures are underexposed and one is overexposed.

One may conclude that the intensity of the polarization colors varies greatly in intensity with the mineral species, the orientation of the specimen, and the degree of perpendicularity of the polarizer and analyzer. Work with polarizing microscopes supports these findings. It is hoped that further testing will help clarify this problem.

Besides testing other exposures with crossed polarized illumination, a comparison of Kodak 100 mm f 4.5 "Enlarging Ektar" with the 105 mm Elgeet "Apos Color-stigmat" is made in film N (see table N). The Elgeet lens will not resolve details in the polished specimens well enough at magnifications above 3½. Exposures taken with the Elgeet lens at the maximum magnification of 4 3/4 are on the border line of acceptability in terms of sharpness. Fine focusing for all of the pictures in film N was done by adjusting the position of the mill vise, a procedure not attempted before, because focusing control using only the rack and pinion on the camera body was believed to be adequate.

Results of the Elgeet-Ektar comparison show that at f 16 these lenses are remarkably similar. Careful study of the transparencies under a microscope tends to favor the Elgeet lens for superior resolving power f 16 (see p.51). The color temperature comparisons were likewise interesting. Previous tests with 3400° Kelvin illumination resulted in transparences that seemed a little bluish . Similar exposures of the same object with 3400° and 3200° Kelvin resulted in transparencies a little bluish and reddish respectively. Is is up to the photographer to decide which color temperature to use, for both give acceptable results: if bluish minerals are to be emphasized use 3400° Kelvin illumination (#1 Photoflood bulb), if yellow minerals are to be emphasized use 3200° Kelvin (PS-25 bulb) illumination.

Further tests with exposures in nearly crossed polarized illumination were made in film O. The bright, oblique illumination of the edges of the specimen, especially at low magnifications, was controlled by the use of several light baffles. Light reflected obliquely from a thin ring on the edge of the metal sunshade was bright enough to affect the illumination. Two built-in baffles plus a third loose, adjustable one suffice well to eliminate all serious stray light.

Tests with films J, M, and N indicate that the color reproduction of the subtle polarization colors of pyrrhotite and cubanite in specimens from Sudbury, Ontario is not true. If one looks at a light through two nearly crossed sheets of type J polaroid the color of the light is deep purple, not gray or black. If one repeats the experiment with two Kodak Pola-Screens the color is brillant deep blue. The combination on the camera of type J polaroid for the polarizer and a Pola-Screen for the analyzer gives a color of blue-purple, instead of the desired very dark gray. To correct for this intense blue in film O an orange filter was inserted in the optical system for some pictures (see table O). The orange filter used is a standard Kodak type A filter for daylight (No. 85*). If the colors with this filter are too red a yellow CC-30Y (or CC-20Y to CC-40Y) filter is suggested instead.**

Much more testing needs to be done regarding the exposure (determining the polarization factor) and the color balance of photographs taken in nearly crossed polarized light. Time did not permit complete investigation of these problems.

* Wratten

** see Table O

Table J

Film: Kodachrome, type A, balanced to 3400° K
speed: ASA 16

Light: #1 Photoflood, color temperature 3400° K
Lens: 105 mm Elgeet 1/29/52

Specimen	Exp. No.	Mag- nfc.	exf	light	exposure sec.	exposure f	Remarks
Texture 11	1	1.2	1.3	pp	1	8	good depth of focus
Texture 11	2	2	2.2	pp	2	8	fair depth of focus
Texture 11	3	4.8	8.5	pp	30	16	poor depth of focus
Texture 8	4	4.8	8.5	pp	30	16	poor depth of focus
SU 5119	5	2.5	3.2	pp	2.5	8	bellows sagging, does not cut
SU 5119	6	2.5	3.2	xp	75 (30X)	8	not refocused
SU 235	7	2.5	3.2	pp	2.5	8	refocused
SU 235	8	2.5	3.2	xp	75 (30X)	8	one edge over illuminated.

General Remarks: All pictures overexposed, none critically sharp. Film stop not operating. Adjustments were made on the film holder to make the plane of the film coincide with the plane of the ground glass. It is necessary to refocus the camera for xp photographs when the analyzer is introduced into the optical system (see Exp. No. 6, remarks).

Feature / Exp.No.	1	2	3	4	5	6	7	8
fairly sharp	x	x	x		x		x	
fuzzy				x		x		x
overexposed				x		x		x
very overexp.	x	x	x		x		x	

Table K

Film: Kodak Plus X (black and white), speed ASA 32

Light: #1 Photoflood

Lens: 105 mm Elgeet 2/22/52

Specimen	Exp. No.	Mag-nfc.	exf	light	exposure sec.	exposure f	Remarks
All specimens are Texture8	1	1.6	2	pp	1	22	film stop not ok
Texture 8	2	3	4	pp	1	8	overexp.
", etc.	3	4.8	8.5	pp	1	11	fair focus at f 8
	4	4.8	8.5	pp	5	22	"
	5	3	4	pp	1	16	correction for #2
	6	3	4	pp	10	16	no photo-flood or room lights
	7	3	4	pp	10	16	as above but room lights on
	8	1/2	1/2	pp	1	22	polarizer turned to cut light

General Remarks: A 6 power magnifier was procured to use on the ground glass for focusing, it makes focusing more accurate and much easier.

Results: (1) Exposure: #1,4,5,8 good, #3 slightly overexposed, #2 very overexposed.

(2) Focus and sharpness: #1,2,5,8 good.

(3) Room light fog test: on #6 a very faint image, on #7 a faint image.

Table L

Film: Kodak Plus X (black and white), speed: ASA 32

Light: #1 Photoflood

Lens: 105 mm Elgeet 3/4/52

Specimen	Exp. No.	Mag-nfc.	exf	light	exposure		Remarks
					sec.	f	
CQ 82	1	1.2	1.3	pp	3/4	22	all pictures very sharp
CQ 147	2	1.2	1.3	pp	3/4	22	"
CQ 150	3	1.2	1.3	pp	3/4	22	"
CQ 66	4	1.2	1.3	pp	3/4	22	"
CQ 47	5	1.1	1.2	pp	1/2	22	"
CQ 94	6	1.1	1.2	pp	1/2	22	"
CQ 99	7	3	4	pp	3	22	"
CQ 130	8	3	4	pp	3	22	"

General Remarks: These pictures were taken to illustrate a term report for Ore Deposits, Ge 202. The eight pictures were taken in about one half hour.

The automatic film stop did not function properly, the film was loose on the take-up spool and the last three pictures were partly fogged.

The sharpness of these pictures is better than that of films J and K.

Table M

Film: Kodachrome, type A, balanced to 3400° K
speed: ASA 16
Light: #1 Photoflood, color temperature 3400° K
Lens: 105 mm Elgeet 3/27/52

Specimen	Exp. No.	Mag-nfc.	exf	light	exposure		Remarks
					sec.	f	
Texture 11	1.0	1.2	1.3	pp	1	18	tests for exposure & sharpness
Texture 11	2	4.8	8.5	pp	9	18	" fuzzy
Texture 8	3	4.8	8.5	pp	9	18	" fuzzy
Texture 8	4	1.8	1.9	pp	1.2	16	"
Brass, ruled mount	5	1.2	1.3	pp	1	18	test for evenness of illumination
SU 235	6	2.5	3	xp	100 (40X)	16	test for focus and color
SU 235	7	4.8	8.5	xp	600 (40X)	22	" overexposed (fuzzy)
Texture 3	8	3.3	5	xp	85 (30X)	16	" underexposed

General Remarks: Pictures #1,4,5,6,8 have acceptable sharpness. All the exposures in plane polarized light are correct, but all of the pictures have a bluish cast. #6, underexposed, has an obliquely illuminated edge, a baffle is needed around the polarizer to cut this light.

Table N

Film: Kodachrome, type A, balanced to 3400° K
speed: ASA 16 4/24/52

Light: #1 Photoflood and PS-25 (3200° K) lamps

Lens: 105 mm Elgeet and 100 mm Kodak Enlarging Ektar

Specimen	Exp. No.	Mag-nfc.	exf	light	exposure		Remarks
					sec.	f	
Texture 8	1	4	6.2	pp	1	16	Ektar lens 3200° K
Texture 8	2	4	6.2	pp	1	16	Elgeet lens 3200° K
Texture 8	3	4	6.2	pp	4.8	16	Elgeet lens 3200° K
Texture 8	4	4	6.2	pp	4.8	16	Ektar lens 3200° K
Texture 12	5	3	4	pp	3	16	Elgeet lens 3200° K
Texture 12	6	3	4	pp	3	16	Elgeet lens 3400° K (#1 Photoflood)
SU 235	7	3	4	xp	70 (45X)	16	Elgeet lens 3200° K
Arsenopyrite*	8	2.5	3.5	xp	65 (50X	16	Elgeet lens 3400° K

General Remarks: Picutres #1-4 are comparative exposures taken of the same specimen with the Elgeet and Ektar lenses. Little difference in sharpness can be seen in the pictures, however the Elgeet pictures may be slightly sharper. This unexpected favorable result may be due to less accurate focusing with the Ektar, but in any case, the Elgeet lens is equal to the more expensive Ektar at f 16.

Pictures# 5 and 6 are very sharp, #5 is reddish and #6 is bluish - both are acceptable.

Picture #7 should have had twice the exposure, stray unpolarized light illuminated one corner.

Picture #8 should have had 3/4 the exposure, it is also bluish. Both #7 and #8 are sharp.

* from "Work Suite - 'Color'"

Table O

Film: Kodachrome, type A, balanced to 3400° K
speed: ASA 16

Light: PS-25 lamp, color temperature 3200° K
Lens: 105 mm Elgeet 5/16/52

Specimen	Exp. No.	Mag-nfc.	exf	light	exposure		Remarks
					sec.	f	
Texture 11	1	1.1	1.1	pp	1	17	film stop not working
Arsenopyrite	2	1.1	1.1	pp	1	20	mineral has high re-flection
Arsenopyrite	3	1.1	1.1	xp	150 (100X)	17	with type A orange fil-ter
Arsenopyrite	4	1.1	1.1	xp	25 (100X)	8	no orange filter
Texture 3	5	1.5	1.7	xp	18 (25X)	9.5	with orange filter, good focus at f5
Texture 3	6	1.5	1.7	xp	12 (25X)	9.5	no orange filter
SU 235	7	1.8	2	xp	80 (80X)	12	no orange filter
SU 235	8	1.8	2	xp	80 (80X)	10	orange filter

General Remarks: In previous test films all pictures taken in nearly crossed polarized light are too dominantly blue. Three pairs of comparative pictures, #3 & 4, 5 & 6, 7 & 8, were taken above, with and without an orange (blue absorbing) filter.

Results: All exposures good. #3,5,8, taken with the #85 (Wratten) orange filter are a little too red, #4,7,6 without the filter are too blue. A #83 filter may be better (it is less dense) but its yellowish color may make the picture too green. Any of the yellow color correction filters mentioned in the text would probably be unsatisfactory, for they would make the picture green.

III

Discussion of the Resolving Power of Lenses

Camera optics - There is a puzzling air of mystery concerning the quality of different camera lenses. The reasons for this mystery are twofold. First, lens designers keep their trade secrets well. Not only are lens formulae guarded but production and testing methods are similarly hidden from the competitor and the general public. Secondly, a lens of given focal length and aperture may be poorly or well corrected depending upon the design of the lens. The average photographer is lost in a muddle of lens names either bonafide or fakes. For example, the Elgeet "Apos Colorstigmat" used on the polished section camera is not apochromatic (or "apo") as the word Apos suggests; the word Colorstigmat implies color correction and astigmatic qualities, which certainly exist to some extent in the lens, but the name sounds over-impressive. Some companies, like Eastman Kodak, reserve one name, e.g. "Ektar", for any lens of high quality, regardless of its desigh. Other companies, notably the German lens makers, each have their own names for a given lens type. There is need for a published lens evaluation of every lens on the market in terms of design and resolving power. If such data were available (and a limited amount is becoming so) the job of selecting a lens for any purpose would be made easier. An organization, like the American Standards Association, should undertake this task.

Resolving power - From the simple concepts of geometric optics one would not expect there to be a limit to the sharpness of an image from any optical instrument. There would be the numerous aberrations to be considered, but a well designed optical system can be corrected to a remarkable extent. The practical limit to sharpness is governed by the laws of diffraction of light, which are functions of the wave (not ray) nature of light. Light passing through or by any object, such as the diaphragm of a lens, will tend to bend around this obstruction, an effect which promotes the scattering of light, reducing the contrast of the image, and which also limits the smallest size of image which may be formed of a point object. The diffraction pattern from a point source constitutes a bright central disc* bordered by alternate dark and light rings. The minimum separation of the central bright portions of two of these discs so that they appear as two points and not as one, is a measure of the resolving power. In practical terms "the resolving power of a lens is measured customarily by its ability to resolve parallel lines of equal width of each line, and is stated in terms of lines per millimeter of the image." (Greenleaf, 1950, p. 31). The diameter of the

* known as the: "circle of confusion", "antipoint", or "Airy disk".

central diffraction disc (d) is given by the following equation for an axial image in air, $d = 1.22 \lambda F \cdot 10^{-6}$, where λ is the wave length of light expressed in millimicrons and F is the f number of the lens aperture. The diameter of the off-axis diffraction discs is given by the equation $d = 1.22 \lambda F \cdot 10^{-6} \cdot \cos^{-1}\theta$ for axial lines and by the equation $d = 1.22 \lambda F \cdot 10^{-6} \cdot \cos^{-3}\theta$ for tangential lines, where θ is the angular separation from the optic axis (Greenleaf, 1950, pp. 29-31). The reciprocal of these equations gives the resolving power expressed in lines per millimeter; the larger this value the smaller the diameter of the diffraction discs. These equations are applicable only for monochromatic light; it is obvious from these equations that greater resolution is achieved if λ is small (i.e. blue or ultraviolet light), if heterochromatic light is used the resolution will be less. The values obtained from these equations show that a lens of large aperture (low f value) will, theoretically, have a greater resolving power than a lens of smaller aperture (higher f value). Table 0-2 gives some values for the theoretical resolving power in monochromatic light of a lens at different apertures along radial lines at different angular distances from the optic axis.

Elgeet lens - In practical terms, the high theoretical resolution obtainable at large lens apertures is never achieved. The many lens aberrations are not

Table 0-2

Theoretical resolving power of an ideal lens for radial lines, expressed in lines per millimeter, in monochromatic light (λ = 5893 Angstrom units)

	Angular distance (θ) from axis, degrees				
f No.	0	5	10	20	30
1	1391	1386	1370	1307	1204
2	695	693	685	654	602
4	348	346	343	327	301
8	174	173	171	163	151
16	87	87	86	82	75
32	43	43	43	41	38
64	22	22	21	20	19

Let:

F = f number of lens

θ = angular distance from the optic axis

λ = wavelength of light in millimicrons

then:

Resolving power (lines/mm) = $10^6 \cos \theta / 1.22 \lambda F$

Table and formula from Greenleaf, 1950, p.30.

well enough corrected at the larger apertures to make use of this greater possible resolution, so most "speed" lenses are sharpest at some intermediate f stop. As the size of the aperture decreases the aberrations usually decrease more rapidly and the practical limit of resolution approaches (but does not nearly reach) the theoretical limit. The f 4.5 Elgeet lens of 105 mm focal length is observed to be "softer" at f 4.5 than at f 5.6, that is, the aberrations at f 4.5 are more detrimental than the resolution limit set by diffraction. As the aperture is decreased in size the resolution should decrease but the visual recognition of this change on a ground glass is hindered by two factors: first, the depth of focus increases as the aperture decreases and the apparent sharpness may seem to increase (especially on images of non-planer objects); secondly, the size of the "grain" of the ground glass inhibits useful detection of resolution finer than the grain of the glass. Inspection of pictures taken with the Elgeet lens at apertures from f 8 to f 22 indicate more apparent sharpness at f 22, with a possible maximum of sharpness at about f 18. This suggests that either the greater depth of focus is needed (not probable) or that lens aberrations are still the limiting factor of resolution at apertures as small as f 8. The qualitative effects are shown in fig. 9 graphically.

Ektar lens - The 100 mm Kokak Ektar enlarging lens

Fig. 9

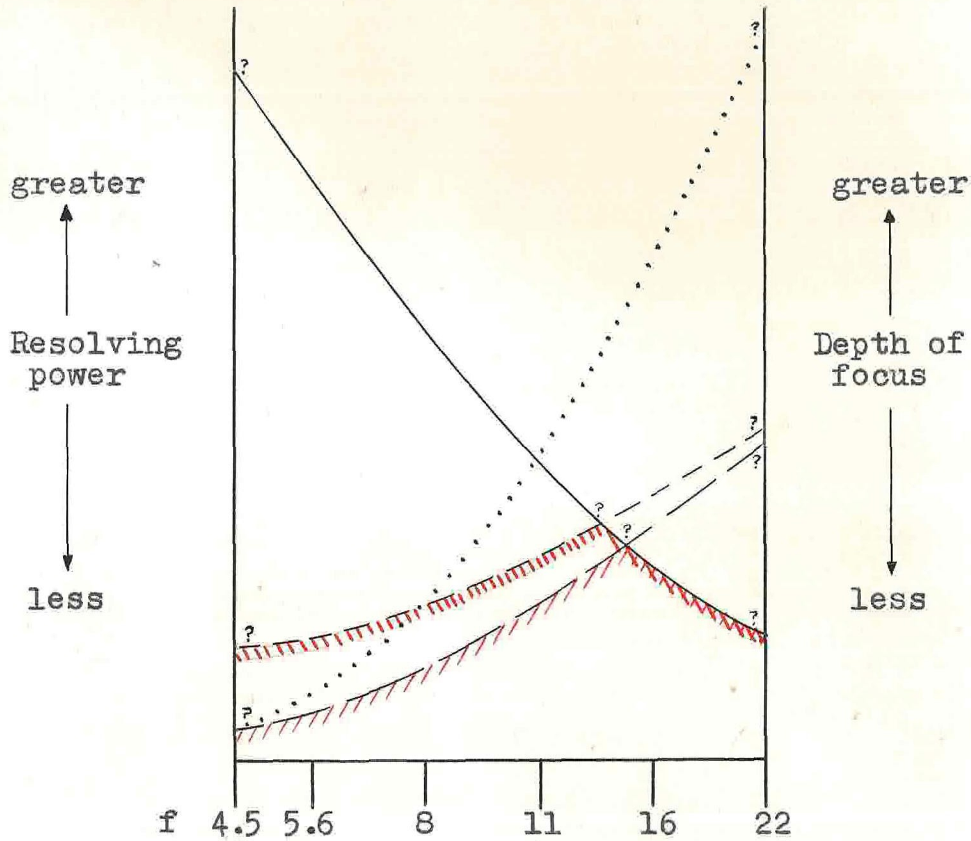


Figure 9 - Apparent effective resolution of the Elgeet and Ektar lenses

Key

——————— theoretical resolution with heterochromatic light

— — — limit of resolution by aberrations: Elgeet

- - - - - limit of resolution by aberrations: Ektar

/////////// maximum effective resolution: Elgeet

\\\\\\\\\\\ maximum effective resolution: Ektar

• • • • • effective depth of focus

Note: at f 16 the resolving power of both lenses is essentially the same.

has not been tested thoroughly. From limited visual observations on the ground glass it appears to have slightly greater sharpness at larger apertures than the Elgeet lens, that is, the aberrations of the Ektar lens are less. Test exposures on film N show that at f 16 both lenses have about the same resolving power. Photomicrographs (fig. 10 a,b) support this conclusion. There does seem to be slightly greater resolution at f16 with the Elgeet lens, however. In terms of cost and photographic reputation the Ektar lens was expected to be superior and the lesser sharpness may be due to less critical focusing (although an attempt was made to focus equally and as accurately as possible with both lenses). Regardless of this unexpected result one may assume at least that both lenses would give approximately equal resolution at f 16.

Resolving power of films - In the beginning part of this report it was stated that the resolving power of Ektachrome film is 45 lines per mm and that of Kodachrome is 55 lines per mm. Visual comparison of Ansco Color film indicates its resolving power is between that of the two Kodak films. Panchromatic black and white films resolve the following number of lines per mm for the following Kodak films: Tri-X Panchromatic-65, Super XX-90, Plus X-95, Panatomic X-100, Microfile-175. "The majority of lenses in ordinary photographic use do not exhibit over their entire fields (which for most

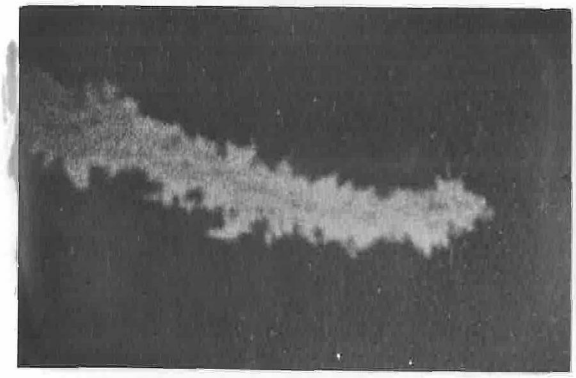


Fig. 10a - Texture 8 (x14), 105 mm Elgeet lens, f 16

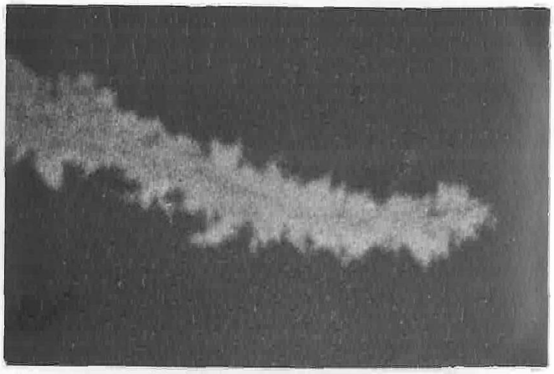


Fig. 10b - Texture 8 (x14), 100 mm Ektar lens, f 16

Note: The resolution is nearly the same but that of the Elgeet lens seems to be slightly better.

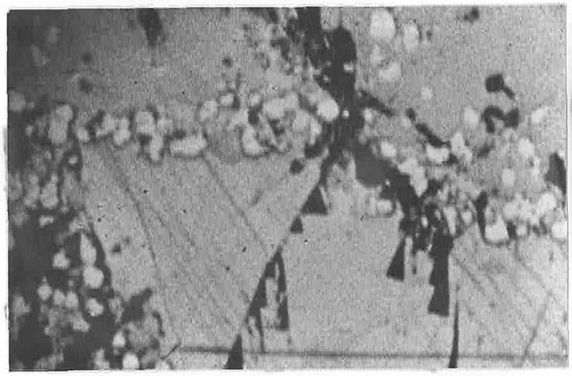


Fig. 10c - Texture 12 (x14), 105 mm Elgeet lens, f 16, gradient of 2-3 grains

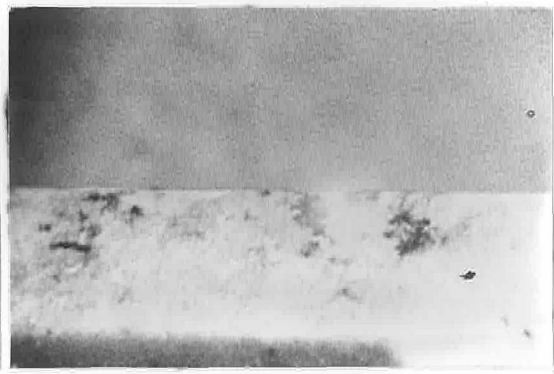


Fig. 10d - Typical sharp boundary (x14) of a "Leica" picture, 100 mm lens, f 10, gradient of 1-2 grains

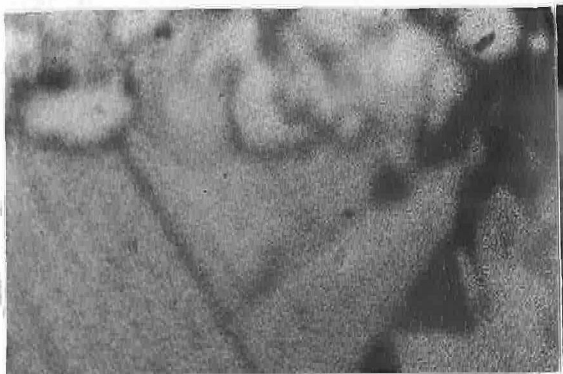


Fig. 10e - Texture 12 (x70), resolution seems poor

Fig. 10f - Typical sharp boundary (x70) of a "Leica" picture

Figure 10 - Photomicrographs showing the "grain" of Kodachrome and the resolution of various lenses.

cameras do not exceed 30 degrees from the axis) a resolving power even approaching the 100 lines per millimeter resolved by Panatomic X film. The tendency is for manufacturers to increase the resolving powers of their emulsions; therefore improvement in lenses is required if full advantage is to be taken of either present emulsions or of this progressive improvement in negative materials." (Greenleaf, 1950, p.33).

At a magnification of 1:1 the lens in the polished section camera, a 4 inch lens, covers a cone of rays 14 degrees in extent, or 7 degrees off the optic axis. Theoretically, at f 4 the lens should resolve an average of 346 lines per millimeter in monochromatic light (λ = 5893 A) between 0 and 10 degrees from the optic axis. Actual tests in heterochromatic light at f 4 with several aerial lenses revealed an average resolution of about 40 lines per millimeter between 0 and 10 degrees from the optic axis (Greenleaf, 1950, p.32), and an average resolution of about 50 lines per millimeter for an f 6.8 lens under similar conditions. It is clear that lens aberrations are the limiting factors of resolution in the f 4 lens. These figures represent only a small fraction of the theoretical value of resolution and illustrate the need for improvement in lenses.

It is reasonable to assume that neither the Elgeet or the Ektar lenses have resolution much superior to the aerial lenses discussed above. The photomicrographs of the Kodachrome transparencies shown in fig. 10 a, b both reveal that neither lens is resolving beyond the "grain" of the film at an aperture of f 16. At this aperture the limitation of the resolution probably is due largely to diffraction effects rather than aberration effects. A decrease in sharpness is especially noticed at the higher magnifications with the polished section camera and the best results can be obtained if focusing is done very carefully, for the depth of focus at this magnification is shallow and the aperture of the lens must be small to give the depth necessary, even with a planar object. This small aperture limits the resolution because of diffraction effects and a median position between these opposing optical limits must be sought.

Microscope optics - As in the case of camera lenses the resolution obtainable with microscope objectives is limited by the size of the central bright portion of the diffraction disc or "antipoint". Again, the size of the antipoint decreases with the increasing aperture of the objective. Instead of using f * values for the aperture, and utilizing the equation in the form of $d = 1.22\lambda F \cdot 10^{-6}$, an index of aperture size called the "numerical aperture" (N.A.) is used. The numerical aper- of the objective, hereafter designated N.A., is defined

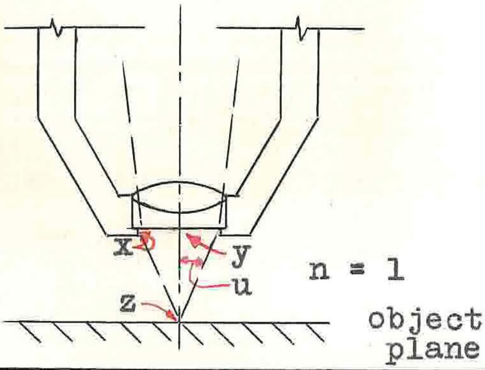
* f = focal length of the lens/diameter of the aperture

as N.A. = n sin u and is the product of the lowest index of refraction (n) between the object and the front element of the objective and the ratio of the effective radius of the front element of the objective to the distance of the edge of this element from the object (fig. 11 a). If a substage condenser is used its numerical aperture is designated n.a., and the most efficient illumination is achieved when N.A. equals n.a. "The distance between the finest detail that can be separated by a microscope objective is equal to the value, d = λ/N.A. + n.a. ... A maximum resolving power is reached when the whole aperture of the objective is full of light and the condenser aperture used is equal to that of the objective. In this case the resolving power becomes equal to λ/2 N.A." (Eastman Kodak Co., 1944, pp. 22,23).

If an air space is left between the object and the objective, n = 1, and the highest N.A. is about .95; the widest cone of rays passing between glass-air surfaces must be at an angle slightly less than the critical angle of light at this interface (fig. 11 b). By the use of an oil immersion objective, utilizing a film of oil in the space between the objective and the object, a wider effective cone of light may be transmitted through the objective. The N.A. is increased because n equals about 1.4 to 1.6 instead of 1.0, and so the resolving power likewise increases. Fig. 11c shows the geometry of

Fig. 11

(after Kodak)

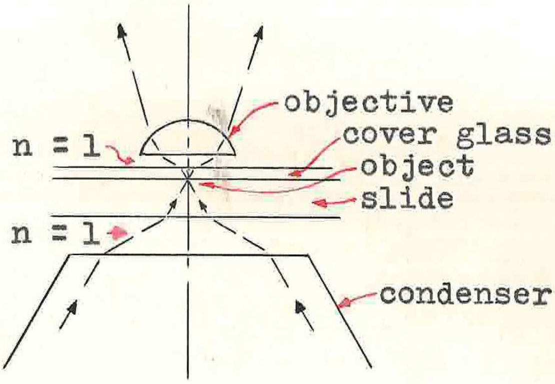


$$\sin u = \frac{xy}{xz}$$

N.A. = n sin u

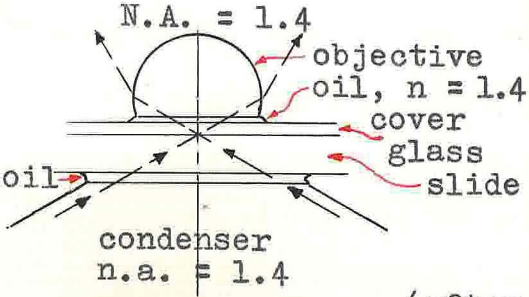
Fig. 11a - Section of a typical microscope objective.

(after Kodak)



The maximum value of the angle u is a function of the critical angle of the glass-air interface.

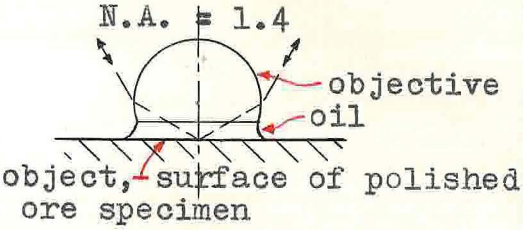
Fig. 11b - Diagrammatic section of a short focal length microscope objective.



N.A. = n.a.

(after Kodak)

Fig. 11c - Diagrammatic section of an oil immersion microscope objective, transmitted light.



N.A. = n.a.

Fig. 11d - Diagrammatic section of an oil immersion microscope objective, reflected light.

Figure 11 - Numerical aperture and oil immersion microscope objectives

an oil immersion lens for transmitted light and fig. 11 d for reflected light. Theoretically, the resolution of an oil immersion objective of an N.A. of 1.4 would approach the value $\lambda/2.8$ or about 1/3 the wavelength of light used. This theoretical value may be limited by the aberrations of the objective, which may not be as serious a limiting factor as those in camera lenses.

Using transmitted light and an oil immersion objective the effective resolution and the contrast tend to be reduced because of the finite thickness of the object and the multilayered nature of the optical system between the condenser and the objective. On the other hand, the simplicity of the optical arrangement for reflected illumination should result in better resolution and contrast, assuming the object plane is optically flat and that there is little scattered light from the vertical illumination system. L. C. Graton believes that the resolution with an objective of 1.4 N.A. which he used with reflected illumination is better than the theoretical $\lambda/2.8$; "indeed, we have ...photographed polishing scratches which we believe have a width of the order of $\lambda/10$ equals 4358 Å" (Graton, 1937, p.376). On the basis of this apparent resolution which is greater than theoretically possible, he urges "that the lens makers, without waiting for a better theory - if one be needed - make efforts to surpass their present best" (Graton, 1937, p. 376).

Conclusions

From the foregoing presentation it is apparent that low magnification pictures of polished ore specimens can be successfully made with equipment costing less than $100. There are many problems that arise concerning the construction and testing of special photographic equipment, some of the problems, such as exposure determination and resolution, are universal with photography in general; others, such as vertical illumination and polarized light photography are unique to the special problem at hand and require an understanding of the nature of the object being photographed. The short discussion of resolution reveals that at present optical equipment is of good quality but that improvements can be made, and gives the reader a limited practical background concerning the limits of resolution in camera and microscope optics.

When this work was started, a study of the nature of the polished surface of ore specimens was anticipated, but there was not enough time to begin this investigation. With the aid of a camera capable of taking consistant photographs of polished ore specimens in color, the comparative study of different types of polishes and their effects on the reflectivity, relief, and color of the common ore minerals could be initiated. The author hopes that someone will undertake such a study in the near future.

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Appendix

Operating Instructions for the Camera*

1. Inspect the equipment, be sure the specimen support is tight in the mill vise (f) and that the camera is securely bolted to the bed (h) with the thumb screws.
2. Clean the lens if necessary, and also the vertical illuminator (l), polarizer, and analyser (if used) with a soft cloth or lens paper.
3. Loading the camera with film: <u>be sure</u> the film holder (b) is out of alignment with the lens (see fig. 2).
   a. Use only Bantam size film (#828 Kodak films).
   b. Open the lock on the side of the film holder and swing the back open, be sure the take-up spool is in line with the film advance knob.
   c. Slip the film spool in the opposite space and pull the free end of the film to the take-up spool and engage it, close the back.
   d. Advance the film until the frame numbers appear in the viewing window and/or until the automatic film stop prevents further advance of the film (pressing the small button by the film knob will release the knob to advance to the next frame).
4. Lighting

* see figures 2 through 8, key parts are lettered

a. Set the pointer on the camera bed (fig. 8) opposite the desired magnification as indicated on the brass scale (g).

b. Turn the light on and open the lens diaphram all the way. Be sure the lens shade is on the lens. Do not leave the light on longer than necessary, it is hot.

c. Move the front of the camera back or forth until rough focus is attained. Center the image as desired by adjusting the rise and fall of the lens board (e) and the cross feed of the mill vise (f).

d. Focus accurately using the rack and pinion adjustment on the camera. Use the magnifier (d) on the ground glass. For pictures at magnifications greater than about $2\frac{1}{2}$ proceed as above and then make final adjustments of focus by using the linear feed on the mill vise (f). The vise should be backed away from the camera as far as possible (except for about two turns of the handle) at all times, otherwise the magnification scale will be in error. At the maximum magnification of 4 3/4 one should be able to detect a change in focus with about a 20 degree turn on the mill vise linear feed handle. It may be necessary to stop the lens down to about f 8 to get fairly sharp focus at high magnifications.

e. If crossed polarized illumination is to be used, focus as above, then:

(1) Attach the analyzer to the lens (fig. 7), and the lens shade to the analyzer.

(2) Turn the analyzer to a position which allows maximum transmission of light (handle (p) will be vertical).

(3) Refocus the image, using the mill vise feed if necessary.

(4) With the magnifier (d) on the ground glass, turn the arm of the analyzer until maximum extinction is obtained. Then move the analyzer a few degrees off this position in one direction and then the other. Seek the orientation of the analyzer which gives the greatest contrast of the polarization colors of the minerals (about 1 to 4 degrees from the extinction position). If the colors are poor, rotate the specimen in the support until the desired colors appear, then using the rotating back of the camera set the image in its original position on the ground glass (if the image area is off the center of the specimen it will be necessary to make adjustments on the rise and fall and lateral feed).

(5) If there are bright edges in the picture it is necessary to use an additional baffle

(black cardboard) next to the baffle on the polarizer, adjust this extra baffle to cut out all oblique light falling on the lens board.

7. Exposure: For magnifications up to 1½ times stop the lens down to at least f 8, up to 2½ times to f 11, to 3½ times to f 16, to 4 3/4 times to f 18.
   a. The basic exposure for a subject of "average" reflection* at a magnification of 1.0 using plane illumination and type A Kodachrome film** is 1 second at f 18. For higher magnifications consult the brass scale (g) for the exposure factors. If the specimen is darker than average allow 1½ to 2 times more exposure, if the specimen is brighter than average allow 3/4 to ½ of the normal exposure. If crossed polarized illumination is used allow from 20 to 100 times more exposure than for that with plane illumination at any given magnification. If a #83 or #85 filter is used to cut the blue color with crossed polarization make allowances for the filter factor.
   b. Set the desired aperture on the lens and the desired time on the electric timer (q).
   c. With the room lights dim (no more than about 10

* about equal parts of pyrite, galena, sphalerite, and chalcopyrite

** for Plux X film use ½ the exposure of the Kodachrome foot-candles of light falling obliquely on the lens) move the film holder into the plane of focus and turn on the illumination as soon as possible (1 to 3 seconds). As soon as the illumination turns off move the ground glass again into the plane of focus.

d. Advance the film to the next frame.