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GEOLOGIC STRUCTURAL ANALYSIS FOR OPEN PIT SLOPE DESIGN, KIMBLEY PIT, ELY, NEVADA

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GEOLOGIC STRUCTURAL ANALYSIS FOR OPEN PIT SLOPE DESIGN, KIMBLEY PIT, ELY, NEVADA

by

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ABSTRACT

The primary objective of the structural geology portion of the Kennecott Copper Corporation-U. S. Bureau of Mines Pit Slope Stability Study was to determine the attitude, geometry, and spatial distribution of geologic structures of the west wall of the Kimbley Pit for use in designing a maximum stable slope for the pit. A corollary objective was to develop and refine techniques for collecting and analyzing geologic structural data with emphasis on numerical methods that could be integrated with other aspects of pit design. Surface mapping techniques used were a modification of conventional joint set mapping and a detailed linear sampling method. For subsurface investigations both oriented core and a borehole camera were used.

It was determined that the major faults in the area were favorably oriented for mining a steep stable slope. The jointing or natural fracturing, although complex, was not random in attitude and consisted of several persistent fracture sets and a number of secondary sets. The attitude of the persistent fracture sets was favorable for steeper slope angles, and

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these attitudes were used in the design considerations.

There was no significant difference between the attitude of the fracture sets determined from the former and new slope face.

INTRODUCTION

The rock of an open pit slope is structurally complex, containing many faults, joints, and lithologic contacts. These structures have appreciably lower strengths than the intact rock and constitute mechanical discontinuities in the rock mass. Thus, a rock mass with many discontinuities should fail at a lower applied stress than rock with fewer discontinuities and failure will typically occur along discontinuities that are critically oriented to the pit wall and the applied stress. Therefore, one part of the Kennecott Copper Corporation-U. S. Bureau of Mines slope stability research project, conducted at the Kimbley Pit, Ely, Nevada, was devoted to an analysis of the geologic structure. The project also consisted of studies of the stress, strain, displacement, and strength of the slope wall with the overall objective of improving methods of designing open pit slopes. This paper covers only the structural geology portion of the study.

The primary objective of the structural analysis study was to determine the attitude, geometry, and spatial distribution of geologic structures in the west wall of the Kimbley Pit. A corollary objective was to develop and refine techniques for collecting and analyzing geologic structural data with emphasis on numerical, descriptive methods. These techniques could then be applied at other pits to provide data for slope design.

The program was divided into two parts: the first, or pre-mining phase, during which structural data were collected, analyzed, and used in the design of a steeper slope angle, and the second, or mining phase, during which additional structural data were collected to verify the results of Phase I.

GEOLOGIC SETTING

The Kimbley Pit is located in the Egan Range in east-central Nevada. The Egan Range is a typical fault block mountain of the Basin and Range structural province. Cretaceous monzonite porphyry stocks intruded and, in part, metamorphosed older, Paleozoic sedimentary rock in an east-west trending zone through the central portion of the range; Tertiary volcanics have intruded and partially covered the older rocks.

The west end of the Kimbley Pit, the area studied in detail, is in monzonite porphyry and granitized shale complex. The rock is hydrothermally altered and contains disseminated copper mineralization. An isometric view of the area is shown in figure 1, and a photograph of the west slope of the pit is shown in figure 2.

DESCRIPTION OF THE PHYSICAL NATURE OF THE ROCK

The rock forming the upper 200 feet of the Kimbley Pit is heavily oxidized. It is a soft, porous material high in clay content and has a specific gravity of 2.3. Seismic velocities range from 1,500 to 4,500 fps.

The laboratory determined unconfined compressive strength is about 1,000 to 5,000 psi[4/]. Small-scale fracturing is very intense, resulting in 20 to 30 fractures per foot. The rocks were excavated with tractor-mounted rippers and a complementary fleet of scrapers. No blasting was required except a few zones of residual silication.

Below the oxidized zones is a hard, silicified porphyry-granitized shale complex. The contact marks a former water table and is the oxide-sulfide interface in the ore body. The rocks have a specific gravity of 2.8 and seismic velocities range from 4,500 to 8,000 fps. Laboratory determined unconfined compressive strengths vary between 6,000 and 10,000 psi. The fracture intensity is on the order of two or three per foot and the rock breaks into angular fragments, generally less than 2 feet in size. Owing to the hardness of the rock, conventional blasting techniques were employed to excavate this portion of the pit.

PHASE I STUDIES

Geologic Model

Most structural discontinuities are essentially planar and may be described by their attitude and position in space. Conventional geologic nomenclature is used to define fracture attitude by strike and dip, while its position in space is determined by reference to some fixed point. Since faults, contacts, and other structures range from a few inches to several miles in extent, a segregation by size is necessary. In this study structures were divided into major

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[4/] The results of the laboratory tests on the rock are discussed in a companion paper "Bureau Contribution to Slope Angle Research at the Kimbley Pit, Ely, Nevada" by Robert H. Merrill.

and minor structures based on their extent relative to the pit. Major structures are those single, continuous features which have an extent in the same order of magnitude as the pit dimensions, in this case about 500 feet or greater. Large faults and lithologic contacts would fall in this category. Minor structures have an extent of less than 500 feet, and are typified by joints, fractures, and localized faults.

The rock mass between major structures was designated a structural domain. Within each structural domain there is a population of minor structures varying in attitude and extent but usually grouped into sets by parallel attitudes rather than being randomly oriented. All of the minor structures, including joints, small faults, and fissures, were referred to as fractures to avoid any generic implication. A series of two or more parallel fracture planes was called a fracture set. Within any structural domain a number of fracture sets could exist.

The structural domain concept was utilized because two rock masses with different structural patterns may be juxtaposed along a major fault; or, displacement of similar rock masses on a fault may result in rotation of one mass relative to the other. By sampling and analyzing each mass separately, the structural patterns for each domain can be compared and, if similar, combined.

Since the large number of minor structures constitutes, for all practical purposes, an infinite population, they can best be sampled and described statistically. Certain geometric and physical properties of fractures and fracture sets can similarly be assigned a numerical value and be treated statistically. These properties such as (1) continuity, (2) planarity, (3) intensity, and (4) fracture filling are considered to affect the strength of the fracture and, consequently, the rock mass, and are described as follows:

Continuity.- Continuity is the two-dimensional extent of a fracture in the plane of its attitude. The greater the continuity of a fracture the lower its effective strength, other factors being equal. The true three-dimensional continuity cannot be measured because the total fracture surface cannot be observed; therefore, the length of the trace of the fracture at its point of observation must be used as an approximation.

Planarity.- Deviations of a real fracture from a true plane surface also affect the strength of a fracture. A planar structure will offer less resistance to sliding than an irregular structure. A fracture trace can be classified as planar, wavey, or irregular.

Intensity.- The intensity is the number of fractures per unit distance along the normal to the fracture set.

Fracture Filling.- The composition and quantity of material such as clay, quartz, or pyrite in a fracture affects the strength of the fracture.

Surface Mapping

Conventional geologic mapping was performed to determine rock types, locate major structures, and delineate structural domains. The area has been mapped by the Geology Department of the Nevada Mines Division of Kennecott Copper Corporation; therefore, the mapping was updated by adding detail and revising the original map based on new information obtained in this study. Special emphasis was placed on the location and physical characteristics of the major structures. Both aerial photographic and plane table techniques were utilized.

Fracture Set Sampling

The fracture sets in the pit slope were visually observed and the attitude measured with a Brunton compass. Spacing, continuity, and area over which the set could be observed were estimated and recorded. This was done by a two-man team systematically observing rock exposed by the pit benches. The location of the points of observation was also recorded. Individual faults were recorded as well as fracture sets. A total of 343 fracture set observations were made by this method. The east-west striking fracture sets, mapped by this method, are shown in figure 3.

Detail Line Sampling

To provide more precise data on fracture attitude and spacing, a detail line technique was utilized. This consisted of stretching a tape along the pit face and recording the attitude and location of each fracture. All the fractures in a zone about 3 feet above and 3 feet below the tape were included. Originally it was intended that planarity, fracture filling, and surface roughness should be recorded; however, most fractures exhibited nearly identical properties. Almost all were wavey and contained some silica and sulfide fracture filling. Therefore, unless unusual conditions were encountered, only the attitude of the fracture set was recorded.

Sample lines were nominally 20 feet long and spaced about 100 feet apart horizontally. The number of fractures observed per sample line ranged from 30 to 140 with an average of 75 . A total of 29 detail-line samples were taken on all four levels (roadways - see fig. 2) in the west end of the pit.

Subsurface Sampling

A major element of the Phase I Geologic Study was the investigation of the rock behind the pit face by drill-hole techniques. This portion of the study was considered important since it provided direct sampling of geologic structures in the pit wall rather than extrapolating surface data. Also, development of subsurface techniques was considered necessary for future application to new mines where drilling would be the only means of exposing data.

The drilling consisted of 21, NC-size (3.6") core holes totaling 9,078 feet. Ten of the holes were inclined 20^{o} from the vertical; the other 11 holes were vertical. In addition six 8-inch holes were vertically drilled for a total of 2,201 feet; about half of this was core drilled. The location of the drill holes is presented in figure 4. The NC holes were for structure and rock-type information. Core from the 8-inch holes was sent to the Denver Mining Research Center, Denver, Colorado, for laboratory tests to obtain estimates of the strength of the rocks in the slope wall.

Core Logging

The NC core was logged for rock type, core recovery, nature of the core breaks, and type of fracturing. The nature of the core breaks was divided into three categories on the basis of fragment size. Core which was intact (except for occasional breaks) was classified as broken; core pieces whose length was about equal to the core diameter were classified as fragmented; material less than 1/2 inch was considered as rubble. Wherever possible, planarity of fracture surfaces was recorded as planar, wavey, or irregular.

The dip of the fracture planes forming the breaks in a 130-foot section of core from a vertical drill hole was obtained by measuring the angle between the fracture and the axis of the core. A total of 790 fracture planes were measured. The number of fractures intercepted by the drill core is dependent upon the angle of the fractures with respect to the drill hole. The frequency distribution was corrected by the following relationship:

$$n = \frac{n_o}{\cos \theta},$$

where n = corrected number of fractures

n_o = recorded number of fractures

θ = dip of fractures.

The frequency distribution in the drill core showed an almost linear increase in number of fractures from 0^o dip to 30^o dip, and an almost uniform concentration of fractures from 30^o to 90^o. This test indicated that the information gained did not warrant the effort involved, particularly as the core was not oriented; therefore, fracture dips were not recorded for subsequent holes.

Borehole Camera

An NX-size borehole camera was also used to obtain oriented photographs of the walls of the drill holes, and techniques were developed to obtain the attitude of fractures observed in the photographs (2)[5/]. Difficulties in maintaining an open hole and in obtaining satisfactory photographs limited the amount of useable data obtained by this method. Suitable photographs were obtained from an average of only 34% of each NC-size hole, resulting in 801 measured fracture attitudes. No useable photographs were obtained in the large diameter holes.

Oriented Core

Of the 1,116 feet of core obtained from the 8" holes only 37 feet was ultimately oriented by use of a television borehole camera borrowed from the U. S. Bureau of Reclamation. The attitudes of 668 fractures were obtained from this core.

DATA ANALYSIS AND RESULTS OF PHASE I

Major Structures

Structures in the west end of the pit consisted of the Kimbley and the Jupiter faults, and a number of smaller unnamed faults. The Jupiter fault strikes north-south across the west pit face, intersecting the slope just below the rim, and dips 25^{o} to the west away from the structure of

[5/] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

the pit. It forms the contact between a sandstone (above) and the quartz monzonite, granitized shale (below). The Kimbley fault strikes northwest and parallels the south slope of the pit. It intersects the pit face about one-quarter of the way up the south side of the pit and projects across the west face of the pit. It dips to the south away from the pit at about 55°. A limestone forms the hanging wall and the quartz monzonite, granitized shale is in the footwall. The unnamed faults strike generally northeast and are either near vertical or dip west away from the pit. These structures formed the boundaries of the structural domains.

Comparisons of fracture patterns and rock types showed little difference between structural domains, with the exception of the areas in the hanging wall of the Jupiter and Kimbley faults, and, therefore, these data were treated as one structural domain. Since the south wall of the pit was not part of the experiment and the rocks above the Jupiter fault represent a very small portion of the west slope, data from these areas were not used.

Fracture Patterns

The complex fracturing of a typical porphyry copper deposit often gives the initial appearance that the fracturing is random. It was established that this was not the case for the Kimbley Pit. A test for randomness for fabric diagrams, utilizing the Poisson exponential-binominal limit, was used to verify the nonrandomness of project data (1).

The fabric diagram is a standard method of portraying structural orientation data and is widely used in structural geology texts (3, 4). The poles of the fracture planes are plotted on a circular grid which is a projection of a reference hemisphere to a horizontal plane. By convention, the lower hemisphere is used in a fabric diagram, and the grid is constructed such that an area on the projection is equivalent to the corresponding area on the reference hemisphere (Schmidt or Lambert equal-area azimuthal). When plotted, the pole of a fracture will be 180° from the dip direction and 90° from the strike direction. The concentration of poles is contoured using a counting circle which represents 1% of the total area of the diagram. A rectangular grid pattern, based on the radius of the counting circle, is superimposed on the fabric diagram and the counting circle is moved systematically over the grid. All fracture poles within the circle are totaled and this number is recorded on the grid intercept. This matrix of numbers can be contoured to provide a diagram to visually inspect the concentration and attitude of the fracture sets.

According to the Poisson limit for the sample of 100 fractures the probability of finding at least x number of fractures in a 1 percent area (with random samples) is as follows:

x	probability
0	1.00
1	.63
2	.26
3	.08
4	.02
5	.004
6	.0006
7	.0001

Thus, a 3% concentration (three fractures) on a fabric diagram would occur only eight times in 100 samples, and a 7% concentration only once in 10,000 samples. Taking a probability of 0.02 as a level of significance (one chance in 50 of being wrong), for any sample of 100 fractures, a concentration of four or more fractures per 1% area would be nonrandom. Because all of the individual detail-line samples of 100 or more fractures had concentrations of greater than four fractures per 1% area, as did the total detail line and the fracture set mapping, the fractures appear to be nonrandom.

However, apparent nonrandom patterns could also be introduced in a plot of a sample because of sample technique bias. Therefore, the statistical test does not prove conclusively that the true population is nonrandom. More significant is the coincidence of concentrations on the plots regardless of the sampling methods. Several of the strong fracture sets reappeared fairly consistently in the individual plots of each detail line, the total detail line, and the plots of the fracture set mapping. Borehole camera data and oriented core data also showed similar concentrations although there was considerable bias in the sampling technique. The stereoplots of the data from the Phase I geologic investigations are given in figure 5. The regularly shaped segments denote areas in which fracture concentrations appear in one, or more, stereoplots.

Three fracture sets appeared to be quite persistent: one striking east-west and dipping 60° to 70° to the south, the second striking north-east and dipping 40° to 55° to the northwest, and the third striking northwest and dipping 75° to 85° to the southwest. A number of other fracture sets are present but are not as clearly defined. In particular, there are two sets striking northwest, one dipping east 70° to 80° and one west 70° to 80°, respectively; and two fracture sets striking northeast, one dipping between 30° and 40° to the east and one dipping 50° to 60° to the east, respectively.

Sample Bias

Apparent differences in fracture intensity between samples can result from (1) orientation of linear samples, (2) the measuring technique, and (3) actual differences of fracture intensity from sample point to sample point. To illustrate, a vertical linear sample, such as a borehole, would not intersect a vertical fracture set unless drilled exactly along a fracture. Also a fracture set at a high dip angle would show fewer intercepts than a fracture set with the same spacing but at a lower dip angle. The geometric relationship is

$$I = \frac{n}{L \cos \theta}$$

where I = intensity
L = length of sample
n = number of fractures observed
θ = dip of fractures.

A horizontal sample (such as a detail line) would intersect very few horizontal fractures or fractures striking parallel to the line. The geometric correction is:

$$I = \frac{n}{L \sin \theta \sin b}$$

where b is the acute angle between the line bearing and the fracture set bearing. The uncorrected plot of the oriented core data (figure 5D) shows the effect of this bias. Note that the uncorrected plot shows fewer high-angle fractures.

Sampling techniques may also introduce a bias. For example, because it is more difficult to log flat fractures in the borehole camera photographs, fewer low-angle fractures appear in the plot (figure 5C). A study is now in progress to determine the optimum bias corrections to be applied to the data.

The 1% counting circle of the contouring method covers a 20° segment on the projection, resulting in a rounding effect when data are combined for the contoured plot. The actual mean attitude of a fracture set could be $\pm$ 10° away from a grid point where the summation is recorded; also, two concentrations which are 10° apart may be combined in a single high value and recorded at a grid point. Thus, a more accurate representation of the attitudes of a fracture set results from a plot of poles or from the computed, mean value of the actual poles.

Fracture Prediction Program

A computer program was developed to calculate the variation of fracture intensity, with respect to the position of the sample location, and estimate the intensity at points where samples could not be obtained (5). Fracture intensity values are predicted for every 50-foot-square block on the basis of a weighted average of the neighboring samples.

The method of weighing and the attitude range to be predicted are the input data. A predictability ratio is also computed for each block based on agreement between predicted values and actual observations at sample points as well as distance from the nearest sample.

A statistical test of Phase I data gave an average of 43% agreement between predicted and measured intensities, 35% agreement for detail-line data, and 14% agreement for borehole camera data. The three persistent fracture sets gave significantly higher agreement than the others.

Determination of Pit Slope Angles

The fracture set data and major structural mapping were used together with the stress and strength determinations to select new slope angles. The major structure mapping showed that no critical failure conditions such as a major structure or an intersection of major structures dipping into the pit was present in the wall of the Kimbley Pit. On the basis that a slope angle which exceeded the dip of a prominent fracture set would leave unsupported wedges of rock which could slide into the pit, the strong fracture set striking east-west and dipping south into the pit at 60° to 70° was considered to be the maximum slope angle along the north wall. (This limit was substantiated during the mining phase where a small wedge failed when inadvertently undercut.) The west wall did not have as clear cut a limit, but an overall slope angle of 57° was chosen on the basis of the fracture set which strikes north-south and dips 50° to 60° to the east.

Several lesser fracture sets strike about north-south and dip 30° to 40° to the east; however, because these sets had not failed in the original pit wall, and the specimens of rock tested in the laboratory did not fail along these sets, there was reason to believe that the lower angle sets would not create slope instability. This result illustrates that fracture strength data are necessary.

PHASE II STUDIES

Following the development of a preliminary pit design, two adits were driven into the west wall of the Kimbley Pit. These were at the 6725 and 6515 elevations. The primary purpose of the adits was to provide a site for strain and displacement instrumentation and to monitor stress changes in the slope behind the pit. In addition, they provided access to a portion of the rock mass that had been previously sampled only by borehole techniques. This information had been used in the structure prediction program and had been part of the basis for the determination of the probable structural fabric existing throughout the rock mass. Direct sampling of visible structures in the adits permitted an evaluation of the borehole sampling technique and formed the basis to prove the ability of the prediction program to provide detailed structural information for inaccessible portions of the rock mass. A section of the pit wall, which shows the relationship of the old and new pit faces, the adits, and some of the boreholes, is given in figure 6.

Sampling Methods

The detail line sampling technique was selected to sample the adit fractures. A line was painted at waist height along both ribs of both adits. A tape measure was strung along the line and the attitude of every fracture that intersected the line was measured and logged together with the tap intercept. A notation as to the visible length (extent) of the fracture trace was also made. In addition, vertical sample lines were run from the floor to the back at 25-foot intervals along both ribs. The data from the horizontal lines and the vertical lines were compiled separately in order to permit an evaluation of the linear sampling technique along a blasted rock face. The fabric diagrams of the data from the Phase II geologic investigations are given in figure 7.

The data were used to refine the detail-line sampling technique. The following parameters were developed to define the requirements of an adequate structural sample:

1. To insure an adequate sample, a minimum of 100 fractures should be recorded.

2. Maximum permissible sample separation to insure continuity between samples is 100 feet.

3. Fractures less than 2 feet need not be included in a sample since they do not contribute significantly to the overall pattern.

It must be emphasized that the quantitative aspects of these parameters will have to be determined anew for each different geologic environment. However, these criteria indicate the approximate magnitudes to be expected in a typical blasted rock mass.

Based on this information, a sampling program was outlined for use on the new pit face as it was exposed by mining. To insure complete coverage, the sample spacing was reduced from the recommended 100 feet to 40 feet and an attempt was made not to exceed this interval. The sampling program produced 35 detail-line samples consisting of about 100 fractures each.

Comparison With Phase I

The general agreement between the results of the Phase I and Phase II was very good, see figures 5 and 7. The three strong fracture sets and most of the lesser sets shown in the Phase I data appear in the plots of the Phase II data. However, the relative magnitude of the concentrations varied considerably, especially in the plots of the data from the adits, see figures 7B and 7C. This difference is probably due to the fact that the sample area in the adits is small compared to the sample area in the slope wall, and to the fact that the adit data is subject to linear bias.

Vertical sampling in the lower adit showed a fracture set that dips into the pit at 20° or less. Although this fracture set appeared in the data from the Phase I investigations, its concentration was so weak that it was not considered significant, see figures 5A and 7A.

Horizontal sampling in the adits (in 25-foot lengths) showed large variations in fracture intensities between the segments and also between opposite ribs of the same adit. It was also observed on the pit face that fracture sets would be pronounced and well developed in one area of the pit and would be less pronounced elsewhere. B. K. McMahon of the Colorado School of Mines made similar observations concerning the metamorphosis of the Colorado Front Range.

The fracture prediction program, which used Phase I data, gave predicted fracture intensities at points along the adit which were in the same range of agreement as the rib-to-rib comparisons. Although the program produced acceptable data, it is being modified to account for the observed variations in fracture intensities over short distances.

Evaluation of Sample Techniques

In regard to future pit slope design investigations, the following comments on sampling techniques are pertinent.

No single sampling technique is clearly superior to the others, in many respects they are complementary.

Fracture set mapping is the most comprehensive technique in that a large amount of information is assimilated by the geologist in choosing fracture sets. It is the fastest and lowest cost technique but relies heavily upon the judgment of the observer. Each fracture set observation has only one attitude measurement, which may not reflect the true mean attitude of the fracture set. In addition, spacing is estimated rather than measured.

Detail-line sampling gives more precise data on fracture set intensity and attitude variability at the sample point. It is more time consuming and thereby more expensive. Linear bias must also be considered.

Ideally, a sample program should consist of a combination of sampling methods, as follows:

1. A conventional geologic mapping program to locate major structures and outline structural domains.

2. A fracture set mapping program to determine the well-developed fracture sets.

3. A detail-line program starting with widely spaced samples. Sequential sampling should be continued between the original sample points until the last few samples make no significant change in the fracture pattern for the structural domain.

4. Oriented core and/or borehole camera techniques should be used to obtain subsurface information. Hole locations and orientations should be laid out so that all fracture attitudes will be sampled.

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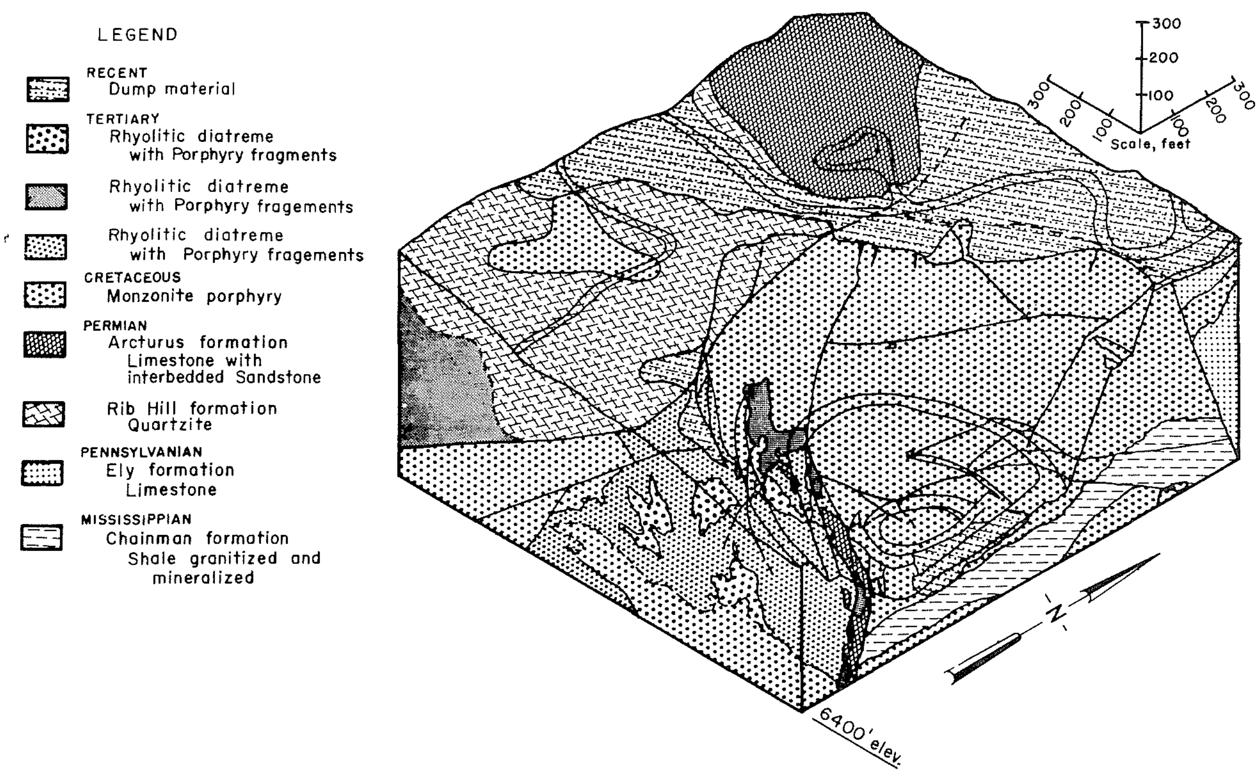


FIGURE 1.—Isometric View of West End of the Kimbley Pit, Showing the Geology

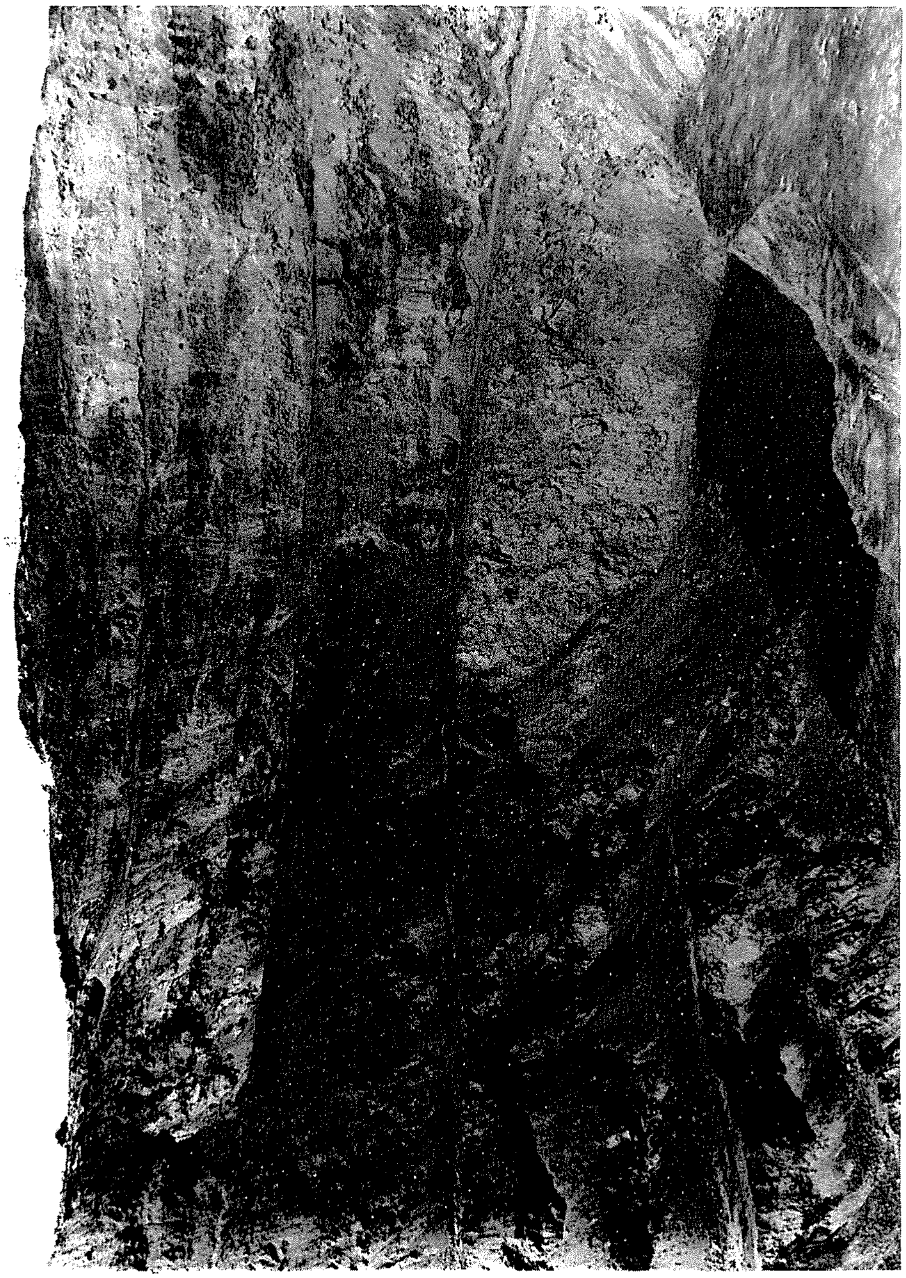


Figure 2.- View of Kimbley Pit
looking west

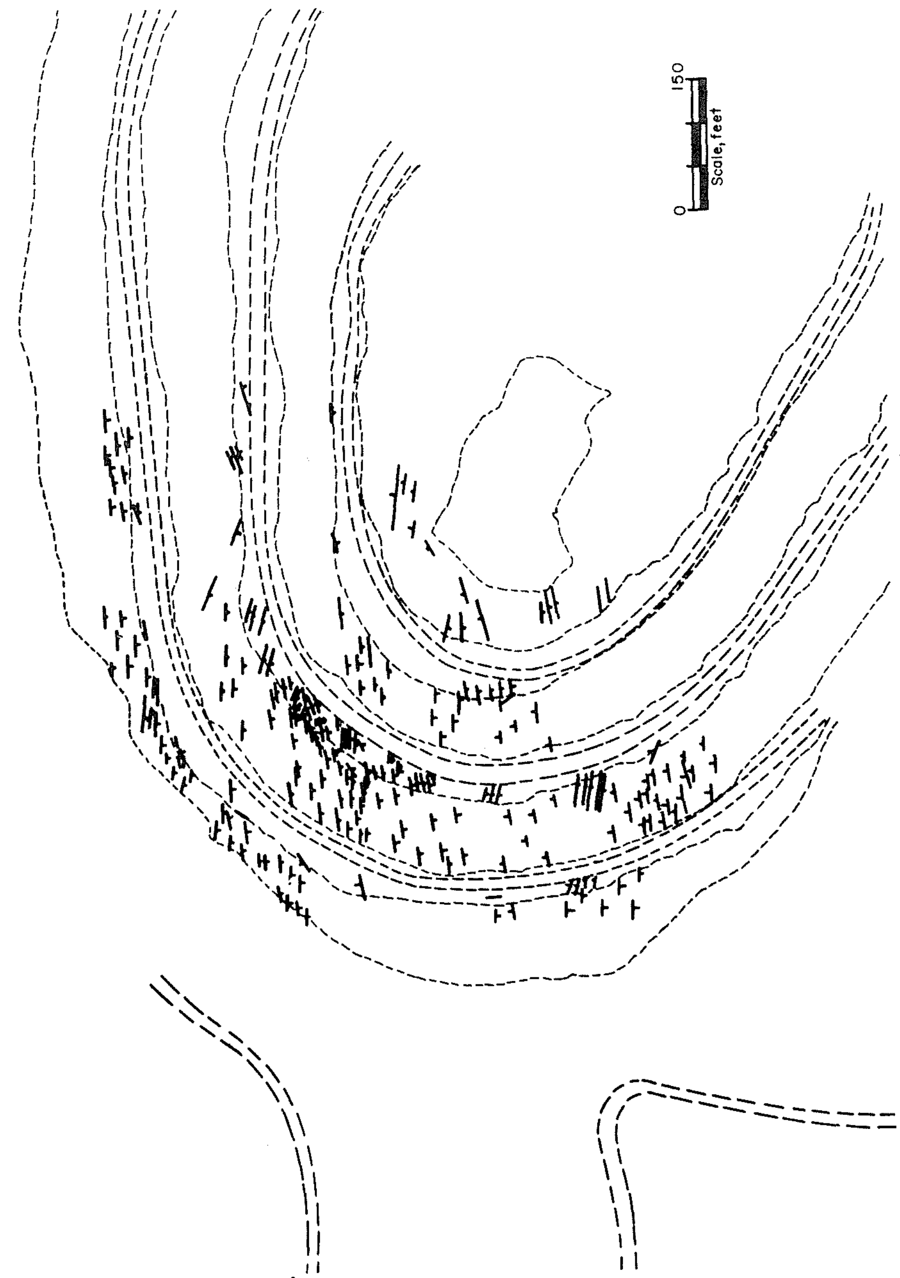


FIGURE 3.-East-West Fracture Sets

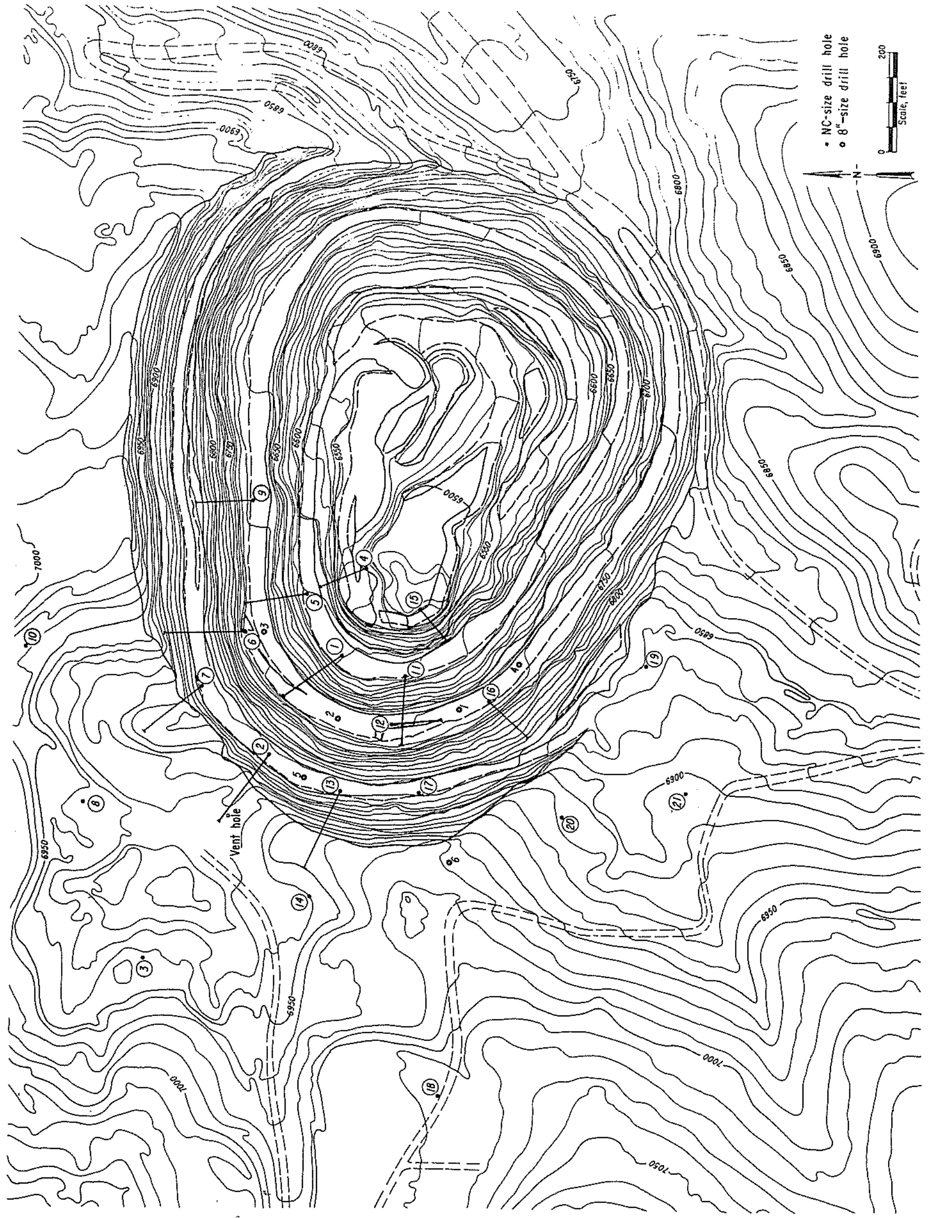
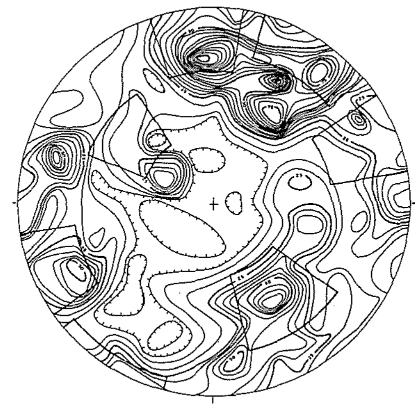
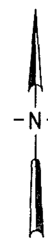


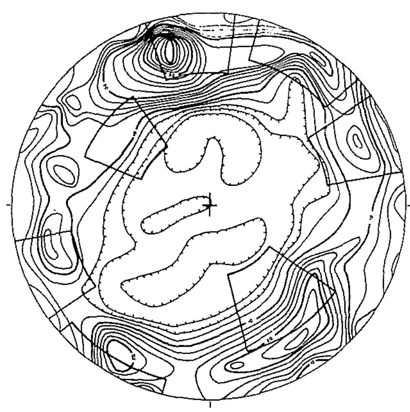
FIGURE 4.—Plan Map Showing Locations of Drill Holes, used for Borehole Investigation

A.–Plot of 211 Fracture Sets, Macro Data; Contour Interval Equals 100 Fractures.



B.–Plot of Detail Line Data; 2,178 Fractures, Contour Interval Equals 5 Fractures.





C.–Plot of Borehole Camera Data; 801 Fractures, Contour Interval Equals 2 Fractures.

D.–Plot of Oriented Core Data; 662 Fractures, Contour Interval Equals 1 Fracture.

FIGURE 5.–Plots of Data from Structure Examinations in Phase I.

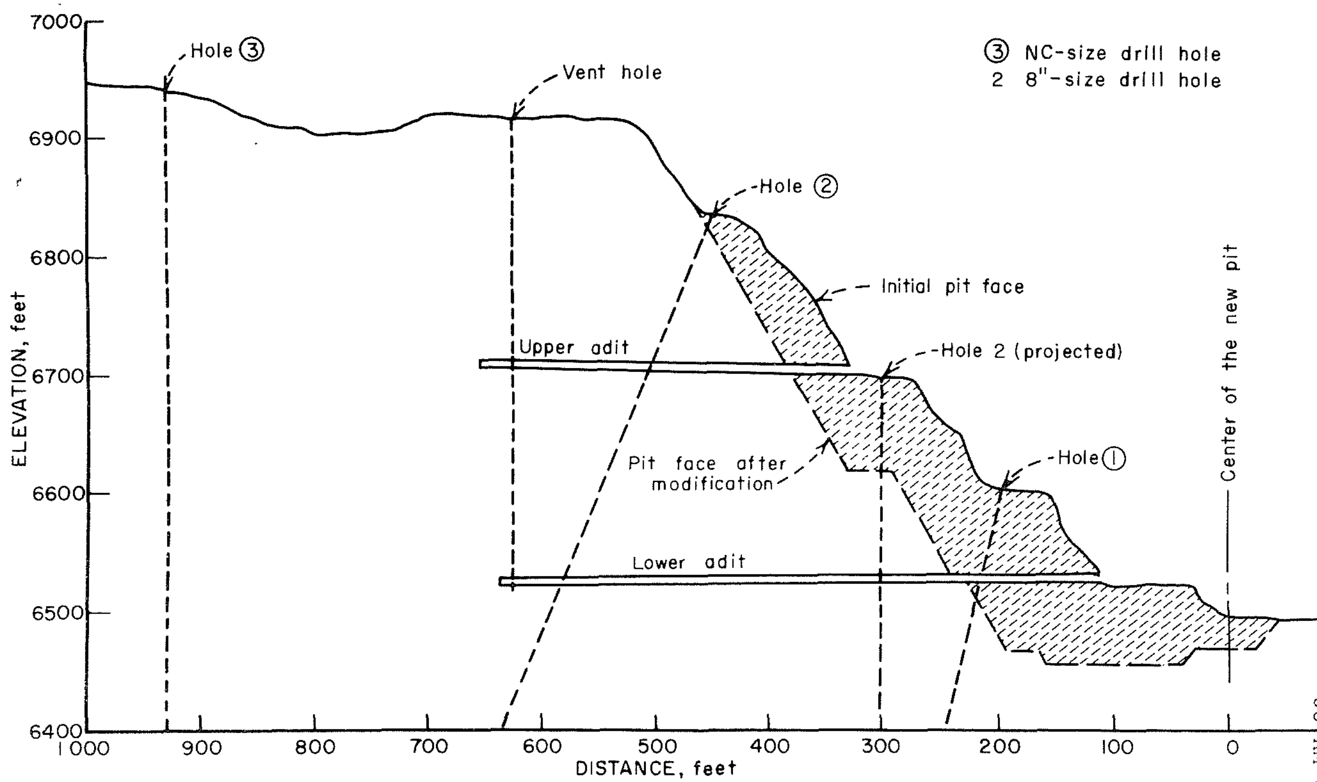


FIGURE 6.—Section Showing the Spatial Relationship Between the Two Pit Faces, the Adits, and Four of the Bore Holes

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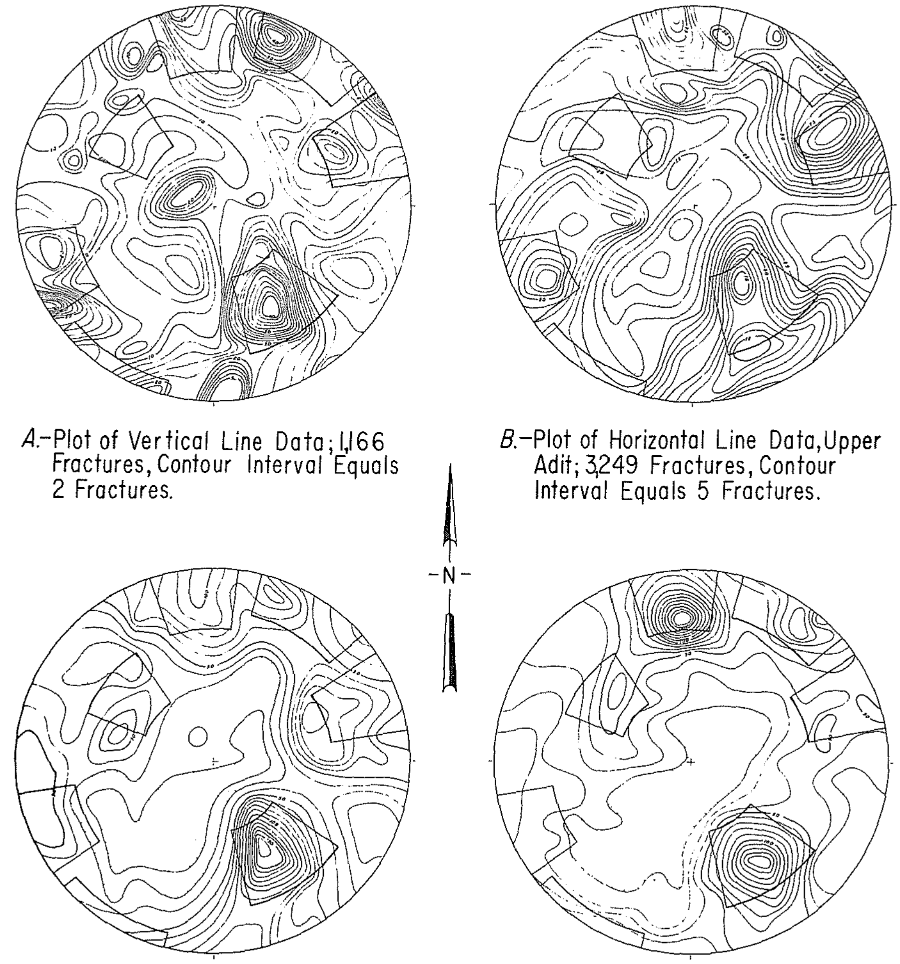

A.–Plot of Vertical Line Data; 1,166 Fractures, Contour Interval Equals 2 Fractures.

B.–Plot of Horizontal Line Data, Upper Adit; 3,249 Fractures, Contour Interval Equals 5 Fractures.

C.–Plots of Horizontal Line Data, Lower Adit; 3,916 Fractures, Contour Interval Equals 10 Fractures.

D.–Plots of Data from New Slope Face; 3,390 Fractures, Contour Interval Equals 10 Fractures.

FIGURE 7.–Plots of Data from Structure Examinations in Phase II.