A PETROFABRIC STUDY OF TECTONIC
AND MINING-INDUCED DEFORMATIONS
IN A DEEP MINE
A PETROFABRIC STUDY OF TECTONIC AND MINING-INDUCED DEFORMATIONS IN A DEEP MINE

By Elbridge W. Gresseth and Rolland R. Reid

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A PETROFABRIC STUDY OF TECTONIC AND MINING-INDUCED DEFORMATIONS IN A DEEP MINE

by

Elbridge W. Gresseth¹ and Rolland R. Reid²

ABSTRACT

Rock deformational structures in a deep mine were analyzed by petrofabric techniques to learn (1) the relative magnitude and direction of the principal stresses involved in tectonic deformations prior to mining, (2) the preferred orientation of rock planar discontinuities which define rock anisotropy prior to mining, and (3) the relationship of mining-induced rock failure to inherent rock stresses and inherent rock anisotropy.

Rock fabric elements used for petrofabric analysis consisted of bedding planes, faults, joints, fractures, foliation, sericite plane (001), quartz axis [0001], quartz deformation lamellae, and microfractures. Structures and structural symmetries from different areas within the mine and from different scales of observation were compared to learn the nature of rock anisotropy and the orientation of the principal stresses defined by rock deformations.

Analysis of such fabric as regional and macroscopic faults, b-c joints, quartz [0001], sericite (001), and microfractures, indicate that during the epochs of tectonic deformation, the maximum and minimum principal stresses were horizontally oriented and acted along northwest and northeast axes, respectively. This condition of regional stress appears to have continued during folding and the associated period of faulting. The most recent tectonic deformation represents a rotation of the minimum principal stresses into a vertical position, as shown by the development of a tensile joint system, quartz deformation lamellae, and microfractures. Good interscale correlation and statistical homogeneity of tectonic fabric indicate a stress field homogeneity in this area during tectonic deformation. Rock physical anisotropy is genetically associated with tectonic fabric and consists of preferentially oriented planar discontinuities intersecting along a nearly vertical axis.

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The mining-induced deformations were correlated with the inherent rock anisotropy which either directly controls or greatly affects their development. This phase of rock deformation shows a greater degree of stress field heterogeneity than was the case with tectonic deformations. This is explained as a result of nonconfinement afforded by underground openings and the increase in ground stresses due to mining activity.

INTRODUCTION

Purpose and Scope of Investigation

The more comprehensive our knowledge regarding the nature of the crustal environment in which we mine, the more we are able to analyze and evaluate rock behavior and to apply this knowledge to further our mining capabilities. Rock anisotropy, rock heterogeneities, and strength anisotropy are important factors affecting the response of rock to residual stresses of tectonic origin and to added stresses created through mining activities. As a means to more fully appreciate the significance of rock structure, this investigation treats rock deformational features as a means to statistically define rock physical anisotropy and as clues in solving the tectonic force field which produced these structures.

This report describes an analysis of petrofabric data obtained principally from two deep underground levels of the Star mine, Burke, Idaho. The degree of mining-induced failure, and the textural anisotropy of the mine rock were among reasons for selecting this site for this study. The data were obtained on several scales of observation (regional, macroscopic, mesoscopic, and microscopic) and were analyzed to determine the directions and relative magnitudes of the principal stresses associated with rock deformations. The rock was evaluated according to its fabric, and a hypothesis is offered describing the directions and relative magnitudes of the induced rock stresses caused by mining. An effort has been made to utilize those fabric elements which have been extensively studied and which have been shown through experimental behavior to possess unique orientations to the principal stresses. Deformation representing brittle-type failure has been favored for dynamic analysis because, in view of present knowledge, this type of failure is more diagnostic for the determination of the principal stress directions than is plastic deformation.

The Star Mine

This investigation was conducted on the 6500 and 6700 levels of the Star mine, Burke, Idaho, 6 miles northeast of the town of Wallace. The mine is operated by Hecla Mining Co. The mine, which develops the deepest known continuous lead-zinc ore body in the world, lies within the Coeur d'Alene mining district, world prominent as a silver-lead-zinc producing area.

The Star-Morning vein, except for its great size, is typical of veins in this district. The principal mining method is horizontal slice cut-and-fill stoping. On the lower levels where the walls of openings suffer greater deformations than the backs, the ore body is developed by lateral drifts
driven in a wall approximately 50 feet from and parallel to the vein. Access to the vein is by means of crosscuts driven at about 175-foot intervals. A blind stoping method is used with cribbed raises carried upward in sandfill from the crosscuts. During the stoping operations the ore is removed in slice intervals of 10 feet (one floor), the width of the vein. Ordinarily stoping is begun on the second floor, leaving a 20-foot section of ore in place adjacent to the lateral. This ore is recovered later as mining operation of the next lower level approaches this zone. The stopes are sandfilled as excavation proceeds upward between levels, a vertical distance of 200 feet. The complete mining cycle of stoping between two levels consumes about 2 years. Generally, stoping operations are carried on simultaneously in different stages of completion at two or more adjacent levels. An effort is made during the mining of a particular level to maintain stope elevations about equal.

Geologic Setting

The district topography is one of high relief and rugged terrain with "V" shaped valleys (fig. 1). Mountain ridges which lie at similar elevations testify to the existence, prior to the present erosional cycle, of a comparatively uniform land surface. Mountain crests in the surroundings of Burke and Wallace are approximately 6,000 feet in elevation, while the canyon floors are approximately 3,000 feet in elevation.

Geologic structure in this district is complex. Domains of cylindrical folding are relatively small and are characterized by tightly compressed and deeply folded strata. Subsequent to folding, a series of large-scale faults have truncated and locally obscured the original fold structures. The large rift or shear zone known as the Osburn fault is a major regional structural feature.

The rocks within the area of study are Precambrian (Beltian) in age and are quartzitic in composition, grading from a highly competent light gray, brittle quartzite to a dark greenish gray argillite, with argillaceous quartzite predominating. Interbedded rock units of varying physical characteristics are exposed along lateral walls. Of particular interest, on the levels investigated, is a comparatively thick stratigraphic unit of schistose or slaty argillite exposed along the laterals for a distance of about 150 feet. This rock unit is extremely fissile in texture, incompetent, and characteristically deforms at a higher rate and to a greater degree than the more competent rock types.

Dikes of mafic composition ranging in thickness from 1 to 4 feet intersect the strata at several locations. Other nonpenetrative structures on the scale of this investigation consist of the ore shear zone and the Star fault located adjacent (about 50 feet to the south in the area of the 6500 and 6700 level) and striking subparallel to the vein.

The underground site of this investigation is located about 8,500 feet south of the mine portal at Burke and is approximately 6,000 feet beneath the surface. The ore body lies in a nearly vertical shear zone and strikes about N 70° W with a maximum strike length of 4,000 feet and an average stoping width of about 10 feet.
FIGURE 1. - Coeur d'Alene Mining District, Idaho. This is a photograph of an Army Map Service Corps of Engineers Relief Map.
Previous Investigations

Fieldwork was begun February 1963. Macroscopic-scale mapping of structure on the 6500 and 6700 levels was carried on intermittently through June 1966 in order to record the results of mining-induced failure throughout as much of the mining cycle as possible.

Under the Bureau of Mines sponsorship, other projects concerned with ground support have been conducted at the Star mine and are related in certain aspects to the current investigation. Included in these studies are the following publications by Galen G. Waddell (15), Robert W. Ageton (1), and E. W. Gresseth (4).

Because of its mineral wealth, much has been written concerning the mineralogy and geology of this district. Included in these studies is a report by R. R. Reid (10), and U.S. Geological Survey reports authored by F. L. Ransome and F. C. Calkins (9), J. B. Umpleby and E. L. Jones (14), and S. W. Hobbs and others (5).

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DISCUSSION

Petrofabrics Defined

The term petrofabrics is derived from "Gefügekunde der Gesteine," a work by B. Sander (11), and later work (12) published in 1948 and 1950. Petrofabrics is defined as the study of all the structural and textural elements of a rock ranging from the configuration of the crystal lattice of the individual mineral grains up to and including large-scale features which require field investigation. Accordingly, petrofabrics deals with the recognition, measurement, and illustration of the spatial arrangement of fabric elements, and with the kinematic and dynamic interpretation of these data (3, pp. 1-45).

Petrofabrics, therefore, involves the collection of fabric data, the techniques of illustrating these data, and the interpretive phase or the kinematic\(^4\) and dynamic\(^5\) solution disclosed by fabric characteristics. Dynamic analysis in petrofabrics is of more recent development than the kinematic

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\(^{4}\)Kinematics is the branch of mechanics that deals with motion in the abstract, without reference to the forces or mass.

\(^{5}\)Dynamics is the branch of physics that treats the action of force on bodies in motion or at rest.
approach, as developed by B. Sander. Both the dynamic and kinematic viewpoints are identical in reconstructing the movement patterns involved in rock deformation. The dynamic approach, however, attaches stress field significance to the movement pattern, and thus relies on a knowledge of the mechanics of deformation for its solution. Knowledge gained in recent years regarding the mechanics and processes resulting in rock deformational fabric has been principally responsible for this achievement.

**Symmetry**

Deformations recorded in the rocks as preferred orientation of fabric disclose patterns of symmetry. It is a basic tenet in petrofabric analysis that the symmetry of rock fabric reflects the symmetry of the deforming movement. This assumption originally applied to petrofabrics by Sander has persisted as a valid hypothesis. Turner states that the symmetry scale stands as a well-tested postulate supported by an imposing body of experimental evidence drawn from such diverse fields as hydrodynamics, sedimentation, metallurgy, and ceramics. Paterson and Weiss (6) discuss the topic of symmetry as follows:

> By a symmetry argument is meant a deduction concerning the symmetry of an unknown quantity from a knowledge of the symmetry of interrelated quantities...

Such considerations of symmetry permit certain minimum deductions in the study of phenomena for which insufficient information is available for a complete analysis. For this reason, symmetry arguments have been invoked in geology where quantitative information on past physical influences is frequently unavailable and quantitative measurements on the physical properties of the rocks in question have not been made. On the other hand, in physics, where quantitative information on all aspects of a phenomenon can be obtained in the laboratory, symmetry relations are not usually discussed explicitly, although they are implicit in a more complete quantitative description of the phenomenon.

An analogy may be drawn between symmetry arguments and dimensional analysis. Thus, in any equation relating the physical quantities concerned in a given phenomenon, the dimensions must be the same on both sides of the equation and use of this fact has frequently been made when more knowledge of the quantities is lacking. Similarly, there are general rules concerning the symmetry of such quantities....Sander's symmetry rule in structural analysis can therefore be viewed as an application of such symmetry considerations to geological phenomena in order to enable some conclusions to be drawn even though full details are not known.

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A rigorous treatment involving symmetry concepts is not attempted in this investigation, but symmetry considerations are implicit in the orientation of the tectonic axes and principal stress directions used in fabric diagrams for both tectonic and mining-induced rock deformations.

**Graphic Methods**

To enable petrofabric data to be illustrated in a manner that discloses the true relations of planes and lines, the equal-area projection\(^7\) method is customarily used. This method satisfies an important requirement of petrofabric analysis in that a unit area on the projection must correspond to an equal unit area on the reference sphere. That is, if statistical inferences concerning the preferred orientation of fabric are to be valid, the projection must be undistorted and represent the spatial relationships of planes and lines of the reference sphere. For this reason the stereographic projection, commonly used for plotting mineralogical and structural data, is not suitable for petrofabric analysis because of its inherent distortions of projected areas.

The surface of the meridional plane is used for projection of petrofabric data and is termed the equal-area net. Fabric data by convention are projected from the lower hemisphere. The equal-area net and its uses are discussed fully by Turner and Weiss (13, pp. 46-75).

The three-dimensional representation of petrofabric data plotted from the equal-area net is called a petrofabric diagram. From these diagrams information relating to preferred orientation, symmetry relationships, statistical inferences, fabric densities, etc., is obtained.

Various types of petrofabric diagrams are used depending upon the purpose of the illustration. This study is principally concerned with the analysis of planar (two-dimensional) fabric. An exception is the diagrams showing the preferred orientations of the quartz [0001],\(^8\) a linear (involving a single dimension) fabric. Since in most cases it is impractical to show the traces of the planar fabric elements on the diagrams, their poles were plotted and used to construct contour diagrams. The contours represent the percentage concentration of poles within a 1-percent unit area of the projection surface. Areas of high concentration of poles are referred to as maxima. These areas represent fabric homogeneity, a high degree statistically of a fabric's preferred orientation.

Composite diagrams are petrofabric diagrams which show fabric data obtained from more than one plane of the rock sample. For example, micro-petrofabric diagrams may contain fabric data obtained from two or three mutually perpendicular sections which were rotated graphically into a single plane,\(^7\)The equal-area projection is also known as the Lambert projection after its inventor, and the Schmidt projection after W. Schmidt who first used it in structural geology.\(^8\) (0001) is the basal pinacoid and axis, [0001] is the crystallographic axis that is perpendicular to (0001) plane.
illustrated by a single petrofabric diagram. Synoptic diagrams are petrofabric diagrams containing data from more than one sample and are, therefore, summary in nature.

Figure 2 is an illustration of the method used for plotting points for contouring. A planar fabric element in figure 2 is represented by plane P, and its trace on the lower hemisphere is shown by the arc A - A'. The point P' is the pole to plane P. From the position of P', or as in the case of numerous points, the angular and density relationships of the planar fabric may be statistically analyzed.

FIGURE 2. - Petrofabric Diagram.
Scales of Investigation

To gain an appreciation of intrascale penetration of fabric, rock structure was investigated on three scales, defined as follows:

Macroscopic scale--geologic structure exposed along underground openings, including faults, fractures, jointing, bedding, and folds. Standard field mapping techniques were followed in the mapping of these structures.

Mesoscopic scale--planar discontinuities observable on hand samples and sawed rock specimens. This scale of observation is particularly valuable in recognizing structure, such as minor fracturing, that may be overlooked on the macroscopic scale. In addition, an analysis of the structure on the mesoscopic scale may help to identify some structures observed on the microscopic scale. Macroscopic fabric such as bedding, jointing, etc., are included as mesoscopic fabric when they are observable on the mesoscopic scale.

Microscopic scale--This scale includes the microfabric elements observed from oriented petrographic thin sections analyzed by means of the universal stage mounted on the petrographic microscope. The fabric elements studied, on this scale, include quartz [0001], sericite (001), quartz deformation lamellae, and microfractures.

In addition to these three scales, the attitude of regional faults within a surface area 6 miles in diameter above the underground mine workings were plotted on equal-area nets (14).

Unbiased sampling of structure is necessary if valid statistical analysis of preferred orientation of fabric is to be achieved. Ordinarily there is a tendency for preferential mapping of those planes which intersect the surface of the exposure at a high angle, with a tendency to ignore the planar discontinuities that parallel or lie at a low angle to the exposure surface. This prejudice is considerably reduced in mapping surfaces of underground openings, since such openings offer a three-dimensional view of the rock mass which they penetrate. However, underground mining-induced failure planes may preferentially develop parallel or subparallel to an opening surface and thus sometimes tend to be "undersampled."

Upon completion of macroscopic field mapping, the data obtained were plotted on equal-area nets for further analysis. In order to gather data pertaining to the development of mining-induced deformation, macroscopic mapping was repeated at intervals during the mining process.

The macroscopic fabric diagrams were oriented to a geographic coordinate system by means of the Brunton compass. Diagrams oriented according to the geographic coordinate system were rotated into coincidence with the mesoscopic and microscopic tectonic coordinate system where intrascale comparisons of fabric were made during the study. However, the rotations were of no significance to the analysis and therefore were not presented in this report.
**Sampling Methods**

Rock samples, to be used in obtaining mesoscopic fabric data, were collected at intervals along the walls and back of the mine openings, and in the laboratory were sectioned along three orthogonally oriented planes. Mesoscopic fabric data consist of all observable planar discontinuities including fractures, foliation, jointing, bedding, and veinlets.

A coordinate system based on fabric symmetry was assigned to the mesoscopic and microscopic samples. This is called the tectonic axis system and consists of three mutually perpendicular axes, $a$, $b$, and $c$. Axis $b$ is oriented nearly vertically, parallel to the plane of the bedding; axis $a$ is oriented approximately horizontally, parallel to the plane of bedding; axis $c$ is oriented perpendicular to the other two axes. In this study the $a\_c$ plane perpendicular to $b$ (hereafter referred to as $b$ section) is illustrated and used for fabric analysis (this is the surface of highest fabric symmetry) and unless otherwise specified is composite in nature containing fabric data rotated from the $a$ and $c$ sections.

Rock thin sections, to supply microscopic fabric data, were prepared normal to each of the three tectonic axes. The rock in the area of this study is predominantly quartzitic and consequently the microfabric data selected for analysis are associated with this rock type. The fabric elements for which petrofabric diagrams were prepared are as follows: quartz [0001] axis, quartz deformation lamellae, sericite (001), and microfractures. These are particularly significant elements since petrofabric literature such as (13) describes numerous laboratory studies relating the development and preferred orientation of these fabric elements to a known externally induced stress field. Other microscopic grain characteristics such as the occurrence of undulatory extinction of quartz grains, size and shape of quartz grains, degree of cataclasism, and constituent minerals were also studied.

Micropetrofabric analysis was performed by means of a petrographic microscope having a five-axis universal stage attachment. Because of the design of the universal stage, fabric elements inclined about 40° or less from the plane of the thin section cannot be examined. This limitation was overcome by analyzing two or three mutually perpendicular oriented thin sections for each sample. The universal stage is a required tool for obtaining micropetrofabric data. For information regarding its operations, one is referred to the work by R. C. Emmons (2).

The 6500 and 6700 levels were divided on the basis of macroscopic fabric homogeneity into fabric domains. The term domain is used here to specify any finite three-dimensional portion of a rock body that is statistically homogeneous on the scale of the domain (12, p. 20). Even though the fabric domain boundaries of the mesoscopic and microscopic scales in many cases appear rather arbitrary, they were determined according to the macroscopic domains in which they lie. Synoptic diagrams are used for analysis where domain boundaries are of little or no significance.
This study is mainly concerned with the preferred orientation and the rock deforming mechanisms involved in the development of planar discontinuities and not with the relative abundance or density of fabric elements. The microscopic, mesoscopic, and regional scale diagrams, because of the data sampling methods used, reflect the density of the fabric in addition to showing their preferred orientations.

It was not conceivable to map all the macroscopic scale fabric within each domain. The macrofabric diagrams therefore do not necessarily reflect the relative densities of these fabric, but are intended to show the preferred orientation of planar discontinuity systems occurring in each domain.

STRUCTURAL GEOMETRY

This section describes the geometry of rock planar discontinuities (fabric elements) resulting from tectonic deformations.

The following diagrams show the geometric relationships of fabric elements so that their preferred orientation may be recognized. The regional, macroscopic, mesoscopic, and microscopic scales are compared so that intra-scale penetration of fabric elements may be learned. In addition, fabric data are treated according to domains to identify possible structural heterogeneities within a larger area of homogeneous strain.

Macroscopic Fabric

The style of folding in the mine area is well shown by a geologic section on the 2000 level, the only level with enough underground workings to expose the axial plane. A pie diagram (diagram showing characteristics of folding (13, p. 83)) for this level shows a fold with its axis oriented N 22° W - 76° SE in a steep axial plane which strikes about N 65° W (fig. 3). The 6500 and 6700 levels of the Star mine are located in the north limb of this fold, which is known from the mine geologic maps to be an anticline, the beds of which dip steeply to the northeast. Other major structural features within the immediate area of the 6500 and 6700 levels are the ore vein which strikes about N 70° W with a nearly vertical dip and the Star fault which is nearly parallel and located approximately 50 feet south of the vein.

The areas in which this study was mostly concentrated are shown in figure 4. On the basis of fabric homogeneity the 6500 level was divided into 11 domains, 3 in the lateral and 8 in the crosscuts. The 6700 level was divided into 20 domains, 4 in the lateral and 16 in the crosscuts. Fabric homogeneity is in many cases preserved across domain boundaries, and therefore could be combined for fabric analysis purposes.

Figure 5 illustrates the preferred orientation and symmetry relationships of macroscopic fabric (bedding, jointing, faults) for domains 1 through 3 (6500 lateral).

The fabric diagrams (fig. 5) disclose several well-defined structural relations. Faults are predominantly bedding plane faults. An exception to
FIGURE 3. Pi Diagram to Illustrate the Character of the Large Fold in the Vicinity of the Star Mine. Contours show poles to bedding. For additional definition of the fold, the statistically defined limbs of the fold, its axis, and its axial plane are shown in the diagram. It may be noted that this fold plunges very steeply; its form is comparable to that of the bow of a ship.
this general penetrative pattern is shown in the fault diagrams, domain 2, which contains a secondary system of faults shown as maxima located in the NE and NW quadrants. Although these fault systems which strike and dip N 70° W - 45° SSW and N 41° E - 80° SE do not appear to be penetrative with respect to domains 1 and 3, they do appear to be associated with structures observed in the microscopic and regional scales.

The joint diagrams (fig. 5) show the development of two major joint systems. Most clearly defined in domains 1 and 2 are maxima located near the N-S poles and near the center of the diagrams. Because of their orientation to the fabric axes, these are termed the b-c and a-c joint systems, respectively, and have a tendency coupled with orientation of bedding to form orthogonal planar discontinuities on the macroscopic scale.

Net diagrams for crosscut domains on the 6500 level are illustrated in figure 6 and show the geometrical relations of macroscopic scale bedding, joint, and fault structures.

Some general geometric relations are apparent. Bedding-plane fault structures predominate as can be seen by similarity in orientation of faulting and bedding. In addition to the bedding-plane faults, a complementary high-angle fault system intersects the bedding-plane fault system at angles of 25° to 45°, with most faults intersecting the bedding-plane faults at about 33°.

The systems of jointing (fig. 6) have the same characteristics of orientation and development as those shown in figure 5. That is, they comprise two distinct joint systems oriented at high angles to each other and to the bedding (see joint orientation, domains 4, 6, and 9 in fig. 6). Heterogeneities in this basic pattern of joint orientation are due to local deformations in proximity to the vein shear zone.

The planar discontinuities (faults and joints), with but few exceptions, show preferred orientations and their development is controlled, in the area studied, by the orientation of the bedding. The bedding and bedding-plane faults form one penetrative system of macroscopic planar discontinuities. Normal to this system of discontinuity are the well-defined a-c and b-c joint systems along with the bedding and bedding-plane faults, develop planar discontinuities. In addition to the discontinuities described above is a locally prominent oblique fault system.

Figure 7 is a compilation of macroscopic fabric diagrams for bedding, faulting, and jointing in domains located on the 6700 level. The attitude of bedding is homogeneous for all four domains, with a tendency for the beds to strike more northerly in domain 12 than in the other domains. The homogeneity of the joint systems is shown by the preferred orientation of maxima in domains 12, 13, and 14. These domains show well-developed a-c and b-c joint systems oriented nearly perpendicular to the bedding plane as in the case of most of the domains on the 6500 level. In the joint diagram for domain 15 the penetrative characteristics of the a-c and b-c joint systems are preserved, although the b-c system is less developed than in the other domains. The strongly developed maxima in the NE quadrant of the fabric diagram (domain 15) show a system of jointing which strike N 70° W and dip NNE at about 70°. The orientation of this joint system corresponds well with the orientation of fault maxima in both domains 14 and 15 (fig. 7).

Homogeneity of fault structure is maintained between domains 12 and 13, and to a lesser degree between domains 14 and 15. As on the 6500 level, bedding-plane faults persist in these domains as a prominent fault pattern. From fault diagrams, domains 12 and 13, a development of a conjugate fault system is apparent. The fault diagram for domain 15 shows a pattern of fault development that corresponds to the regional patterns of N-S, NW-SE, and WWW-ESE faulting.

The net diagrams for domains on the 6700 level crosscuts are illustrated in figure 8. The bedding within these domains is nearly vertical to vertical, and strike generally in a northwesterly direction. In the domain south of the ore vein, the beds tend to strike somewhat more northerly than in the domain north of the ore vein.

The a-c and b-c joint systems are less well defined in the domains shown in figure 8 than in the domains on the 6500 level and the 6700 lateral. Domains 18, 19, 20, 21, 24, 28, and 29 show a-c and b-c joint systems oriented nearly perpendicular to each other and lying oblique and normal to the bedding. Other domains show partial development of these joint systems. The fabric diagrams for domains 18 and 19 represent an example in this area of
FIGURE 7. - Macroscopic Fabric—6700 Lateral.

LEGEND
□ Beds  ○ Joints  △ Faults  ○ Domain
displacement of adjacent walls of the ore vein by faulting. The original angular relation between jointing and bedding has been preserved although rotated clockwise about 50° relative to the orientation of jointing and bedding north of the vein in domain 18.

The diagrams of figure 8 show the penetrative nature of the bedding-plane faults. They are strongly developed in most domains (20 through 31) and poorly developed or obscure in domains 16 through 19. Local nonpenetrative fault orientations (as in the case of faults in the diagram for domain 16) are due to local deformation in areas adjacent to the ore shear zone and the Star fault.

The faults in domain 18 contain maxima representing rock failure caused by mining. These are more correctly defined as fractures instead of faults and are shown as three maxima of moderate to high dips located in the northwest and northeast quadrants of the diagram.

**Regional Faults**

In order to compare the preferred orientation of large-scale fault structure with the structure of other scales of investigations, the regional faulting within a 6-mile diameter surface area above the underground workings was plotted from available geologic maps and is shown on a fabric diagram (fig. 9).

From figure 9 the predominant pattern consists of faults striking about N 70° W with fairly steep NE dips. The second most important system strikes nearly north-south with nearly vertical dips. The third system strikes northwest and dips steeply northeast and southwest. These patterns of regional faulting are reflected in some of the macroscopic domains of faulting.

**Mesoscopic Fabric**

Fabric diagrams for the mesoscopic scale were prepared to show: (1) concordant and discordant relationships of the mesoscopic fabric compared with the fabric of other scales, (2) dynamics of deformation based upon mesoscopic symmetries of fabric, and (3) the characteristic mesoscopic rock anisotropy.

Oriented mesoscopic rock samples were collected from each domain on the 6500 and 6700 level crosscuts and laterals, and their planar fabric data were plotted normal to the b tectonic axis. The fabric data plotted include fractures, joints, bedding planes, foliation, veinlets, and lenticular inclusions (undifferentiated). The macroscopic diagrams for the 6500 lateral (fig. 10) include bedding, jointing, and faulting, and have been oriented with respect to tectonic axes and compared with the mesoscopic fabric according to domains.

The symmetries and preferred orientations of fabric elements disclosed by macroscopic diagrams (figs. 5-8) are all reflected in mesoscopic fabric diagrams. The mesoscopic diagrams show penetration of well-defined a-c and b-c joint systems on the mesoscopic scale. In addition, well-developed planar discontinuities on the mesoscopic scale correspond in orientation to bedding-plane faulting on the macroscopic scale. Some partial correlation of fabric
FIGURE 9. - Regional Fault Diagram.

LEGEND

1-2%  2-4%  4-7%  > 7%
Percent per 1% of Area
between the mesoscopic and regional scales (fig. 9) is indicated in all three domains. The orientation of mesoscopic fabric elements, with the exception of the a-c joint system and similarly oriented fabric, consist of discontinuities which tend to intersect along a line parallel to tectonic b. In general, this symmetry and preferred orientation of mesoscopic fabric elements is similar to the macroscopic fabric described previously. These are, for the most part, inherited planar fabric elements, the results of tectonic deformation, and they define the rock anisotropy. Figure 11 illustrates six examples of mesoscopic samples used for fabric analysis.

Figure 12 illustrates fabric diagrams for two crosscut domains on the 6500 level. Here, as in previous examples, the mesoscopic diagrams reflect the important planar discontinuities of the macroscopic scale, that is, the a-c and b-c joint systems, and the bedding-plane faults.
FIGURE 11. - Mesoscopic Rock Samples.
FIGURE 11. - Mesoscopic Rock Samples—Continued
FIGURE 12. Comparative Diagrams of Macroscopic and Mesoscopic Fabric for 6500 Crosscuts.

FIGURE 13. Comparative Diagrams of Macroscopic and Mesoscopic Fabric for 6700 Lateral.

The diagrams illustrated in figure 13 compare the mesoscopic and macroscopic fabric domains on the 6700 lateral. It may be seen in a comparison of these diagrams that, as is the case of the domains on the 6500 level, the major discontinuity systems and the a-c and b-c joint systems are represented. Structure corresponding in orientation to bedding-plane faulting is also
revealed. In addition, the mesoscopic diagrams show a pattern of planar discontinuities that tend to intersect the a-b planar discontinuity (bedding-plane faults and bedding) at acute angles. These structures are shown as maxima located along the perimeter of the diagram in proximity to the E-W poles, and correspond to the conjugate fault system discussed earlier under macroscopic fabric. In mesoscopic fabric domains 13 and 14, the symmetry of the diagram is reduced by the occurrence of structures represented by minor maxima located in a zone between the perimeter and the center of the diagrams. These maxima represent planar discontinuities oriented nonsymmetrically to the tectonic anisotropy and are believed to be mining-induced fractures superimposed over the earlier rock fabric.

Figure 14 compares the preferred orientation and symmetries of the mesoscopic scale with those of the macroscopic fabric elements in the crosscut domain of the 6700 level. These can be compared with the regional trends by referring to figure 9. Of general interest is the tendency for fabric elements in both the macroscopic and mesoscopic scales to be more randomly oriented than in the domains discussed previously. Discernible within these patterns of maxima is the tendency for the prominent macroscopic planar discontinuities to be repeated in the mesoscopic fabric domains. For examples, the a-c joint system is fairly well represented and the a-b discontinuity (bedding-plane faulting) is well developed in both mesoscopic and macroscopic diagrams. The b-c discontinuity system, well developed in previous domains,

FIGURE 14. - Comparative Diagrams of Macroscopic and Mesoscopic Fabric for 6700 Crosscuts.
appears to be absent or weakly developed in the domains of figure 14. The diminished importance of the b-c discontinuity system in these domains may be partially explained by a description of their geologic setting. The domains (fig. 14) are located adjacent to the ore vein (shear zone) and the Star fault (located approximately 50 feet south of the ore vein). Because of this location, these domains are located within an area of locally intensive deformation associated with faulting. A stress couple would likely develop in this area during movement along the planar discontinuities discussed above and would tend to rotate the principal stresses around an imaginary vertical axis. This would result in a displacement of maxima along the perimeter of the fabric diagram, as is the case in most of the domains of figure 14.

Prominent in the patterns of maxima in mesoscopic and macroscopic diagram (fig. 14) are those which represent planar discontinuities with moderate dips (30° to 60°) asymmetrically oriented to established tectonic axes. This is an area of high stress (mining induced) and because of their nonsymmetrical relationship to tectonic anisotropy probably represent mining-induced rock failure. This type of deformation will be discussed more fully in the "Mining-Induced Rock Failure" section later in this report.

Microscopic Fabric

Petrography

The rocks in the mine area are principally sericite quartzites produced by the recrystallization of quartzose siltite with minor clay admixture and a little carbonate material.

Quartz grains, making up the bulk of the rock, are largely subequant and approximately 0.1 mm in diameter. They have moderately sutured boundaries, and marked undulatory extinction.

Quartz grains are surrounded by an intergranular mesh of sericite flakes and tiny quartz grains. Sericite flakes are 0.01-0.02 mm in diameter where equant and up to 0.05 mm long in elongate flakes. Meshwork quartz grains are in the diameter range 0.005-0.02 mm. Some show undulatory extinction and some are strain free. All quartz grains appear to have been recrystallized. Sericite preferred orientation is weak to strong, as viewed in thin sections of different orientations. Photomicrographs in figure 15 illustrate the appearance of quartz grain boundaries and undulatory extinction.

Accessory minerals observed include the following: a carbonate mineral, leucoxene, pyrite, zircon, tourmaline, and rutile. Tourmaline occurs in subequant grains about 0.1 mm in diameter. Leucoxene occurs as tiny scattered flakes about 0.02 mm in diameter. Pyrite and rutile occur as rare, tiny grains about 0.1 mm in diameter. Zircon occurs in rounded to subrounded grains about 0.02 mm in diameter. The carbonate mineral occurs in tiny, scattered rhombs under 0.01 mm in diameter or, less commonly, in granular aggregates 1-2 mm in diameter. Total accessory minerals are visually estimated to make up less than 1 percent of the rock.
FIGURE 15. - Microscopic Structure.  

A, Photomicrograph of quartz grain boundaries.  
B, Photomicrograph of quartz undulatory extinction.
FIGURE 16. - Micropetrofabric Diagrams.
FIGURE 16. - Micropetrofabric Diagrams.—Continued
Micropetrofabrics

The purpose of the micropetrofabric examinations was to establish concordant and discordant relationships between the microfabrics and the orientation of fabric of the macroscopic and mesoscopic scales, and therefore supply information concerning the penetration characteristics of rock anisotropism. In addition, micropetrofabrics supplied information concerning the chronological sequence of deformational events.

The microfabric elements analyzed and illustrated in figure 16 are quartz c axes [0001], quartz deformation lamellae, microfractures (filled and unfilled), and sericite (001).

Quartz [0001]

The preferred orientation of quartz [0001] axes in figure 16 shows a rather weak orientation pattern. However, figure 17, a synoptic diagram combining the data from all domains of figure 16 shows that quartz [0001] axes tend to develop a small circle girdle about each tectonic axis. This preferred orientation for quartz [0001] is suggested in samples 11, 32, 35, and 37, and almost entirely obscured in samples 31 and 45. It was observed during thin section analysis that the appearance of quartz grains in different samples varied from highly strained (possessing undulatory extinction) with cataclastic grain boundaries to comparatively large unstrained equidimensional grains with smooth noncataclastic grain boundary contacts.

Sericite (001)

The sericite (001) fabric (fig. 16) discloses well-developed preferred orientation. This orientation consists of a single girdle concentration of (001) symmetrically arranged about tectonic b. This is consistent with the macroscopic folds in this area. Figure 18 shows the homogeneity of sericite fabric as observed on the tectonic b section.

Microfractures

Heterogeneity of fabric exists between different domains shown in figure 16, although the microfractures in each domain correlated in some respects to fabric of a different scale. For example, the microfracture diagram, sample 31, shows a tendency for microfractures to intersect parallel to tectonic a. Sample 32 shows good orthorhombic symmetry and correlates with the macroscopic and mesoscopic fabric illustrated in figures 10 and 13 excluding the a-c planar discontinuity (a-c joint system). Microfracture diagrams, samples 35 and 36, show homogeneity of fabric and are characterized by fractures oriented parallel to and forming a large circle girdle about tectonic b. Maxima within this girdle correspond to orientation of the a-b and b-c planar discontinuities of the macroscopic and mesoscopic diagrams (figs. 10 and 13).

During microscopic analysis of thin sections, fractures varying considerably in their appearance were observed. Some fractures extend through many grains with rough, uneven fracture surfaces containing inclusions of opaque
minerals and sericite flakes (mineral filled). Others confined to a single grain are curvilinear to planar with smooth fracture surfaces containing few or no visible inclusions and appear as "hairline fractures" (unfilled). Photomicrographs (fig. 19) show intergranular microfractures occurring on the a-c section. Figure 19, parts A-B, represent the "mineral filled" variety and figure 19, parts C-D, represent the "unfilled" variety. In the case of
samples 35 and 36 (fig. 16), these fractures were differentiated into filled and unfilled varieties of fractures and plotted on separate diagrams and compared to determine any significant factors affecting their origins. The diagrams for unfilled microfractures, samples 35 and 36, disclose the development of fractures parallel to the macroscopic and mesoscopic a-c joint system, and the absence of this system of microfracture in the filled variety. Microfracturing for samples 10, 14, and 20 (not illustrated) show good homogeneity and partial correlation with microfracturing in other domains of figure 16. The discordance of microfracturing between and within domains (fig. 16) indicates local heterogeneities in stress fields on a microscopic scale. Examples of microfracturing represent specimens of mine wall rock and in some cases represent rock failure due to mining-induced stresses along favorably oriented planar discontinuities. A later section of this report will discuss the dynamics involved in the development of the microfabrics described above.
Deformation Lamellae

Discordant relationships of the deformation lamellae are disclosed by comparison of the diagrams in figure 16. The nonhomogeneity of this fabric is presumed to be due to local deformational heterogeneities. Sample 31 shows a general tendency for the deformational lamellae to partially reflect microfracture development and the macroscopic fabric disclosed in domain 3 (fig. 10). The deformation lamellae, sample 35 (fig. 16), show maxima which represent planes striking east-west, east-northeast with high-angle dips, and lamellae planes striking northwest and dihing gently to the northeast (subparallel to the a-c joint system). The steeply dipping series of lamellae appear to form a weakly developed conjugate system that corresponds in orientation to macroscopic b-c joint system (figs. 10 and 13) and to the microfracturing of the same domain.

The lamellae, sample 36 (fig. 16), appear to form two conjugate lamellae systems. One system is represented by maxima located in the NW, SW, NE, and SE quadrants along the perimeter of the net. The other system is shown by two maxima on tectonic c located between the center and the perimeter of the diagram. The first system corresponds to macroscopic planar fractures and to microfracturing. The second system consists of a system of two intersecting fracture planes that nearly parallel the a-c macroscopic joint system. The pairs of lamellae maxima which lie along the a axis subparallel to the a-c joints are repeated again in samples 37, 15, and 18, and partially in samples 45, 21, and 32, and therefore represent an important fabric homogeneity. The lamellae maxima located along the perimeter of the diagrams (planes intersecting along tectonic b) have a tendency to coincide or lie at a low angle to the b-c joints. Shown in figure 20 are examples of deformation lamellae development.

Summary of Structural Geometry

Through the analysis of fabric data, conclusions may be drawn regarding the nature of the anisotropy of the rocks which comprise the 6500 and 6700 levels of the Star mine. Bedding-plane anisotropy appears to have affected, to a large extent, the orientation of subsequent tectonic discontinuities. This is shown by the tendency of the fabric of all scales investigated to develop at preferred orientations to the bedding planes. On the macroscopic scale this is shown by the mutual relationships of fabric orientations between domains on the 6500 and 6700 levels (figs. 5-8).

Certain dominant systems of planar discontinuities are reflected not only between domains but between scales. Systems of planar discontinuities which dominate the macroscopic structure in this area of the Star mine are summarized in figure 21, a synoptic diagram, combining the macroscopic fabric data for the various domains of figures 10, 12, 13, and 14. It can be seen from figure 21 that the major discontinuities of the macroscopic scale, bedding, bedding-plane faults, and joints show a tendency towards orthorhombic symmetry. The effect of these fabric elements in terms of rock anisotropy is to weaken the rock mass by an orthogonal pattern of planes of discontinuity. Macroscopic faults in many of the domains (figs. 10, 12, 13, and 14) show in addition to
FIGURE 19. - Photomicrographs of Microfractures. A and B, "filled" variety of microfractures (arrows).
FIGURE 19. - Photomicrographs of Microfractures. C and D, "unfilled" variety of microfractures (arrows).—Continued
FIGURE 20. - Photomicrographs of Quartz Deformation Lamellae.
the fabric described above, a slightly less developed system which is represented by maxima located in the NE quadrants of the diagrams. This orientation of this faulting system correlates well with the orientation of the regional faulting of this area. A synoptic diagram, prepared from the fault diagrams of figures 10, 12, 13, and 14 and containing the maxima of this
secondary fault system, is shown in figure 22. For comparison regional faults are also shown in this diagram.

The statistically prominent fabric maxima from mesoscopic diagrams (figs. 10, 12, 13, and 14) are summarized in a synoptic diagram (fig. 23). This diagram shows the penetrative characteristic of the macrofabric structures in the mesoscopic scale, and are labeled as follows: A is equivalent to the macroscopic bedding and bedding-plane faults; B is equivalent to the macroscopic a-c joint system; C corresponds to the macroscopic b-c joint system; and D correlates to the regional faulting.

The microfabric diagrams (fig. 16) show the preferred orientation of planar and linear fabric data which represent at least two deforming mechanisms. One of these mechanisms, a syntectonic or plastic type of deformation, is represented by the quartz [0001] and the (001) sericite orientations. These deformations principally are associated with the dynamics of folding. Their main use in this study is to indicate, by their symmetries, the dynamics of deformation involved in the folding of the strata. Also, their symmetries compared with other fabric elements indicate chronological sequences of deformation. More closely associated with the macroscale and mesoscale fabric of this study are the quartz deformation lamellae and the microfracture deformations. These are of more recent origin and represent (brittle) failure. Figure 24 illustrates synoptic diagrams summarizing the quartz deformation
FIGURE 23. - Synoptic Diagram of Mesoscopic Fabric.

lamellae and microfracture fabric data from individual domains. The preferred orientation of the quartz deformation lamellae fabric (fig. 24, part A) show the following relationships: (1) The lamellae labeled A show a tendency to develop subparallel to the macroscopic, mesoscopic, and microscopic a-c planar discontinuity (figs. 21, 23, and 24); and (2) lamellae labeled B (fig. 24, part A) tend to develop subparallel and parallel to the macroscopic,
mesoscopic b-c planar discontinuity (figs. 21 and 23), and to the b-c microfracture labeled C in figure 24, part B.

Microfractures (fig. 24, part B) show good correlation to macroscopic and mesoscopic structure. The microfractures labeled A correlate with the macroscopic and mesoscopic a-b planar discontinuities (bedding and bedding-plane faulting) (figs. 21 and 23). The microfractures labeled B (fig. 24) correspond to the macroscopic and mesoscopic a-c planar discontinuity, and those fractures labeled C correspond to the b-c planar discontinuities in figures 21 and 23.

DYNAMIC AND CHRONOLOGICAL INTERPRETATION OF ROCK FABRIC

In order to gain knowledge regarding the nature of the inherent tectonic stresses and their possible significance in mining-induced rock failure, this section deals with the relative magnitudes and directions of the principal stresses, and the chronological sequences of rock deformation events. These analyses treat data drawn from the previous section on descriptive geometry together with information concerning the symmetrical characteristics and the mechanism of failure responsible for fabric development. Some recent books by Ramsey (8) and Whitten (16) are of interest on the subject.
Fold Structures

The earliest deformational features indicated by the fabric studied in this area are represented by the plastic and syntectonic crystallization associated with folding.

Most of the pi diagrams constructed from mine maps yielded little useful data concerning the style of folding except that the domains of cylindrical folding are not large and that generally, the folds in this area plunge steeply. A pi diagram constructed from bedding-plane data for the 2000 level was most enlightening concerning the style of folding for the area studied and may be interpreted to indicate folding about a N 22° W 76° SE axis. The grouping of maxima supported by surface observations indicate that the style of folding was chevron with sharp hinges. The development of the fold in this area is compatible with the same force field that created the strike-slip faulting, but folding would precede faulting because of its displacement by the later structures.

The choice of tectonic axes a and c for this study varied by a horizontal angle of 45°, depending on whether the folding movements have been mostly resolved into the plane of the bedding as for flexure folding, or have mostly been in the direction of the axial plane as for plastic folding. As most of the diagrams showed the highest symmetry relations for an orientation of tectonic axes in the bedding, the choice, that of flexure folding, was used. Relations for the other case are readily visualized after a mental 45° counterclockwise rotation about tectonic b.

The dynamics involved in the folding deformation are shown by the preferred orientation of quartz [0001] axes and sericite (001). The sericite symmetry, as shown in the diagrams of figure 16, consists of a single girdle about tectonic b, which according to the theories of fabric development of sericite is consistent with the type of folding of this domain (fig. 3). Sericite, a form of mica, showed well-defined preferred orientations in all samples examined, thereby disclosing fabric homogeneity for all domains of figure 16.

Analysis of mica fabric may be thought of as reflecting one of two basically different processes. One idea interprets mica orientation as controlled by preexisting S surfaces (13, p. 22) within the host rock, in which the (001) plane of mica forms parallel to the controlling S surface. In this case mica would play a passive role in the deformational processes, crystallizing as a post-tectonic mineral. Its orientation therefore would have little or no tectonic significance outside of information relating to the chronological development of S surfaces in tectonic deformations.

The other process may be thought of as one in which mica assumes an active role in reflecting the dynamics involved in tectonic deformation. This approach does offer unique conclusions, but presupposes several mechanisms of deformation that result in preferred orientation of mica crystals. The mechanics of deformation involved in the preferred orientation of mica (001) have received much attention, and are discussed by Turner and Weiss (13, pp. 440-441).
It is interesting to note that most of the ideas dealing with the preferred orientation of mica in tectonics, with the exception of mica formed in S planes, have mica (001) forming at a high angle to the c direction, or possibly parallel or subparallel to the plane containing \( \sigma_1 \) and \( \sigma_2 \) as in certain cases of translation gliding. Based on the general tendency for mica to develop in tectonites symmetrically to \( \sigma_1 \) direction, the diagram (fig. 16) indicates that \( \sigma_1 \) acted in a horizontal plane during the development of the sericite fabric. A unique bearing for \( \sigma_1 \) is not definite since the sericite forms symmetrically about tectonic b. This is consistent with the macroscopic fold in this area, and the observed orientation of sericite (001) may be explained as follows. It appears that sericite (001) may have grown parallel to bedding planes during metamorphic recrystallization accompanying bedding-plane shear operative during concentric folding (perhaps on nearly horizontal axes). Subsequent deformation about steeply inclined axes associated with penetrative strike-slip movements resulted in some folding of the mica fabric, reflected now in mica girdles about a steeply inclined tectonic b. It is also possible that the steep folds are primary structures.

Much data describing symmetrical patterns of quartz [0001] has been recorded in petrofabric literature, but because of the difficulties of duplicating syntectonic crystallization of quartz through laboratory methods and because of its frequent discordant relationship to other subfabric symmetries, little is known regarding the mechanics of deformation involved in the orientation processes of quartz [0001]. In the case of the preferred orientation of quartz [0001] axes, the criteria used to reveal the dynamics of deformation arise from the nature of its symmetrical relation to the principal stress directions.

Concerning the preferred orientation of quartz [0001] (fig. 16), the synoptic diagram (fig. 17) shows the orientation to consist of three small-circle girdles symmetrically located about tectonic a, b, and c, and thus symmetrical to the bedding (fig. 21). Tectonic c therefore would coincide with an axis of greatest symmetry of the quartz [0001] fabric. Regarding the relationship between symmetry patterns of quartz [0001] and principal stress direction, experimental work by C. Barry Raleigh (7) shows the following: "... that the c-axis fabric is symmetrical about the direction of compression (cylinder axis), and (2) the c-axes [0001] are preferentially oriented in a zone with 15° of the plane normal to the direction of compression, \( \sigma_1 \). It seems likely from the symmetry of the sample and the stress (\( \sigma_1 > \sigma_2 = \sigma_3 \)) that the c-axes lie in a girdle or girdles symmetrical to \( \sigma_1 \)." He speaks of other tests in the same series and states "It can be shown, however, that the c-axes of the quartz in these specimens are preferentially oriented at greater than 45° to \( \sigma_1 \)." During the period of folding in which the syntectonic crystallization and orientation of quartz [0001] developed, the maximum principal stress direction was directed nearly horizontally in a west-northwesterly direction parallel to tectonic c (fig. 16). \( \sigma_2 \) and \( \sigma_3 \) were located mutually perpendicular to \( \sigma_1 \) but according to quartz [0001] symmetry they occupied no unique positions. Early in the work, it was thought that the quartzite had been completely recrystallized to a quartz fabric of subequant grains about 0.1-0.2 mm in diameter. Subsequently, it was postulated, a penetrative cataclastic deformation ensued, which produced the fine-grain quartz of the meshwork (as a
kind of mortar structure among remnant quartz clasts of the original quartzite), and partial recrystallization of the mortar ensued. Later in the work, this rather complicated hypothesis gave way to the simpler one of recrystallization of the coarse to fine grains of quartz in the original sedimentary matrix, followed by moderate cataclastic deformation which produced the undulatory extinction observed in many grains, both coarse and fine.

Bedding-plane faults are important elements of structure within the area studied and represent macroscopic fabric developed during folding. They form closely spaced planes of discontinuity and are reflected in fabric development of the mesoscopic and microscopic scales. Visual observation of bedding-plane fault surfaces shows local development of gouge, slickensides, and striations. Locally, the striations trend from nearly vertical to nearly horizontal. Assuming that sense of movement may be determined by the direction of striations, the fault movements indicated are fairly complex showing at least two periods of deformation. The first epoch of deformation during the development of the bedding-plane faulting occurred during folding, at which time the vertical to nearly vertical striations were formed. Other evidence of vertical fault displacements is shown by the attitude of drag folding of beds between closely spaced bedding-plane faults.

**Regional Shear Deformation**

Following the episodes of folding (plastic deformation), the syntectonic recrystallization of quartz and sericite, and the development of bedding-plane faulting, the mechanism of rock deformation changed. This change is expressed by the development of the regional and macroscopic shear faulting, jointing, and the associated mesoscopic and microscopic fabric.

The second period of bedding-plane fault movement occurred during the epoch of shear faulting (the WNW-trending faults) at which time the nearly horizontal striations occurred. In this case, the bedding-plane faults or bedding plane were favorably oriented to the planes of high shear values generated in the earth's crust. Concerning the present study, this period of deformation represented by lateral fault displacements is more closely associated with possible inherent stress that would be encountered in mining.

The regional faulting diagram (fig. 9) shows the orientation of the regional faults within a surface area 6 miles in diameter above the 6500 and 6700 levels of the Star mine. These fault data, available from field maps (14), were plotted in order to discover penetrative characteristics of rock fabric on a regional scale. Figure 9 shows three major regional fault systems, the most important of which are those with general trends of about N 70° W with southerly dips. This system of faults is of shear type with right lateral displacements, is represented by associated structures in all scales covered by this study, and represents rock deformation reflecting the most recent tectonic stresses. A second system of regional faults strikes about N 35° W and dips steeply to the SW and NE. Although correlation to other fabric is not entirely satisfactory, this system may be the result of tensile forces present at the time of the shear system of faulting; and therefore, would tend to form normal to the σ3 direction. The third fault system, shown
in figure 9, is characterized by N-S trending faults with high angle dips and correlates only partially with fabric elements of other scales. Because this system is displaced by the above-mentioned system of shear faulting as described in geologic literature (5, pp. 126-127), it is believed to correlate chronologically with an earlier epoch of tectonic deformation. Nevertheless, from the standpoint of fabric development, more recent movement along this system contemporaneously with other regional fault movements is indicated.

Inspection of macroscopic faulting diagrams (figs. 5-8) reveals in addition to the bedding-plane faults a complementary system of faults which tends to intersect the bedding-plane faults (bedding direction) at an acute angle. Compiled from these diagrams, a synoptic diagram (fig. 25, part A) shows the preferred orientation of the bedding plane and other macroscopic fault planes, for domains on the 6500 and 6700 levels. Macroscopic faults tend to dip steeply and to be concentrated in zones, shown in figure 25, part A, by maxima concentrations in the NE quadrant. As the macroscopic faults appear to correlate with the preferred orientation of regional faulting shown in figure 25, part B, it appears likely that development of the major macroscopic fault systems are associated with regional fault development.

As shown in figure 25, part A, the fault planes approximately corresponding to the maxima strike N 14° W and N 78° W, forming a conjugate angle of 64°. The bisectrix of this angle has a bearing of N 46° W and indicates the direction of σ3 according to macroscopic faulting. If the same procedure is followed in figure 25, part B, regional faults strike N 74° W and N 02° E, forming a conjugate angle of 76°. The bisectrix of this angle bears N 36° W.

and in the direction of the regional $\sigma_1$ during that tectonic deformation period. The variation between the conjugate fault angles and the inferred direction for $\sigma_1$ in the macroscopic and regional scale is due to heterogeneities in the respective stress domains. In the macroscopic scale this heterogeneity is probably due to the variation in the attitude of the bedding planes.

Local deviations from the general attitude of bedding are noted on the maps for the 6500 and 6700 levels (fig. 4). This is particularly noticeable in the domains which are located in the crosscuts between the vein and the Star fault. According to drag-fold development and fault-orientation data in these domains, the Star fault underwent right-lateral displacement, striking N 65° W, which agrees with the trend of the major shear faults of this area.

Joints are both abundant and strongly developed within the area of the 6500 and 6700 levels of the Star mine and consist of two sets which have been designated in this report as the b-c and the a-c joint systems. The b-c joint system characteristically lies nearly perpendicular to the orientation of the bedding plane (tectonic a-b plane) as disclosed by a comparison of the bedding and jointing diagrams in figures 5-8. They also have a strong tendency to lie parallel and subparallel to the macroscopic and regional shear faults shown in figure 25, parts A and B, and figure 26. Figures 26 and 27 are synoptic diagrams of macroscopic faults and joints in all lateral domains on the 6500 and 6700 levels. Figure 27 shows the occurrence of jointing in which b-c system (maxima located along net perimeter) is shown to develop nearly perpendicular to the bedding-plane faults and nearly parallel to the macroscopic faulting which intersects the bedding-plane faults (fig. 26). The b-c joint system therefore is thought to have developed by the same regional dynamics which formed the regional and the macroscopic conjugate shear fault systems. The tendency of the b-c joints to be nearly normal to the bedding is probably due to the effect of orientation of bedding (anisotropy) into which the maximum shear stresses were resolved during faulting.

The microscopic elements, quartz deformation lamellae and microfractures, appear to have developed during the same period and under similar conditions of stress as the macroscopic fabric elements discussed previously. The penetration characteristics of the fabric reflect a stress homogeneity in the rocks of this area during the period of rock deformation (brittle failure) which followed folding.

In experimentally deformed quartz the deformation lamellae develop along planes of high resolved shear stress. Contrary to a once-prevalent belief, they are of late origin, postdating a state of preferred orientation of the quartz lattice already achieved by some unknown mechanism (13, p. 433).

A comparison of different domains (fig. 16) shows an inhomogeneity regarding the development of the deformational lamellae fabric. Apparently this condition represents a heterogeneity of stress conditions within the microscopic scale during the period of deformation lamellae development. In relationship to quartz [0001] orientation, sample 45 of figure 16 shows a strong tendency of the deformation lamellae to lie parallel to the preferred orientation of the quartz [0001]. The significant relationship here is the
FIGURE 26. - Synoptic Diagram of Macroscopic Faults—6500 and 6700 Level Laterals.

The possibility of preferential alignment of deformation lamellae which is a glide mechanism along the quartz [0001] direction (13, p. 431), provided that the [0001] direction is suitably oriented to the maximum principal stress direction.
FIGURE 27. Synoptic Diagram of Macroscopic Joints—6500 and 6700 Level Laterals.

Correlation of deformation lamellae to rock fabric of other scales can be seen from the synoptic diagram (fig. 24A). A strongly developed deformational lamellae fabric is oriented parallel and subparallel to the macroscopic and mesoscopic b-c jointing system. Thus, this group of deformation lamellae is
believed to have developed simultaneously with this system of jointing. Directions and relative magnitudes of the principal stresses according to the orientation of this deformation lamellae system would indicate that \( \sigma_2 \) acted parallel to tectonic \( b \) during their development. \( \sigma_1 \), acted east-northeast with \( \sigma_3 \) mutually perpendicular to \( \sigma_1 \) and \( \sigma_2 \). This orientation for \( \sigma_1 \) and \( \sigma_3 \) does not agree in bearings with the hypothesized direction of these principal stresses during the tectonic deformation in which the faulting and jointing developed. Since the development of the deformation lamellae is believed to be contemporaneous with the faulting and jointing episodes, the discrepancy in orientation of the inferred direction of \( \sigma_1 \) and \( \sigma_3 \) may be due to a stress couple which developed in the rock during the shear faulting which would have the effect of rotating \( \sigma_1 \) and \( \sigma_3 \) about \( \sigma_2 \). Another possibility, though not favored, is that this system of deformation lamellae represents the direction of ground forces of some earlier episode of tectonic deformation, possibly folding.

The gross characteristics of microfracturing are disclosed by synoptic diagram (fig. 24B). Reflected in this diagram is the tendency for microfractures to correlate in general orientation with the tectonic deformations observed in the macroscopic fabric already discussed. That is, these tectonic planar discontinuities tend to form a-c girdles whose intersections lie parallel to tectonic \( b \). A more detailed analysis of this a-c girdle system reveals a strongly developed maxima of microfractures oriented parallel to the b-c joint system observed in the macroscopic and mesoscopic fabric diagrams in figures 21 and 23. The grouping of microfractures parallel to the b-c plane therefore are believed to agree in chronological development and to represent the same condition of stress as inferred for the development of the b-c joint systems on the macroscopic and mesoscopic scales. Other maxima on the a-c girdle (fig. 24B) represent microfracturing corresponding to the bedding and bedding-plane faulting direction. Microfractures oriented parallel to the a-b plane are believed to have originated simultaneously to the bedding-plane faulting and under similar stress conditions. Apparently the microfracturing reflects the period of deformation represented by macroscopic faulting and jointing following the epoch of folding and the later stage of regional fault development.

**Regional Tensile Deformation**

The most recent period of tectonic deformation involves a reorientation of \( \sigma_2 \) and \( \sigma_3 \). Rock failure reflecting this change are disclosed by the a-c joints, the quartz deformation lamellae, and microfractures.

The a-c joints are shown by the strongly developed maximum at the center of the joint diagram (fig. 27). These joints developed nearly normal to the b-c joints and to bedding, and are believed to represent rock failure due to high tensile stresses induced in the rocks due to the following processes. During the periods of folding and faulting, the rock in this region deformed in response to a directional compression (\( \sigma_1 \)) acting laterally in a north-westerly direction. The high-angle preferred orientation of regional faulting, macroscopic faulting, and jointing (b-c system) indicates that \( \sigma_1 \) and \( \sigma_3 \) were oriented nearly horizontally while \( \sigma_2 \) was oriented vertically.
Subsequently, erosion of the former surface reduced the superincumbent load resulting in a vertical reorientation of $\sigma_9$ and caused the development of the a-c tensile joint system. This system of jointing therefore is believed to be one of the most recent of the tectonic deformation in this area.

A second important system of deformation lamellae fabric, shown in figure 24A as maxima located along tectonic $c$, represents lamellae with moderate east and west dips. This system of lamellae does not correlate exactly in orientation with any previously observed fabric; however, these lamellae planes are inclined to the macroscopic a-c joint orientations and are therefore believed to correspond to the shear components of the stress field in which the a-c planar discontinuity developed. Thus, this lamellae system developed simultaneously with the a-c joint system. This system of deformation lamellae indicates that $\sigma_3$ acted parallel to tectonic $b$ during their development and $\sigma_1$ and $\sigma_2$ acted in a nearly horizontal plane and appears to vary greatly in direction of strike. No deformation lamellae are parallel to bedding-plane faults, or to the regional north-south faults, northwest faults, and the west-northwest faults. It appears, therefore, that the deformation lamellae are not related to the major fault systems, but are related to the earlier b-c joint system and the more recent a-c joint systems.

In an effort to learn age relations of microfractures, they were subdivided into two classes: One of filled fractures and the other of unfilled fractures. Samples 35 and 36 were analyzed in this way; orientations of these fractures are shown in figure 16. The resulting diagrams for both types of fractures appear to reflect the b-c joints, bedding-plane faults, and the north-south faults. Microfractures, which appear to correlate in orientation with the a-c joints seem to be well developed in the unfilled type of microfracture. These fractures both from orientation and appearance probably represent tensile failure of extension variety in which $\sigma_1$ and $\sigma_2$ would lie horizontal and $\sigma_3$ vertical, normal to a-c microfracture system. Inherent ground stresses and erosional unloading are two phenomena that could explain the inferred ground stress condition and the resulting fabric.

The preferred orientations of the macroscopic planar discontinuities are all represented by preferred orientations of mesoscopic fabric shown in figure 24. The mesoscopic fabric discloses the penetrative nature of the macroscopic faulting and jointing and appears therefore to agree chronologically with their development.

As shown in figures 12, 13, and 14, the mesoscopic fabric in many domains has a tendency for a more random distribution of maxima than the macroscopic diagrams. This discrepancy between the fabric patterns of the mesoscopic and macroscopic is due to the following reasons. First, local irregularities in preferred orientation of planar discontinuities on the mesoscopic scale tend to be averaged out on the macroscopic scale of observation. Therefore, the mesoscopic diagrams would tend to show a greater "spread" in the plotting of poles to planes than would be the case on the macroscopic diagrams. Secondly, the mesoscopic diagrams in many domains (figs. 12-14) indicate a superimposed fracture system. This superimposed system is of recent development and reflects mining-induced failure. Within the domains studied the induced rock failure is most readily observable on the mesoscopic scale.
MINING-INDUCED ROCK FAILURE

The results of investigations regarding the inherent anisotropy of rock on the 6500 and 6700 levels of the Star mine show a tendency for tectonic discontinuities to lie in a girdle about tectonic b. Maxima within this general girdle pattern have a tendency to occur parallel and normal to the bedding; in addition, other inherent systems of discontinuity in this same girdle pattern lie at oblique angles to these systems. The result of these patterns of discontinuities would tend to weaken the rocks for an induced stress system in which the $\sigma_1$ and $\sigma_3$ components of stress would act horizontally. This rock would be relatively strong if $\sigma_1$ were directed vertically; the plane of maximum tensile stress (parallel to $\sigma_1$) would in most probability lie parallel to an inherited weakness plane normal to $\sigma_3$.

Data pertaining to structure genetically associated with induced stresses caused by mining activities were obtained by periodic mapping of macroscopic deformations. Renewed movement along old discontinuities (faults, joints, bedding) were recorded along with direction of displacement when obtainable. Data on the development of new fractures with information regarding fracture type (tension or shear), orientation, and displacement were obtained; also, general ground deformation data were recorded and evaluated with the macroscopic deformational information. Pertinent data were plotted on equal-area diagrams, and compared with the tectonic fabric diagrams in order to determine possible association of mining-induced failure to the tectonic anisotropy of the rock. Evaluation of the orientation of principal stresses associated with mining-induced rock failure can depend on the stage of the mining cycle at which the analysis is conducted as the stress direction may change during the mining cycle. For an analysis of the dynamics of induced deformation, several sets of diagrams representing distinct sequences of deformation would be appropriate. In this study the diagrams showing induced failure were not differentiated, and the patterns of failure therefore may in some cases represent more than a single episode of mining-induced failure. Because fieldwork for this study was terminated prior to the late stage of deformation on the 6500 and 6700 levels, data representing this stage is not included in the diagram analysis.

Figure 28 shows diagrams of domains on the 6500 and 6700 levels and depicts the preferred orientation of failure planes genetically associated with mining-induced stresses. These data consist of macroscopic fabric elements observed in wall rock surrounding underground openings.

The diagram for domain 1 (fig. 28) shows induced failure for an area of the 6500 level somewhat removed from the stope (fig. 4). Rock failure in this domain is characterized by almost perfect correlation with the attitude of prominent tectonic planar discontinuities. Rock failure of this type may be seen in figure 29, where the principal planes of rock failure are the tectonic $a-c$, $b-c$, and $a-b$ discontinuities.

Domain 2 (fig. 28) is located in an area of the lateral adjacent to the stope and therefore would be subjected to greater stresses due to mining than those located in domain 1. The pattern of induced failure in domain 2 reflects
the inherited a-c girdle anisotropy of the rock. A tendency is noted in
domains 2 and 3 (fig. 28) for a moderate amount of failure to occur along
planes not defined by tectonic fabric discontinuities. These are shown in
domains 2 and 3 by maxima representing planes having 20° to 60° easterly dips.
The rocks in these domains are locally highly stressed because of adjacent
mining excavations, and some of the rock failures in these domains reflect a
change in the orientation of the principal stress directions responding to
local stress heterogeneities. These fracture systems are complex, represent-
ing both tensile and shear failures.

Figure 30, part A, shows mining-induced rock failure at the junction of
the lateral and a crosscut on the 6700 level. In the lower right corner of
this photograph, a conjugate shear fracture system is shown in which an inher-
ent planar discontinuity is utilized as one of the failure planes. Near the
center of the photograph, slightly above and to the left of the conjugate
FIGURE 29. - Rock Failure Along Inherent Planar Discontinuities of Mine Rock.

fracture system, is a series of parallel tensile fractures. Figure 30, part B, is a schematic diagram representing the mining-induced failure shown in photograph in figure 30, part A. According to the orientation of the fabric elements and mechanism of failure (fig. 30), $\sigma_1$ would lie diagonally across the plane of the photograph from lower right to upper left in a plane which bisects the conjugate shear system and parallels the tensile fractures. $\sigma_2$ would lie approximately normal to the plane of the photo, and $\sigma_3$ would lie mutually perpendicular to $\sigma_1$ and $\sigma_2$. Information concerning the relative magnitudes and directions of the principal stresses can be obtained for any locality desired by a similar analysis of the preferred orientations and the mechanism of failure of mining-induced deformations.

Induced rock failure in domains 12 through 15 (fig. 28) of the 6700 lateral show the development of failure planes coinciding in orientation to inherited tectonic fabric ($b-c$, $a-c$, and $a-b$ planes). In addition a well to poorly developed fracture system is disclosed in these diagrams by a maximum located in the NE quadrant representing fractures striking northwest with moderate to steep dips. In comparing these diagrams with similar domains (figs. 13 and 14), it appears that these induced fractures correspond in orientation to the north-northwest regional faults.

The patterns of rock failure in the crosscut domains are more complex. The diagrams illustrating induced failure in the crosscuts (fig. 28) show this condition by a more random pattern of maxima than was the case of tectonic discontinuities and the induced failure pattern in the domains which comprise
the lateral. Not only do these diagrams represent an increased stress acting on the rocks within the crosscut domains, but they show the development of a failure system in which the maximum and minimum principal stresses assume a different orientation than was the case in premining tectonics. New failure planes resulted in some cases when the orientation of preexisting failure planes were at the wrong attitude for displacement in the new stress field.

The rock anisotropy investigated in this study is summarized in a diagram shown in figure 31, part A. This diagram shows the maxima of poles of planes of discontinuity which developed during the tectonic (premining) period of deformation. The result is several preferentially oriented systems of discontinuities which tend to intersect parallel and nearly parallel to b tectonic axis and the a-c jointing system which developed at a high angle to b tectonic axis. Figure 31, part B, is a diagram representing induced (post-mining) failure of mine rock. It may be seen through comparison of figure 31, parts A and B, that the inherited rock anisotropy controlled to a large extent the post-mining patterns of rock failure. Superimposed upon this pattern of induced rock failure and of more recent occurrence are rock failure systems which did not utilize existing weakness planes for their development. These systems of failure and their reorientations which reflect a change in the directions and magnitudes of the principal stresses are represented as maxima randomly scattered in diagram B (fig. 31). Most of these fractures are of shear type and have developed in combination (conjugate fracture systems) with the inherent a-c joint system or less frequently with some other inherent planar discontinuity. These fractures at the time of this investigation were

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more highly developed in the crosscut domains and in large strain areas along the laterals. By their orientations they appear to represent wide variations in the inferred direction of $\sigma_1$. In most cases $\sigma_3$ tend to lie at high angles to the rock faces of the underground excavations and $\sigma_1$ and $\sigma_2$ are not uniquely fixed in direction.

The induced fractures represented by maxima (fig. 31, part B) include mining-induced failure through at least two periods of mining-induced deformation where the principal stresses assumed different orientations and magnitudes. The initial induced fractures occur as the rocks surrounding openings are in an unconfined condition and the rock tends to close into the opening. Along lateral walls the mechanics of this initial deformation involves separation of rock along the inherent b-c joint system which tends to lie as penetrative planes of rock weakness parallel and subparallel to the lateral walls. Figure 32 typified this type of mining-induced failure along the laterals of the 6500 and 6700 levels. Figure 32, part A, represents failure along the lateral walls, whereas figure 32, part B, shows rock failure along the lateral backs. Locally because of irregularities in the fold, the orientation of bedding is nearly parallel to lateral walls in which case failure is developed along bedding planes (the a-b weakness plane). This is representative of initial failure along crosscut walls which in direction closely parallel the a-b planar discontinuities. Initial failure along the lateral backs is characterized by rock closure into the opening thereby developing tensile stress normal to the a-c joint system causing parting along this inherent planar discontinuity. Because of the inherent horizontal orientation of maximum principal stresses within this region, the lateral backs have been subjected to a relatively high maximum principal stress trending in a northwesterly direction which has tended to form shear systems of failure in areas of the back. This inherent stress system has also tended locally to separate the wall rocks along the a-c system of discontinuity during the initial stage of induced deformation. This is generally a minor phenomenon in comparison to induced failure along the b-c discontinuity.

As mining proceeded, there was a gradual change in the magnitude and direction of the principal stresses as shown by deformational phenomena. As the ore in place progressively diminished, an additional force was transmitted through the remaining ore to compensate for that part of the vein removed; the increased mining-induced maximum principal stress direction and the direction of the inherent tectonic maximum principal stress axis approximated the same direction and were additive. Rock failure at this period of the mining cycle mainly resulted in high-angle shear displacements along the tectonic b-c and bedding-plane discontinuities. Deformation principally occurred in the rock zones between the vein and the lateral. The mechanics of this deformation are complex, but generally result in movement in a direction normal to the horizontally oriented maximum principal stress direction. Figure 33 shows this stage of rock failure as developed in the more competent quartzite-type rocks. Figure 34 shows this stage of rock failure as reflected in the more incompetent argillaceous rocks.
FIGURE 33. - Mining-Induced Shear Failure in Competent Rock Along Lateral Walls.
FIGURE 34. - Mining-Induced Failure in Incompetent Rock Along Lateral Walls.

The orientation of the principal stresses are similar in the examples of rock deformation shown in figures 33 and 34. The rock anisotropy and competency of the rock apparently determined the particular mechanism of failure.
As the rock in the zone between the laterals and vein progressively fails, the ability of this zone to support loads is diminished and the sill areas of the lateral on the vein side and the sill areas of the crosscuts are displaced vertically into the openings. Vertical displacement of this nature varies from about 1-3 feet. The rate and magnitude of deformation are described in an earlier publication (15). After the ore is removed or has completely failed in place, the stress concentration that caused this deformation was eliminated since lateral stress could no longer be transmitted through the ore "pillar" and a new stress field began to evolve. Rock formerly in compression now relaxed and began to move towards the mined out stopes which are "sandfilled." The principal stresses were reoriented with a tendency for tension fractures to form parallel to the b-c and a-b planar discontinuities. Figure 35 is a schematic representing the mining-induced cycle of ground stresses.

Omitted from the analysis of induced deformation are the mesoscopic and microscopic fabric. Although certain elements of these scales may represent induced failure, particularly those fabric elements which are nonsymmetrical to tectonic fabric, no special effort was made to identify them with induced deformation. Since the mesoscopic and microscopic samples were obtained for the most part from rock in early stages of induced deformation, the deformation data yielded by these samples would not include deformatonal features that were subsequently developed in the mining cycle. An exception to this may exist in some of the mesoscopic and microscopic samples of the crosscut domains, where the rock preceded other domains in the development of mining-induced deformatonal features.

SUMMARY AND CONCLUSIONS

The deformatonal pattern of this area has been shown by synoptic diagrams (figs. 21-23), which disclosed a tendency for regional, macroscopic, mesoscopic, and microscopic fabric to exhibit similar preferred orientations of fabric. Characteristically these structures form an a-c girdle about tectonic b and thus reflect ground stresses associated with the tectonic deformational epoch represented by folding and faulting.

The earliest period of deformation with which we are concerned here is reflected in the preferred orientation of quartz [0001] and sericite (001) which mainly involved plastic and syntectonic deformation. During this period the strata folded about a steeply inclined fold axis plunging to the southeast at 76°. An analysis of quartz [0001] fabric does not give unique orientations of the principal stress directions. However, a synoptic diagram of quartz [0001] shows symmetry to the tectonic axis and thus indicates that this fabric was developed during folding about a steeply inclined axis and because of its symmetrical relation to a axis indicates that σ1 acted laterally.

Good fabric homogeneity is shown by sericite (001) orientations. Because of the symmetrical orientation of this fabric (a-c girdle) its development was associated with the epoch of folding described previously. A dynamic analysis of the sericite fabric indicates that σ1 acted laterally consistent with the fold development in this area. Continued tectonic deformation is believed to
have caused some degree of annealing in the previously formed [0001] preferred orientation of quartz. Assuming that the regional maximum principal stress direction or regional couple was acting in a northwesterly direction, the tendency for the microscopic and macroscopic fabric mentioned above to maintain a symmetrical relationship with the bedding indicates that the forces engendered during the folding epoch were resolved into the plane of the bedding.

At the conclusion of the development of structure intimately associated with folding, the pattern of regional faulting and the macroscopic conjugate fault systems developed. It is believed that the regional maximum principal stress, $\sigma_1$, acted horizontally in a northwesterly direction, and $\sigma_3$ was also oriented horizontal. At this time renewed movement occurred along bedding-plane faults and the conjugate macroscopic fault system developed along with regional faulting and the b-c jointing. Following the period of regional faulting, through processes of continued regional lateral compression and/or reduction of vertical load by erosional unloading, $\sigma_3$ became oriented in a vertical direction, allowing the development of the prominent a-c joint system. Of course, there was a tendency even during the folding deformation to create vertical tensile forces in the rock, and it would have been possible for the a-c joint system to have developed locally at any period following or during folding. But due to the absence of mimetic crystallization of sericite along the a-c discontinuity and since later microfractures appear to reflect the a-c orientation, it is believed that rock failure on the a-c joint system represented fairly late development.

Regarding inherent rock anisotropy, we find that tectonic deformations on all scales have resulted in planar discontinuities, which with the exception of the a-c joints, form partial a-c girdles, and that this inherent anisotropy has weakened the rock in a symmetrical and predictable manner. Thus, the rock has been rendered anisotropic and therefore is more susceptible to failure under unique orientations of subsequently induced stresses through mining or natural causes. In some fabric domains, particularly in the mesoscopic and microscopic scales, rock failure patterns depart from the general tectonic deformational characteristics. These fabric patterns are not homogeneous with respect to other domains, and may represent local tectonic stress heterogeneities (drag folding, etc.), or rock failure fabric due to mining-induced stresses. Since many of these domains are located in highly stressed mine areas, and because failure might be expected to develop first in the microscopic and mesoscopic scale it is believed that these failure planes are the results of rock failures due to induced mine stresses.

To determine the affect of rock anisotropy upon mining-induced rock failure, the mining-induced failure planes were mapped and compared with the pre-mining (tectonic) anisotropy of the rock on the 6500 and 6700 levels. In most cases of mining-induced rock failure, the tectonic anisotropy defined the orientation of the mining-induced fracture plane. It was also noted that mining-induced failure planes developed with orientations not defined by the tectonic anisotropy. These fractures are thought to be the result of an orthogonal stress system in which $\sigma_1$ and $\sigma_2$ were oriented in a nearly lateral direction and $\sigma_3$ acted normal to $\sigma_1$ and $\sigma_2$ in a more vertical orientation. These mining-induced fractures developed mainly in a conjugate shear system.
and utilized the tectonic a-c fabric as one member in this conjugate failure system. It appears that the principal cause of induced deformation is due to the increased horizontal forces transmitted by the ore "pillar" which through mining becomes increasingly smaller. The increased compression parallel to $\sigma_1$ (horizontal) and the strain (Poisson's effect and plastic flow) normal to $\sigma_1$ set up rock stresses which cause failure and greatly reduce the load-carrying capabilities in the rock zones located between the lateral and the ore vein. The location of the laterals and crosscuts in respect to the position of the ore in place during the mining cycle is a consideration regarding the inferred direction in which $\sigma_3$ acts upon the opening. In order to determine precise associations between mining-induced failure systems and the tectonic anisotropy of the rock, domains defined by local symmetries and heterogeneities of the induced failure systems, would have to be determined. This was not done in the current study, as only general relationships were sought. Two important factors which affect the development of mining-induced failure are the premining rock anisotropy and the orientations of the inherent and mining-induced stresses which act upon the anisotropy. This information coupled with data concerning the theoretical stress analysis of rocks surrounding underground openings would greatly assist in improving designs of underground openings.

One area of petrofabric study, which deserves more attention in investigations relating to the dynamics of rock deformation, involves an analysis of the symmetries of deformation. Provided that care is taken to define particular domains of rock failure and single episodes of rock deformation, the symmetries of rock fabric, illustrated by proper graphic methods, define the positions of orthogonally oriented fabric axes. These axes could be used to locate the principal stress axes to which they appear to lie coincident. Further analysis concerning the mechanisms of failure of the fabric elements, which make up the fabric symmetry identifies the principal stresses, and the nature of the stress field. This knowledge would help in prediction and understanding of deformational fractures which result from in situ rock stress.
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