GEOLOGIC FACTORS RELATED TO BLOCK CAVING
AT SAN MANUEL COPPER MINE, PINAL COUNTY, ARIZ.
PROGRESS REPORT, APRIL 1954-MARCH 1956

BY E. D. WILSON
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BUREAU OF MINES
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SUMMARY AND INTRODUCTION

A study of factors related to subsidence was specified in a project proposal entitled "Structural Analysis of Block-Caving Operation, San Manuel Copper Mine, Pinal County, Ariz.," approved by the Bureau of Mines early in 1953. This proposal was designed by Charles H. Johnson, then chief of the Base Metals Branch of the Minerals Division, Washington, D. C., assisted by Dr. Leonard Obert, chief of the Applied Physics Branch, Region VIII (now Region V), College Park, Md., and E. D. Gardner, chief mining engineer, Bureau of Mines, Washington, D. C. It read as follows:

This project is a study of the mechanics of undercut block caving in a deep ore deposit. The San Manuel is a low-grade disseminated copper deposit containing nearly a half billion tons of ore lying at depths of 500 to 2,000 feet. Development is just starting. Production is to begin in 3 to 4 years (in 1956) at a rate of 30,000 tons of ore a day, or 60,000 tons of copper a year. A Government loan of $90,000,000 (subsequently increased to $94,000,000) and a long-term Government purchase contract support the capital investment, which will total about $110,000,000.

Justification for the proposed investigation is partly in the belief that a better understanding of the laws that govern caving, subsidence, and the transmission of ground pressures will have application in future mining ventures of this type, and partly in the expectation that the San Manuel operation itself will benefit from such knowledge as is gained.

The work will consist first of a structural analysis of the problem based on a thorough study of the geology, the physical properties of the rock types, and the proposed system of mining; secondly, the use of various test techniques and types of equipment to measure ground movement and rock stresses from the time of initial development until a substantial segment of the ore body has been extracted, so that the complete pattern of behavior can be determined.

Although devoted mainly to such structural features as faults, fractures, and joints, the geologic study also concerns miscellaneous factors that might affect rock strength.

LOCATION AND ACCESSIBILITY

The San Manuel copper mine, owned by the San Manuel Copper Corp., is situated in the Old Hat district of southeastern Pinal County, Ariz., 45 miles by highway northeast of Tucson, 5 miles southwest of Mammoth, and 8 miles north of the new town of San Manuel (fig. 1). The San Manuel ore body is less than 1 mile south of
Figure 1. - Index map showing location of San Manuel copper mine.
the Mammoth-St. Anthony or Tiger mine area, which has been described by Peterson\(^2\) and by Creasy.\(^3\)

**HISTORY**

Detailed accounts of the discovery and development of San Manuel have been published.\(^4\) From these sources and subsequent information, the history may be outlined as follows:

1870–80, approximate: Small-scale prospecting of copper-stained outcrop area at southern base of Red Hill.

1906: Location of some claims in Red Hill area.

1915–17: Two exploratory churn-drill holes put down on or near the outcrop, with discouraging results.

1925: Location of San Manuel claims 1–5.

1942: The owners of the San Manuel group of claims applied to the Reconstruction Finance Corporation for a development loan. Henry W. Nichols, one of the owners, submitted a supporting report.


1944: Federal Bureau of Mines drilling gave important results. Magma Copper Co. arranged to purchase property and began drilling in December. Shortly afterward Anaconda Copper Mining Co. began drilling on adjacent ground, the Houghton group.

1945: Federal Bureau of Mines drilling terminated in February after attaining a total of 15,839 feet in 17 holes. San Manuel Copper Corp., a subsidiary of Magma Copper Co., organized in September.

1948: San Manuel Copper Corp. completed churn-drilling program and started shaft sinking and underground development.


1955: By latter part of year, the fifth shaft had been sunk, and underground development was sufficient for block-caving operations to be begun. The new town of San Manuel, including concentrator and smelter, in addition to 29-1/2 miles of railway to Hayden, had been built.

1956: Production of copper was begun early in the year. San Manuel is rated as probably the world's largest underground copper mine from the standpoint of ore tonnage.

FIELD WORK AND ACKNOWLEDGMENTS

The geologic field work for this project was begun in April 1954. To March 15, 1956, approximately 100 days had been spent in underground mapping and 21 days in surface studies.

Mapping of the faults, fractures, and joints underground was done by means of a 15-inch plane table, Brunton compass, and tape on a scale of 1 inch equals 50 feet. In many places, however, the compass was unsatisfactory because of strong local magnetic variation caused by electric trolley systems, iron pipe, steel sets, or equipment. For measuring directions in such areas, a special direct-reading azimuth protractor (fig. 2) was designed. It has been found to be adequate for this purpose as well as more rapid and accurate than the compass for mapping structural features, wherever good base maps are available.

A transit was used for control in mapping surface features.

Officials of San Manuel Copper Corp. generously made available maps, information, and facilities for the work. Special acknowledgments are due H. J. Steele and J. D. Pelletier, geologists, and H. W. Seaney and M. A. Zappia, stope engineers, for their efficient cooperation. Richard T. Moore of the Arizona Bureau of Mines, University of Arizona, contributed valuable assistance. Much fundamental information was obtained from B. S. Butler of the University of Arizona, and P. C. Benedict, geologist for Newmont Exploration Limited. S. C. Creasey and Robert Davis of the Federal Geological Survey mapped the Mammoth 7-1/2-minute quadrangle during 1954, and Creasey continued underground studies in 1955 for a forthcoming report.

PHYSICAL FEATURES

The San Manuel mine area is within secs. 34 and 35, T. 8 S., R. 16 E., on a sharply dissected slope that rises southwestward from the San Pedro River. Thus the topography is characterized by steep-sided, northeastward-flowing gulches between moderately hilly ridges. Locally the relief ranges from 3,450 feet above sea level on Red Hill to 3,000 feet in Tucson Wash west of shaft 1, and 2,400 feet at the San Pedro River, 3-1/2 miles east of Red Hill.

Rainfall there probably amounts to about 13 inches per year. Most of it occurs during July-August and December-February.

During the summer rainy seasons, the washes and the San Pedro River may carry torrential floods, although throughout most of the year they tend to be dry.

The relations of water levels to oxidation and block caving will be discussed in a subsequent section of this report.
Figure 2. - Direct-reading azimuth protractor. Compass card (A) is adjusted so that bearing of drift being mapped is indicated at (B); it is then locked to strike board (E) with friction lock operated by thumb screw also located at (B). If edge of strike board is held parallel to strike of a fracture, and handle (D) is held perpendicular to bearing of drift, the strike of the fracture is shown by pointer (C). Designed with collaboration of Richard T. Moore.
ROCKS OF MINE AREA

The principal rock units of the San Manuel mine area, from oldest to youngest, may be generalized as follows: 5/

**Pre-Cambrian:** Quartz monzonite or Oracle granite. Consists essentially of coarse-grained feldspar, quartz, and biotite. The quartz monzonite is one of the principal host rocks of the San Manuel ore body.

**Upper Cretaceous (?):** Basaltic and andesitic flows, flow breccia, and agglomerate or conglomerate. Forms a thick series, termed the "Cloudburst" by San Manuel geologists. Locally shows hypogene sulfide mineralization, according to Pelletier. Encountered in shaft 3-B between elevations 1938 and 1384.

**Late Cretaceous or early Tertiary:** Monzonite porphyry. Consists essentially of quartz, feldspar, and biotite. Its feldspar phenocrysts characteristically appear as white spots in grayish groundmass. Intrudes, with irregular and commonly gradational contacts, the quartz monzonite. The monzonite porphyry, like the quartz monzonite, is one of the principal host rocks of the San Manuel ore body.

**Late Cretaceous or early Tertiary:** Diabase. Typically fine-grained, dark gray, or reddish gray. Forms dikes and irregular intrusive bodies. Mineralized in the mine area.

**Tertiary:** Rhyolite, light gray to pink. Occurs as dikes and irregular intrusive masses, not known to be mineralized.

**Late Tertiary and Early Quaternary:** Gila conglomerate. A series of weakly stratified, moderately to durably consolidated gravels and boulders in a sandy to silty cement. Locally contains beds of tuff. Absent over a very small portion of the ore body, but thickens from a feather edge to more than 1,300 feet in hanging wall of San Manuel fault.

**Later Quaternary and Recent:** Alluvial slope deposits of locally stratified, weakly consolidated gravel, sand, and silt, unconformably overlying the Gila conglomerate northeast of the Cholla fault.

STRUCTURE OF MINE AREA

Many of the main structural elements of the San Manuel mine area are not yet well enough understood to be illustrated satisfactorily in cross section.

Although Gila conglomerate mantles all features earlier than itself over the entire area planned for block caving, a considerable array of facts regarding the fractures and other items that might affect block caving is available from mine openings, as shown on figures 5 to 50 and from drill-hole records. Much detailed mapping and correlation are required before these data can be thoroughly appraised.

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Steele, H. J., and Pelletier, J. D., unpublished information.
Figure 3. - Composite map of San Manuel mine workings.
One of the earliest structures deduced in the mine area is indicated by the configuration of the monzonite porphyry. This rock intrudes the quartz monzonite in a complex manner that probably was controlled largely by a preexisting low-angle fault zone; as stated by Schwartz, the principal mass of monzonite porphyry in the explored area lies above quartz monzonite and becomes thicker eastward.

Numerous fractures of both high- and low-angle types cut the quartz monzonite and monzonite porphyry in the mine, as described in subsequent paragraphs. Some of these breaks are pre-mineral, and others are later than mineralization.

Most of the latest fractures observed in the mine are of low-angle type, exemplified by the San Manuel fault, which separates the Gila conglomerate and the Cloudburst formation from the older rocks. The outcrop of this great fault, however, is displaced by steeply dipping faults of N. 20°-30° W. strike.

The San Manuel fault, so far as known, strikes between northwest and westward and is traceable for several miles. Within the mine area it dips approximately 30° southwestward at the surface but flattens to 15° or less at depth. In its hanging wall the Gila conglomerate beds prevailingly strike northwestward and dip northeastward 20°-45°; at least one reversal of dip in the conglomerate beds occurs south and east of the outcrop known as the Purcell window. The San Manuel fault characteristically forms a gouge zone several feet thick, immediately above which the conglomerate shows relatively little disturbance other than the aforementioned tilting. In strong contrast, the porphyry below the gouge zone is markedly sheared (fig. 6); this shearing is common at many places throughout the mine workings and in surface exposures.

In previous descriptions the San Manuel fault has been interpreted as a normal fault, formed before the conglomerate beds were tilted to their present attitude. On the contrary, evidence obtained during the present study indicates it to be a thrust fault of rather wavy strike and dip that rolls northeastward over the porphyry outcrop 2,000 feet northeast of shaft 2.

The type or relative direction of displacement on the San Manuel fault is an important item from the standpoint of fracture-pattern interpretation; it generally is recognized that the compressive stresses causing a thrust fault would result in a fracture pattern quite different from the pattern associated with a normal tensional or gravity fault.

In summary, the main events since deposition of the Cloudburst series are interpreted by the writer as follows:

1. Regional compression and development of fracturing. The deformation culminated with low-angle faulting and emplacement of the monzonite porphyry. Continuance of the compressional forces caused the fracturing to extend throughout the monzonite porphyry.

2. Primary (hypogene) sulfide mineralization.

3. Long period of erosion accompanied by oxidation and secondary (supergene) enrichment.

4. Deposition of Gila conglomerate.

5. Renewal of regional compression; development of San Manuel fault as a low-angle thrust, accompanied by folding and tilting of rocks in its hanging wall.

6. Relaxation of regional compression, followed by normal faulting of N. 20° to 30° W. strike.

ORE BODY

For descriptions of the San Manuel ore body, the reader is referred to the works of Steele and Rubly,8/ Chapman,9/ Goss,10/ and Schwartz.11/ A brief outline, based largely upon their descriptions, is given for orientation.

With a copper content of 0.5 percent or more, the ore body is 6,800 feet in known length, trending N. 60° E., by 3,000 feet in maximum known width. The greatest thickness of ore drilled was 1,700 feet. The depth to ore averages several hundred feet. According to Schwartz,12/ the western part of the ore body is a tabular mass dipping southeast, with a lower boundary of hydromica-pyrite rock and an upper boundary of marginal biotite rock.

To the east, however, the deposit expands in width, particularly at depth; and the copper-bearing zone swings around to the south, making it hook-shaped.13/

The copper ore consists of mineralized quartz monzonite, monzonite porphyry, and a minor amount of diabase, with little distinction in grade between different kinds of rock that have undergone similar hydrothermal alteration.14/

The ore mineralization is associated with hydrothermal rock alteration to sericite, pyrite, quartz, chlorite, kaolinite, and minor amounts of other minerals.

Oxidation, in general, ranges from 285 to more than 1,600 feet below the surface. Supergene or secondary enrichment here is relatively unimportant from the standpoint of ore. Neither the oxidation nor the enrichment is related to the present erosion surface or the present water table. Their structural history appears to be somewhat complex.

The water table before the beginning of mine development ranged from 2,450 to 2,992 feet above sea level, or approximately 300 to 800 feet below the surface.

13/ Work cited in footnote 12.
14/ Work cited in footnote 12.
Water in the mine workings has not been excessive; for example, in shaft 4, below the 1475 level, it amounted to 750 gallons per minute during January 1955.

FEATURES MAPPED IN SAN MANUEL MINE

Scope and Limitations of Study

The present study thus far has been devoted largely to structural features within or near the areas scheduled for early caving, where mapping operations would be prohibited after subsidence began. Also, incidental observations were made of other factors that might affect block caving, especially rock types, alteration, mineralization, oxidation, and presence of water; fortunately, many supplementary data regarding these items are available from churn-drill and core-drill records.

The observations underground are hampered to a considerable extent by lagging in the timbered drifts. It effectively conceals all drift backs except in portions of the undercut level. The grizzly drifts for the most part are tightly lagged. Wall lagging throughout much of the fringe, panel, ventilation, and haulage drifts is spaced so closely that comprehensive mapping there is difficult. Satisfactory exposures of the walls were available in the undercut level and most of the 1285 level.

Fracture Systems

Figure 4 explains the principal symbols used on the map sheets. Mapping for this study on the 1285, 1415, undercut, and 1475 levels of San Manuel mine (figs. 5 to 51) has demonstrated that the fractures do not as a rule strike at random or "in every direction"; on the contrary, they trend in definite systems or sets, with relatively few exceptions. These systems are: N.-S.; E.-W.; N.30°E.-S.30°W.; N.45°E.-S.45°W.; N.60°E.-S.60°W.; S.60°E.-N.60°W.; S.45°E.-N.45°W.; and S.30°E.-N.30°W. For this report, the designations are simplified as N.-S., E.-W., N.30°E., N.45°E., N.60°E., N.60°W., N.45°W., and N.30°W.

Density of Distribution

Although the number or density of fractures belonging to each system varies from place to place, as shown by the graphs (figs. 52 to 66), a rather consistent order of dominance exists within those areas for which actual counts were made, as shown by the following table;
**EXPLANATION FOR STRUCTURAL MAP SHEETS**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cp</td>
<td>chalcopyrite</td>
</tr>
<tr>
<td>Fe</td>
<td>iron</td>
</tr>
<tr>
<td>Cu</td>
<td>copper</td>
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<tr>
<td>py</td>
<td>pyrite</td>
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<tr>
<td>porph</td>
<td>porphyry</td>
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<tr>
<td>st</td>
<td>stain</td>
</tr>
<tr>
<td>ox</td>
<td>oxidized</td>
</tr>
<tr>
<td>wk</td>
<td>weak</td>
</tr>
<tr>
<td>sp</td>
<td>spaced</td>
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<tr>
<td>gen</td>
<td>generally</td>
</tr>
<tr>
<td>loc</td>
<td>locally</td>
</tr>
<tr>
<td>b</td>
<td>blocks</td>
</tr>
<tr>
<td>&lt;</td>
<td>less than</td>
</tr>
<tr>
<td>&gt;</td>
<td>more than</td>
</tr>
<tr>
<td>fracs</td>
<td>fractures</td>
</tr>
<tr>
<td>gg</td>
<td>gouge</td>
</tr>
<tr>
<td>jts</td>
<td>joints</td>
</tr>
<tr>
<td>d</td>
<td>dark</td>
</tr>
<tr>
<td>hw</td>
<td>hanging wall</td>
</tr>
<tr>
<td>fw</td>
<td>footwall</td>
</tr>
<tr>
<td>v</td>
<td>vein</td>
</tr>
</tbody>
</table>

### Directions

- **N**, **S**, **E**, **W**: directions

### Fracture Angles

- $\angle_{fs}$: fracture, dip in degrees
- $\angle$: fracture, vertical

**BASE MAP OF MINE WORKINGS FURNISHED BY SAN MANUEL COPPER CORP**

**Figure 4.** - Explanation of symbols used on structural map sheets.

Geology by E. D. Wilson.
Figure 5. - Index of structural map sheets, 1285 level.
Figure 6. - Structural map sheet, 1285-1.
Figure 8. - Structural map sheet, 1285-3.
Figure 12. - Structural map sheet, 1285-7.
Figure 13. - Structural map sheet, 1285-8.
Figure 14. - Structural map sheet, 1285-9.
Figure 16. - Structural map sheet, 1285-11.
Figure 18. - Index of structural map sheets, 1415 level.
Figure 19. - Structural map sheet, 1415-1.
Figure 20. - Structural map sheet, 1415-2.
Figure 21. - Structural map sheet, 1415-3.
Figure 23. - Structural map sheet, 1415-5.
Figure 24. - Structural map sheet, 1415-6.
Figure 30. - Structural map sheet, 1415-12.
Figure 31. - Structural map sheet, 1415-13.
Figure 33. - Structural map sheet, 1415-15.
Figure 35. - Structural map sheet, 1415-17.
Figure 36. - Structural map sheet, 1415-18.
Figure 38. - Structural map sheet, 1415-20.
Figure 40. - Structural map sheet, 1415-22.
Figure 41. - Structural map sheet, 1415-23.
Figure 42. - Structural map sheet, 1415-24.
Figure 43. - Index of structural map sheets, 1475 level.
Figure 45. - Structural map sheet, 1475-2.
Figure 46. - Structural map sheet, 1475-3.
Figure 47. - Structural map sheet, 1475-4.
Figure 48. - Structural map sheet, 1475-5.
Figure 49. - Structural map of part of block 7-1, undercut level.
Figure 50. - Cross section through southeastern portion of block 7-1, looking northwest (refers to fig. 49).
Figure 51. - Structural map of part of block 9-1, undercut level.
Figure 52. - Fracture-density graph, block 7-1, 1285 level.
Figure 53. Fracture-density graph, block 7-1, undercut level, drifts 1-N and 3-S.
Figure 54. - Fracture-density graph, block 7-1, undercut level, drifts 6-S and 9-S.
Figure 55. - Fracture-density graph, block 7-1, undercut level, drift 1-W.
Figure 56. - Fracture-density graph, block 7-1, undercut level, drift 12-W.
Figure 57. - Fracture-density graph, block 7-1, 1415 level, panel 7, fringe drift.
Figure 58. - Fracture-density graph, block 7-1, 1415 level, panel 8, fringe drift.
Figure 59. - Fracture-density graph, block 7-1, 1475 level, drift A.
Figure 60. - Fracture-density graph, block 7-1, 1475 level, drift B.
Figure 61. - Fracture-density graph, block 7-1, 1475 level, drift C.
Figure 62. - Fracture-density graph, block 7-1, 1475 level, drift C, continued.
Figure 63. - Fracture-density graph, block 9-1, undercut level, drifts 1-N and 5-S.
Figure 64. - Fracture-density graph, block 9-1, undercut level, drifts 1-W and 4-W.
Figure 65. - Fracture-density graph, block 9-1, undercut level, drifts 8-W, 9-W, 10-W, 11-W, and 12-W.
Figure 66. - Fracture-density graph, block 9-1, 1415 level, panels 9 and 10, fringe drifts.
<table>
<thead>
<tr>
<th>Level</th>
<th>Interval</th>
<th>Feet of drift</th>
<th>Fractures mapped</th>
<th>Percent E.-W.</th>
<th>Percent N.-S.</th>
<th>Percent N.45°W.</th>
<th>Percent N.45°E.</th>
<th>Percent N.60°W.</th>
<th>Percent N.60°E.</th>
<th>Percent N.30°W.</th>
<th>Percent N.30°E.</th>
<th>Percent with low-angle dip</th>
</tr>
</thead>
<tbody>
<tr>
<td>1285</td>
<td>Uncaved before May 1954</td>
<td>2,400</td>
<td>612</td>
<td>41.0</td>
<td>15.7</td>
<td>14.7</td>
<td>13.9</td>
<td>5.7</td>
<td>4.1</td>
<td>2.6</td>
<td>2.3</td>
<td>23.5</td>
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<tr>
<td>1285</td>
<td>Block 7-1</td>
<td>400</td>
<td>113</td>
<td>31.8</td>
<td>23.0</td>
<td>15.0</td>
<td>9.8</td>
<td>6.2</td>
<td>6.2</td>
<td>3.5</td>
<td>4.4</td>
<td>17.7</td>
</tr>
<tr>
<td></td>
<td>do.</td>
<td>1,340</td>
<td>233</td>
<td>37.3</td>
<td>13.7</td>
<td>3.0</td>
<td>4.7</td>
<td>9.9</td>
<td>16.3</td>
<td>7.7</td>
<td>7.3</td>
<td>21.0</td>
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<tr>
<td></td>
<td>Block 7-1, panel 7 fringe drift</td>
<td>375</td>
<td>185</td>
<td>37.3</td>
<td>14.0</td>
<td>5.4</td>
<td>6.0</td>
<td>13.5</td>
<td>10.8</td>
<td>7.0</td>
<td>6.0</td>
<td>17.3</td>
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<tr>
<td></td>
<td>Block 7-1, panel 8 fringe drift</td>
<td>360</td>
<td>148</td>
<td>36.5</td>
<td>20.9</td>
<td>4.0</td>
<td>2.0</td>
<td>13.5</td>
<td>8.8</td>
<td>12.8</td>
<td>1.3</td>
<td>17.6</td>
</tr>
<tr>
<td></td>
<td>Block 7-1, drift A</td>
<td>350</td>
<td>91</td>
<td>38.5</td>
<td>17.6</td>
<td>4.4</td>
<td>5.5</td>
<td>13.2</td>
<td>10.9</td>
<td>5.5</td>
<td>4.4</td>
<td>16.5</td>
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<tr>
<td></td>
<td>Block 7-1, drift B</td>
<td>425</td>
<td>93</td>
<td>30.1</td>
<td>26.9</td>
<td>1.1</td>
<td>0</td>
<td>18.3</td>
<td>7.5</td>
<td>7.5</td>
<td>8.6</td>
<td>18.3</td>
</tr>
<tr>
<td></td>
<td>Block 7-1, drift C</td>
<td>600</td>
<td>147</td>
<td>40.1</td>
<td>17.7</td>
<td>.7</td>
<td>.7</td>
<td>12.9</td>
<td>7.5</td>
<td>18.4</td>
<td>2.0</td>
<td>21.8</td>
</tr>
<tr>
<td>Undercut</td>
<td>Block 9-1</td>
<td>1,340</td>
<td>269</td>
<td>41.6</td>
<td>25.3</td>
<td>.3</td>
<td>0</td>
<td>9.7</td>
<td>9.7</td>
<td>4.1</td>
<td>9.3</td>
<td>29.0</td>
</tr>
<tr>
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<td>200</td>
<td>62</td>
<td>38.7</td>
<td>8.1</td>
<td>1.6</td>
<td>0</td>
<td>17.7</td>
<td>9.7</td>
<td>14.5</td>
<td>9.7</td>
<td>29.0</td>
</tr>
<tr>
<td></td>
<td>Block 9-1, panel 10 fringe drift</td>
<td>1/400</td>
<td>106</td>
<td>37.7</td>
<td>34.0</td>
<td>0</td>
<td>0</td>
<td>7.5</td>
<td>2.8</td>
<td>11.3</td>
<td>6.6</td>
<td>33.0</td>
</tr>
</tbody>
</table>

1/ Includes connecting 25-ft. segments of grizzly drifts 9-1-1 to 9-1-7, inclusive.
Density Graphs

Variations in density for each fracture system within the areas of blocks 7-1 and 9-1 are shown graphically in figures 52 to 66.

On these graphs a relatively high point denotes for its particular fracture system a fault or a zone of weakness generally less than 25 feet wide. A plateau or high average of points denotes for its system a correspondingly wider fault zone or zone of weakness.

For example, on figure 58, block 7-1, 1415 level, panel 8, fringe drift, a N.-S. high, at sta. 136 + 50 ft. SE., indicates a narrow fault zone which the map (fig. 36) confirms as narrow.

On figure 58, panel 8, fringe drift, a notably strong E.-W. high, at sta. 137 + 175 ft. SE., indicates a fault zone that projects on the map in alignment with a similarly strong E.-W. high indicated on figure 66, panel 9, fringe drift, at sta. 154 + 80 ft. NW. On the map (figs. 18, 36, and 49) it projects from the southeast portion of block 7-1 undercut, drift 12-W, westward past the intersection of coordinates E. 12600 and N. 9800, a total distance of more than 600 feet.

Figure 57, block 7-1, 1415 level, panel 7, fringe drift, provides examples of wide zones of fracturing. From sta. 104 to 104 + 140 ft. SE. to 104 + 300 ft. SE. it builds up a high average and indicates an important zone. On the same graph, E.-W. fracturing is seen to be important throughout; also it forms a high average from sta. 104 to 104 + 50 ft., and a higher plateau from sta. 104 + 25 ft. to 104 + 350 ft.

The graphs serve also to show at a glance the abundance and persistence of low-angle fractures. For example, figures 52 to 66 indicate that low-angle fractures are more abundant in block 9-1 than in block 7-1.

Displacement and Gouge

As shown on the maps (figures 4 to 51), many of the fractures are marked by gouge, which commonly ranges from less than 0.1 inch to a few inches in thickness. At many places it occurs associated with breccia to form zones as much as 10 or more feet across.

As a rule, gouge is most abundant along fractures of wavy, rather than planar surface. Wavy fractures of steep dip are relatively abundant among the N.-S and E.-W. systems, much less common on the N. 60° W. and N. 60° E., and rare but not lacking among the other systems. Wavy surfaces and gouge are characteristically common on the low-angle fractures.

Although numerous gougy fractures or fracture zones may be traced for considerable distances horizontally and vertically, a large proportion may not be projected with certainty from one level to another or even across a drift. This lack of continuity may represent local pinching together of the fracture walls, but more commonly it is found to result from displacement.

Aside from the interesting question as to the amount of displacement implied, the presence and quantity of gouge are important from the standpoint of block caving; a weak material, gouge is noted for acting as a lubricant, especially when wet.
Relative Age

The present fracture pattern at San Manuel was initiated before sulfide mineralization, as proved by primary sulfide veinlets in the fractures of all eight systems. As pointed out by Schwartz\(^{15}\) on the basis of drill records, the premineral fracturing occurred during at least three intervals - before and after intrusion by the monzonite porphyry and after intrusion by the diabase. He also noted the existence of many preconglomerate shear zones.

So far as determined by the present study, the N.-S. and E.-W. fractures are mutual in age and as a rule cut all other steeply dipping fractures in the mine workings, except possibly those of the Cholla, East (Mammoth?), and West type, which vary from approximately N. 30° W. to N. 60° W. in strike. The relative ages of the steeply dipping fractures of the other systems have not yet been determined. So far as observed underground, some low-angle fractures are earlier than the sulfide mineralization, but in many places low-angle fractures of a late generation, presumably akin to the San Manuel fault, cut or displace all others.

Detailed mapping of 950 feet of surface drainage ditch, less than one-half mile south of shaft 3-A, shows N.-S., N. 45° W., and N. 30° W. fractures to be the most common in the Gila conglomerate at that locality. A few fractures of the N. 30° E. and E.-W. systems were noted, but the other three systems appear to be rare or lacking. The N. 45° W. fractures seem to cut all others there.

It is believed that the influence of a fracture upon subsidence will depend somewhat upon its age relation to the other fractures present. For example, the youngest fractures, cutting all others, would tend to form relatively persistent and predictable zones of weakness.

Relation to Known Faults

The steeply dipping faults that are prominent at the surface may be projected only with difficulty or considerable uncertainty underground. So far as known, the fracture pattern in the rocks beneath the San Manuel fault bears no tangible relation to them. On the other hand, the faults mapped underground generally constitute zones of breccia, gouge, or intense shearing which are reflected by the fracture pattern within adjacent ground; in many instances the strike and dip of a major zone of weakness may be deduced in advance from the predominant system of fracturing within its walls.

Numerous low-angle breaks occur throughout the mine workings. For the most part, these fractures roughly parallel the San Manuel fault, although wavy in both strike and dip, as shown in figure 50. Cutting essentially all the other fractures, they form sheets of variable thickness that are of primary importance from the standpoint of block caving.

To a certain extent, at least, the E.-W. fractures of 60°-80° N. dip occurring in the footwall of the San Manuel fault possibly are complementary to it.

\(^{15}\) Schwartz, G. M., work cited in footnote 4, pp. 59-60.
Origin of Fractures

As aptly stated by Schwartz,16/

The conditions at San Manuel seem effectively to dispose of the suggestion that shattering of the rock in the "porphyry-copper" deposits was a result of cooling of the intruded porphyry. The grade of the ore is remarkably uniform in pre-Cambrian quartz monzonite, in much younger (Mesozoic or Tertiary) monzonite porphyry, and diabase. A tectonic origin seems necessary to account for equal shattering of three distinct rocks of different age.

The present study has demonstrated that the fracture pattern in the mine workings is tectonic. The fracturing is systematic and can be explained best as the results of compressional forces that were of regional scope and reacted in a systematic manner intermittently through long geologic time. The San Manuel fault fits well into the compressional pattern as a low-angle reverse fault wavy in both strike and dip.

SUMMARY OF GEOLOGIC FACTORS RELATED TO BLOCK CAVING

General Statement

The geologic factors that affect block caving are essentially those which pertain to rock strength. As far as determined by the present study, the principal ones in the San Manuel mine are structure, rock types, alteration, mineralization, oxidation, and presence of water.

Fractures

Here the main structural feature is fracturing. The caving rock breaks or spalls along definite fracture surfaces. Folding is of potential importance insofar as it has affected the conglomerate in the hanging wall of the San Manuel fault.

The density of fracturing in the several different systems, discussed on previous pages and shown by the graphs (figs. 52 to 65), constitutes an index of the zones of weakness trending in those directions. Large fault zones or shear zones appear to be reflected by the relative density of fractures in adjoining ground.

The density of low-angle fracturing is particularly significant, as exemplified by comparing block 7-1 with block 9-1 (figs. 49 to 66). Characterized by a strong predominance of steeply dipping fractures of the E.-W. system, these two blocks show somewhat similar structural patterns except that block 9-1 displays a relatively greater abundance of low-angle fractures. Partly for this reason, as indicated by the caving operations before March 1956, the rock of block 9-1 tends to break into boulders small enough for ready passage through chutes and grizzlies; on the other hand, the rock of block 7-1, less thinly laminated by low-angle fractures, tends to break into boulders often thick enough to clog chutes and grizzlies.

Gougy fractures, as well as zones of gouge and breccia, are recognized as zones of weakness, especially where wet.

16/ Schwartz, G. M., work cited in footnote 4, p. 60.
During the mapping efforts were made to estimate the average diameter of boulders or blocks into which the rock would break when caved, and these estimates are indicated on the maps (figs. 5 to 43) as less than 3 inches, less than 6 inches, or less than 12 inches. Areas where the broken fragments average less than 3 inches tend to include considerable gouge and are notably weak.

The youngest fractures within an area as a rule exert the most influence upon subsidence.

As premineral and postmineral fractures alike tend to be gougy, there appears to be little difference in their effects upon rock strength.

**Rock Types, Alteration, Mineralization, and Water**

Thus far, little distinction has been noted between the relative strengths of the quartz monzonite and monzonite porphyry. It is believed that the strongest rock here is indurated Gila conglomerate, and the weakest is kaolinitized porphyry. Comprehensive data regarding the influence of various types of alteration and stages of oxidation have not yet been obtained.

As the presence of water tends to result in heavy ground, wet spots were indicated on the maps. Commonly they are associated with rhyolite dikes and persistent fracture zones.

In general, the ore tends to be less blocky than the barren rock.

**SUGGESTIONS FOR FURTHER WORK**

The progress already made during the current study, as set forth on preceding pages, seems clearly to indicate that the geologic factors related to block caving at San Manuel are tangible in character. Much additional effort will be required, however, before they can be thoroughly appraised.

Many fundamental data may be obtained by continuing the detailed mapping of the fracture pattern throughout the mining area, including the haulage level, grizzly level, and undercuts. As this mapping proceeds, adequate cross sections may be drawn to show further correlation among the caving operations, fracturing, rock types, alteration, mineralization, and presence of water. Progress to date suggests that such correlations would lead to better understanding of block caving.