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STEREOSCOPIC RADIOGRAPHY IN THE STUDY OF ORE TEXTURES

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ABSTRACT

Stereoscopic radiography provides a simple and effective method to study ore textures in three-dimensions. The technique is based upon the same principles as stereoscopic vision and consists of taking two radiographs with different focal positions. When the resulting x-ray pictures are oriented in their proper relative positions and viewed under a stereoscope, a stereoscopic model is produced showing the three-dimensional relations of the size, shape, and orientation of the minerals within the specimen.

Stereoradiographs of ore samples may be made with either a medical or industrial x-ray unit. Best results were obtained from specimens $\frac{1}{2}$ to 1 inch thick exposed for 1 minute, 50 seconds at 3 milliamperes (330 MAS) and 70 kilovolts. The target-film distance may vary from $1\frac{1}{2}$ feet to 3 feet with an optimum stereoshift of 5 inches. Kodak industrial x-ray film type AA or type M produce the greatest contrast and sharpest detail. Exposure time, type of film and intensity of radiation, however, may easily be varied to enhance various textural features in different rock types. If care is taken in measuring thickness of specimen, focal-film distance, and stereoshift, photogrammetric instruments may be employed to measure directional properties of the ore fabric.

This technique provides an entirely new perspective for the study of ore textures by allowing direct observation of the special arrangement of the component minerals. It is simple, inexpensive, and non-destructive and greatly supplements the type of data obtained by conventional microscopic techniques.

INTRODUCTION

One of the principle problems in ore microscopy is determining the true three-dimensional geometry of ore textures. With the conventional techniques of studying thin and polished sections the only possible procedure is to interpolate what the three-dimensional texture might be like based on observations of one or more two-dimensional surfaces. For simple textures this procedure may be satisfactory but seldom can one accurately visualize the complete geometry of complex textures from their expressions on plane surfaces. As a result the literature concerning the interpretation of ore textures, although voluminous, is incomplete and commonly contradictory.

Attempts to gain a greater insight to the textural framework of a rock by photographing a sequence of new surfaces after laborious grinding and repolishing have met with little success. In such a procedure, the specimen is completely destroyed and the results have seldom merited the tedium and expense involved.

The purpose of this paper is to demonstrate how stereoradiography overcomes the limitations inherent in flat-field studies and provides an entirely new perspective for viewing ore textures. With this technique one can look into a rock as if it were transparent and directly observe the complete three-dimensional arrangement of the component minerals. The technique is simple, inexpensive, and non-destructive and greatly supplements data obtained by microscopic work.

Technique

Basic principles Stereoscopic radiography has been used for many years in medicine and in various fields of non-destructive testing. The technique is based upon the same principles as stereoscopic vision and involves taking two separate radiographs of a specimen from focal points 2 to 8 inches apart. When the radiographs are oriented in their proper positions and viewed under a stereoscope, a stereoscopic model is produced so that the structural units recorded on the *x*-ray film are seen in their proper three-dimensional relations. In most respects the technique is exactly analogous to stereoscopic aerial photography. The major difference is that the stereo model in aerial photography represents the surface relief, whereas stereoradiography employs some form of penetrating radiation and thus reveals the internal texture in three-dimensions.

Specimen preparation Ore specimens for stereoradiography need only to be cut in the form of a large thin slice, the thickness of which may range from $\frac{1}{4}$ to more than 1 inch. Polishing or grinding are not necessary if the surface exhibits no deep saw marks. The most critical factor is that there be no variations in thickness throughout the specimen that would affect the intensity of radiation transmitted through the sample. If variations in thickness do occur they will likely produce tonal variations on the radiograph which could affect the quality of the stereo model and make interpretation difficult.

The writers found that specimens ranging from $\frac{1}{2}$ to 1 inch thick produce the best balance between a sharp negative and stereo relief. If the specimens are too thick, crystals near the upper part of the sample will be out of focus so the image will appear blurred and indistinct. Moreover, many subtle density differences within the sample may not be recorded by the hard *x*-rays produced at the higher voltage necessary to penetrate exceptionally thick specimens. Thin samples are undesirable because the stereo relief produced by them is too small to be effective. In addition, there is less chance to obtain a complete picture of the textural framework of the sample if the slice is cut too thin. The length and width of the specimen is limited only by the size of the available cutting equipment and stereoscopic viewing devices.

Procedure

The stereoradiographs were made with the portable Norelco industrial x-ray unit, PG 200 which allows voltage between 50 and 200 PKV. This unit has a tungsten target and a 1.6 mm focal spot. The x-ray tube is mounted on a tripod and can be tilted along an axis perpendicular to the x-ray beam. All exposures were made with the tube stationary and the stereoshift was accomplished by moving the specimen. Reference lines were marked on the table and film envelope so that the specimen could be oriented in precisely the same relative position in each exposure. Eastman Kodak ready pack industrial x-ray film type AA was used and processed in Kodak liquid x-ray developer and fixer.

The first film was exposed with the specimen located $2\frac{1}{2}$ inches to the right of the vertical axis of the x-ray beam with the x-ray tube tilted approximately 2 degrees towards the specimen. The second exposure was made with the specimen positioned $2\frac{1}{2}$ inches to the left of the vertical axis and the tube tilted 2 degrees to the left. Thus, the stereoshift between the two exposures was 5 inches with a composite tilt of 4 degrees in the direction of shift. Focal-film distance for all exposures was 24 inches.

A stereoscopic model can be obtained directly from the resulting negative using a common lens or mirror stereoscope and a light table for background illumination; or positive prints can be made from the x-ray negatives and analyzed following the same procedures used in aerial photo interpretation. Moreover, if care is taken in measuring focal-film distance, stereoshift, and tilt, accurate photogrammetric measurements may be obtained using parallax bars, stereocomparagraphs, and other photogrammetric instruments. If high precision photogrammetric work is desired, negatives may be mounted in glass plates and used in a Kelsh plotter or other high order photogrammetric instruments. Samples $\frac{1}{2}$ inch thick, 2 inches wide and 3 inches long may thus be enlarged so the stereo model has an apparent relief ranging up to 6 inches. The net result of this technique is to permit one to actually look inside a greatly enlarged model of an ore sample and see the fabric and textural elements in three-dimensions.

For routine analysis, examination of the x-ray negatives on a light table with a lens stereoscope holds several distinct advantages over an analysis of positive prints. Subtle tonal variations representing various mineral species are clearly defined on the negative, but may be difficult or impossible to faithfully reproduce in a positive print.

Stereoscopic relief or the illusion of depth in stereoradiography results from the parallax produced by the two point source projections. Many technical details are important, foremost among which are

(1) base length between the centers of the two exposures, (2) thickness of the specimen, (3) target-film distance, and (4) orientation of the x-ray beam.[1]

The amount of parallax and the resulting stereoscopic relief is directly proportional to the stereoshift and the thickness of the specimen, and is inversely proportional to the distance between the film and the x-ray tube. Tilting of the x-ray beam will also induce parallax, but the effects may either add to or detract from the depth perception in the stereo model. A small amount of tilt in the proper direction may, however, greatly enhance the three-dimensional effect. It should be emphasized that the apparent shape of the component minerals will be distorted by parallax so there is a practical limit to the relief that may be produced in stereoradiography. The writers found that best results were obtained within the following limits:

(1) stereoshift or distance between exposures—2 to 8 inches.
(2) thickness of the specimen—$\frac{1}{2}$ to 1 inch
(3) distance between the film and the x-ray tube—$1\frac{1}{2}$ to 3 feet.
(4) orientation of the x-ray beam—perpendicular to a tilt of 3 degrees in the direction of lateral displacement.

Exposure Factors

The quality of a radiograph is a function of several variables which must be in proper balance for correct exposure. Paramount among these in radiography of ore samples are:

(1) focal-film distance, (2) voltage, (3) amperage, (4) exposure time, (5) type of material in the specimen and (6) type of film.[2]

For maximum sharpness the focal film distance should be no less than 15 inches and for optimum detail the lowest voltage capable of penetrating the sample should be used. The time-amperage product can be varied to maintain the proper intensity of radiation. An increase in the time-amperage product will produce a corresponding increase in contrast. The relation between voltage and amperage is complex so a certain amount of experimentation is generally necessary in order to obtain a correct exposure. The best results obtained with the equipment available were from specimens $\frac{1}{2}$ inch thick exposed for 60 seconds at 3 milliamperes and 70 kilovolts from a distance of $2\frac{1}{2}$ feet. Practically any medical or industrial x-ray unit is suitable as a source of radiation and any non-screen, fine-grained, high contrast x-ray film suitable for radiography at low voltage is adequate for radiography of ore samples. The most desirable film from

[1] For a detailed account of the elements of stereoscopy see *Manual of Photogrammetry*, p. 521–534.

[2] For a concise treatment of the physical principles of radiography see *Radiography in Modern Industry*, 2nd Ed. Eastman Kodak Co., *X*-ray Division, Rochester 4, N. Y.

the standpoint of convenience, contrast and resolution is Kodak ready pack industrial x-ray film type AA. Ilford non-screen medical film, Ansco Superray B, and DuPont type 506, however, are entirely adequate. Intensifying screens are generally not necessary. Kodak liquid x-ray developer and replenisher and Kodak x-ray fixer and replenisher are recommended for processing the film.

The image density or tone on a radiograph depends upon the amount of radiation reaching the film which in turn is governed by:

(1) the total amount of emitted radiation, (2) the amount of radiation reaching the specimen, and (3) the proportion of radiation passing through the specimen.

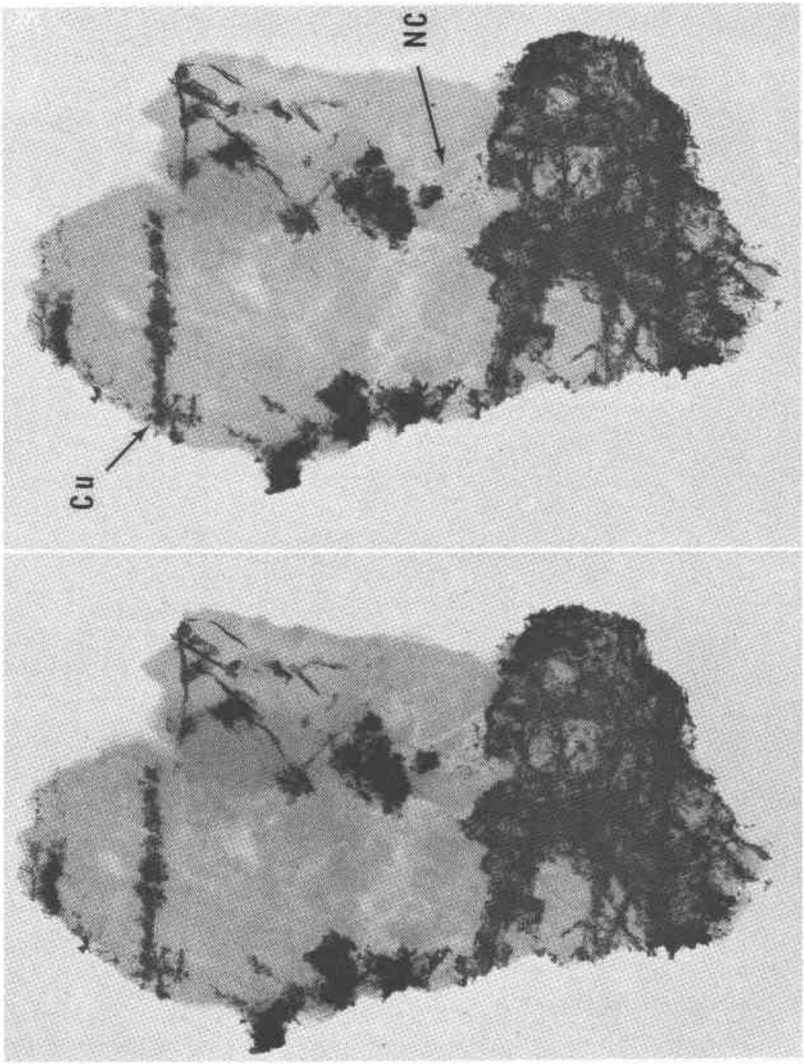
Many variable factors exist in each of these steps, all of which may affect the image density to some extent. Even under ideal conditions of constant amount of soft radiation, constant distance from source to specimen, and uniform thickness of the sample, it would be undesirable to attempt to identify and distinguish many ore minerals by tonal differences alone. Below the absorption edges of the elements irradiated, x-rays will be absorbed in direct proportion to the densities of the minerals. Inasmuch as most common ore minerals have specific gravities near 5 (except sphalerite and chalcopyrite, both somewhat lower, and galena, considerably higher) only very subtle tonal difference will be recorded on the radiograph. When absorption differences caused by vectoral density variations within the crystal structure are considered, the slight absorption differences resulting from small variations in specific gravity lose their meaning.

Applications

The results obtained from specimens representing several different ore types are shown in Figs. 1–4. The illustrations are actual size and consist of a photograph showing the specimen in reflected light in addition to the stereo pair of positive prints made directly from the x-ray negatives. Details of the mineralogy of each specimen were determined from a study of thin and polished sections.

The specimen illustrated in Fig. 1 is from the Keweenawan copper deposits of northern Michigan. The contrast between the copper and the basalt is much greater in the radiograph than in the hand specimen and from the stereo model the distribution of copper throughout the entire rock can be seen in remarkable detail. Not only is the structural control of the copper emplacement accentuated, but the complete attitude of the fractures can be visualized in three-dimensions. In addition, the replacement of basalt immediately adjoining the fractures can be seen in delicate detail.

Figure 2 represents a molybdenite-bearing ore from Climax, Colorado.



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Intermittent fracturing has controlled the emplacement of molybdenite and quartz which exist primarily as small veinlets with various orientations. Small particles of molybdenite are also dispersed throughout much of the sample and highly sericitized feldspar can be distinguished in its proper three-dimensional relation.

A common texture in polished sections is that of crystallographically

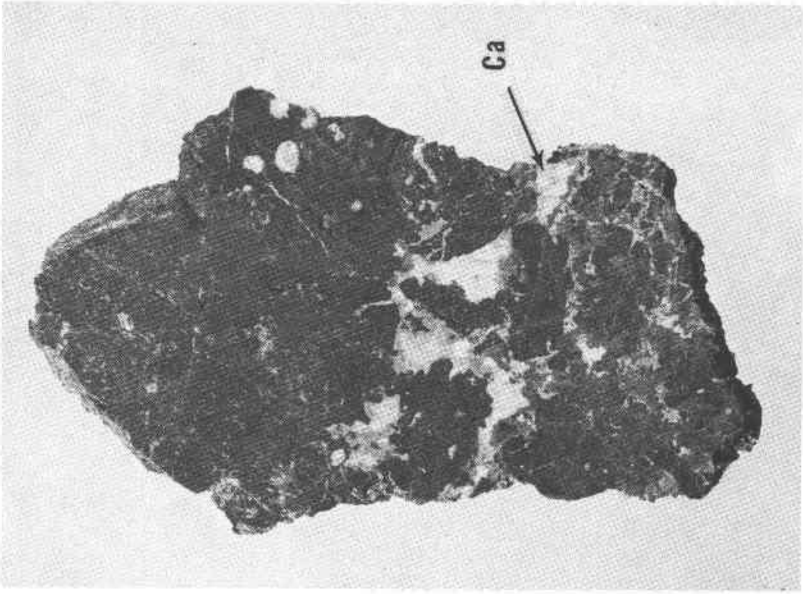
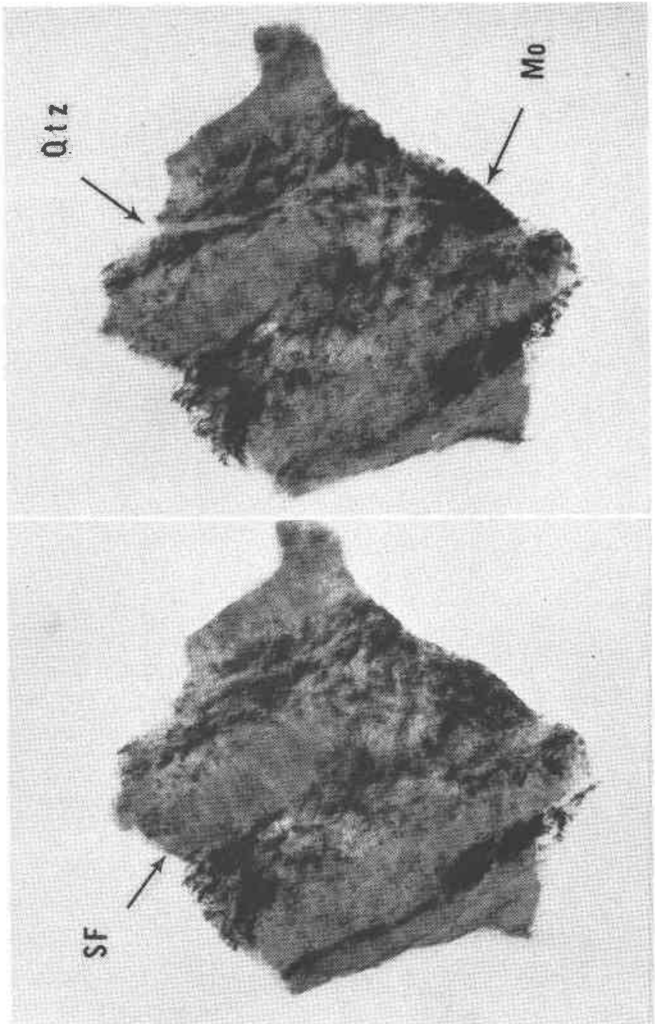


FIG. 1. Native copper in Copper City basalt flow St. Louis exploration, Houghton County, Michigan.

Native copper introduced along very tight fracture system in basalt. Replacement of the basalt has proceeded outward from the fractures. Copper (Cu) mineralization (black tones) is best developed along the east–west and northeast–southwest trending fractures. Northwest–southeast fractures chiefly contain a non-calcite gangue (N.C.) which appears as light gray. Calcite (Ca) has about the same x-ray absorbability as basalt and consequently is poorly defined.

Exposure Factors: Positive prints of stereoradiographs; target film distance 24 inches; specimen 5 mm thick; 65 peak kilovolts; 3 milliamperes; 1 minute and 40 seconds (300 MAS); stereoshift 4 inches.

continuous, but physically separated fragments of the same mineral. A correct paragenetic sequence depends upon establishing whether such fragments are skeletally connected in depth, and hence likely younger than the matrix, or are isolated fragments of an older mineral. Conventional studies of thin and polished sections fail to provide an answer but these relations are readily apparent in a stereoradiograph. The stereo model in Fig. 3 clearly shows that although the galena is the last mineral to form and the fragments are crystallographically continuous, it is non-skeletal. Each grain exists within the specimen as a discrete, isolated unit. The factors that controlled the common orientation are not apparent, but without the stereoradiograph the characteristics of this texture in three-dimensions could not be determined and this most interesting feature would have remained unnoticed.



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One of the most significant advantages of stereoradiography is the ease with which one can determine the true geometry of microstructural control of ore location. In many deposits details of structural control are extremely difficult to observe in hand specimen and are generally obscure or only vaguely expressed on a polished surface. In a stereoradiograph, however, these features generally constitute the most striking elements of the sample. An example of this is shown in Fig. 4 which represents a speci-

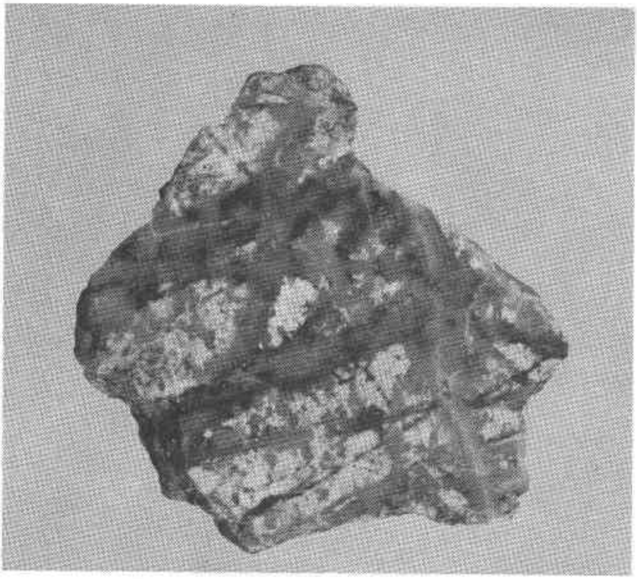


FIG. 2. Molybdenite-bearing silicified granite, Climax, Colorado.

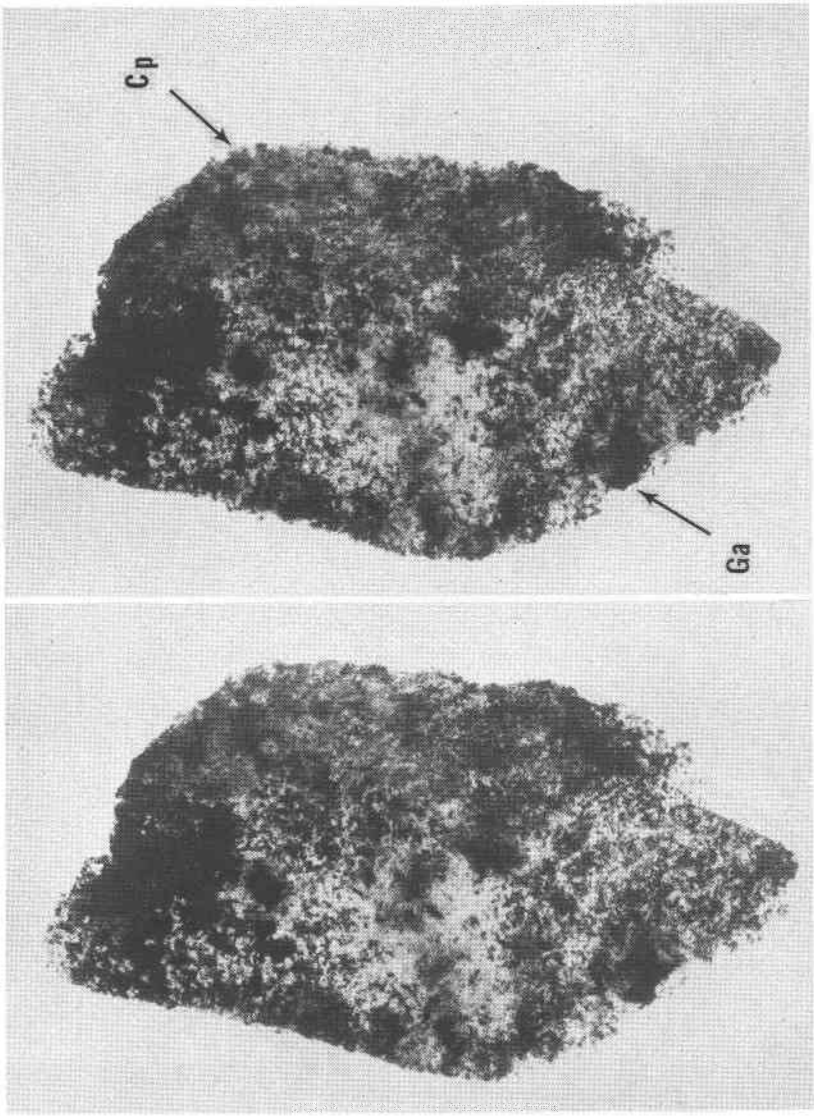
Highly altered granite clearly shows the results of intermittent fracturing and the introduction of both molybdenite-bearing and barren quartz veinlets. The turbid gray masses are highly sericitized feldspar (S-F). The dark diffuse parts are fine-grained molybdenite (Mo); the clear veinlets are quartz. Note that the apparent random orientation of the mineralization in the hand specimen is in sharp contrast to the true northwest–southeast trend of the molybdenite bearing veinlets shown in the stereoradiographs. Barren quartz veinlets absorb essentially the same amount of radiation as the altered feldspar and therefore are not recorded on the radiograph. This greatly accentuates the molybdenite so that its distribution in the sample can be easily studied.

Exposure Factors: Positive prints of stereoradiographs; target-film distance 24 inches; specimen 12 mm thick; 88 peak kilovolts; 3 milliamperes; 60 seconds (180 MAS); stereoshift 4 inches.

men of mineralized, coarsely crystalline diopside from the cotopaxi mine in Colorado. The control of ore deposition is not at all obvious in hand specimen and is completely unrecognizable in polished section. The strong control exerted by the diopside structures over ore deposition, however, clearly shows on the radiograph.

Conclusions

Stereoradiography as used in this article is intended only to provide textural information for samples that have been mineralogically identified by other means. The technique is not considered capable of supplanting any of the standard mineragraphic investigations. On the contrary, it



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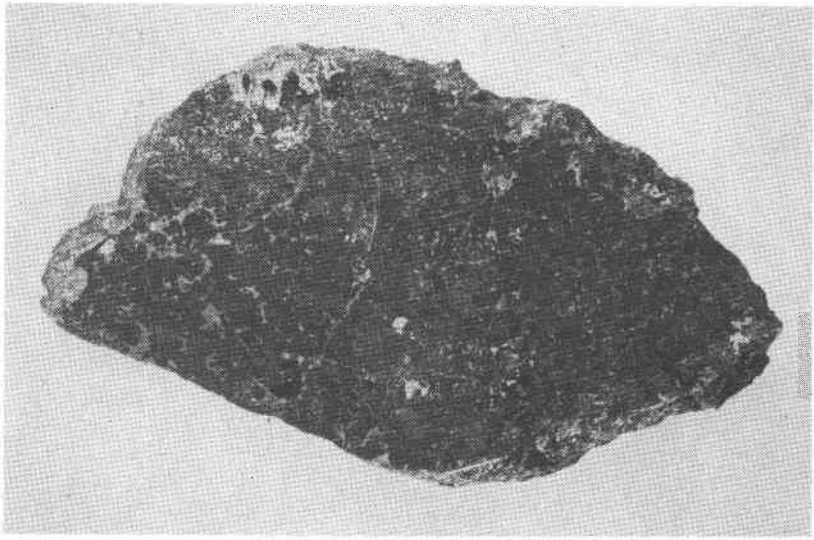


FIG. 3. Mineralized amphibolite, Cotopaxi Mine, Fremont County, Colorado.

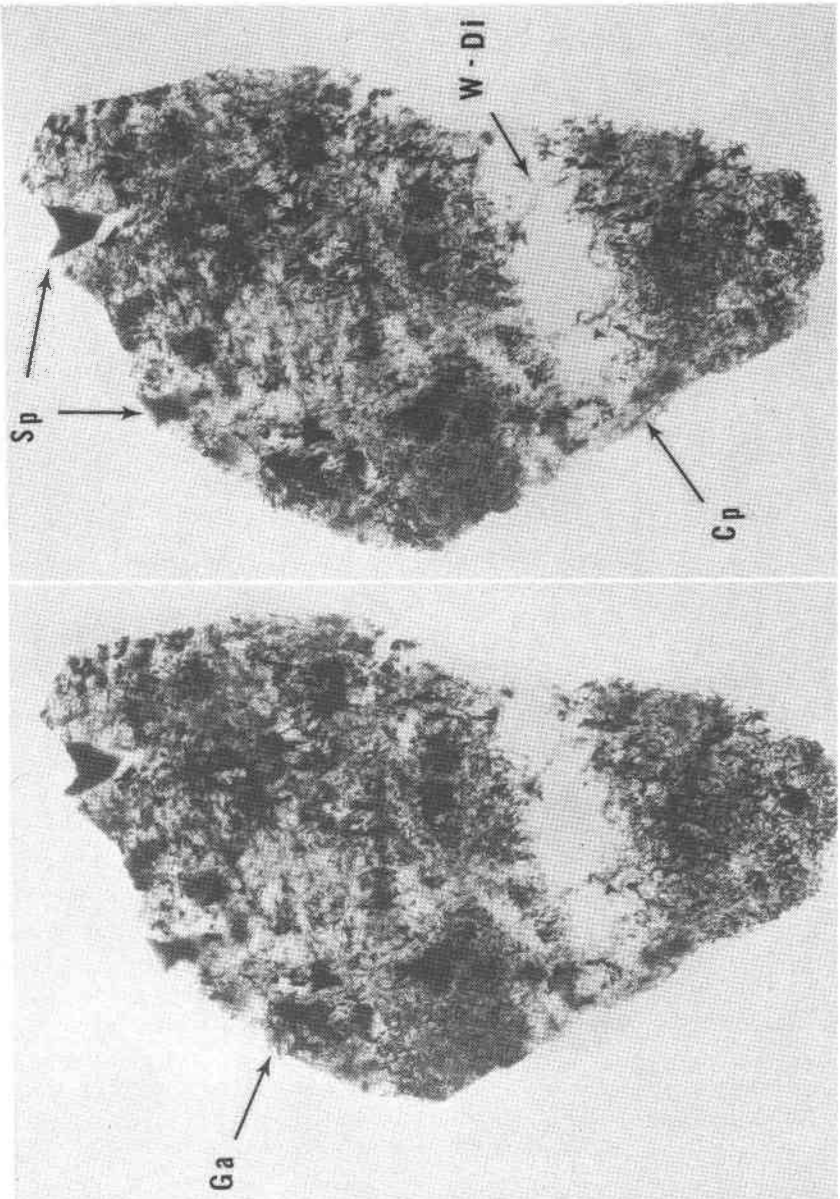
Chalcopyrite (Cp) and galena (Ga) in matrix of serpentinized amphibolite. Galena (shown in black) and the older chalcopyrite ("cloudy" gray) are not spatially associated. Galena formed by replacing amphibolite (shown in white). Over much of the specimen parallel cleavage reflections from galena prove a common crystallographic orientation but the stereoradiograph clearly shows that galena is not skeletal.

Exposure Factors: Positive prints of stereoradiograph; target-film distance 24 inches; specimen 7 mm thick; 70 peak kilovolts; 3 milliamperes; 1 minute 50 seconds (330 MAS); stereoshift 4 inches.

should be used only as a supplement to thin and polish section work. The one great advantage of stereoradiography is that it provides a means whereby the three-dimensional aspect of the texture can be quickly and accurately visualized. Any attempt to identify most minerals by their "tone" or "shade" will soon lead to serious error. Much information concerning textural relations in complex ores, however, may easily be obtained by stereoradiography if there is a significant difference in the amount of radiation absorbed by the various constituents of the sample.

ACKNOWLEDGMENTS

The writers wish to express their appreciation to their colleague, Professor James A. Barnes for a critical discussion of the pertinent principles of stereoscopy. The National Science Foundation through Research Grant NSF-GP-432 generously supported all phases of the investigation.



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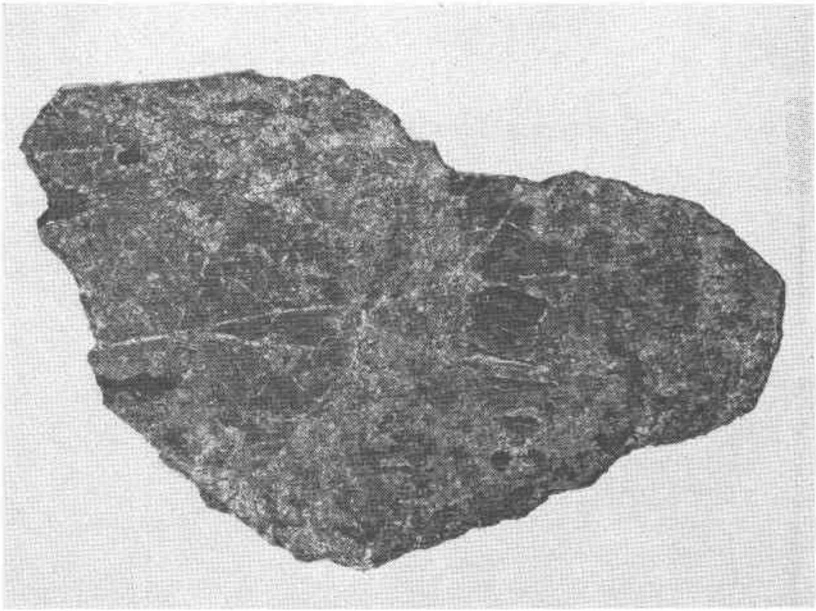

FIG. 4. Mineralized coarsely crystalline diopside, Cotopaxi Mine, Fremont County, Colorado.

Complex skarn ore containing early sphalerite (Sp), chalcopyrite (Cp), and late galena (Ga) in very coarse-grained diopside. The strong control over ore deposition by the diopside structure proves a distinct temporal separation between silicate skarn formation and sulfide mineralization. Sphalerite and chalcopyrite show much less effect from crystallographic control by the diopside structure than does the younger galena. The volume of very weakly mineralized diopside (W-Di) has a different crystallographic orientation than does the mineralized part.

Exposure Factors: Positive prints of stereoradiograph; target-film distance 24 inches; specimen 8 mm thick; 70 peak kilovolts; 3 milliamperes; 1 minute 50 seconds (330 MAS); stereoshift 4 inches.

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