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San Manuel

JOHN E. KINNISON

SAN MANUEL PROSPECT

H. J. Steele and G. R. Rubly

This paper describes the exploration by churn drilling of the San Manuel disseminated copper deposit in Arizona. The discussion covers the generalized geology and mineralogy, tonnage and grade developed to date, and the drilling and sampling operations.

Ashby

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SAN MANUEL PROSPECT

LOCATION AND HISTORY

The San Manuel property is located in townships 8-south and 9-south, range 16-east, Gila and Salt River Base and Meridan, State of Arizona. This area is in the Old Hat mining district, southern Pinal County, and is about 3-1/2 miles southwest of the town of Mammoth on the San Pedro River and one mile south of the Mammoth Mine at Tiger, Arizona. The property consists of over 150 contiguous lode claims.

The Old Hat district was prospected prior to the Civil War, but there was little or no production until 1881[1]. The chief producers have been the Mammoth and Mohawk Mines, now consolidated and operating as the St. Anthony Mining Development Company, Ltd. Production to 1936 was $5,200,000, of which 83% was gold[2]. Since 1940 the production has been chiefly lead and zinc, and some molybdenum and vanadium. There are a few small properties in the vicinity that have produced very minor tonnages of copper ore.

In the San Manuel group there are claims, located in 1906, that have been held continuously to the present time, and at least two churn drill holes were put down on or near the outcrop in 1917. No logs for these holes are available, but it is assumed that the grade of copper encountered was not sufficient to encourage further exploration.

A small amount of ore has been shipped from open cuts on the San Manuel outcrop area, but there is no record of the tonnage or grade. It is estimated that not more than 50 tons were mined. These cuts, plus a few shallow shafts and some short adits indicate limited and unenthusiastic prospecting at San Manuel.

In 1942, through the efforts of James M. Douglas, R. B. Giffin, Victor Erickson, and Henry W. Nichols, owners of the San Manuel group, the Reconstruction Finance Corporation and War Production Board authorized the United States Geological Survey to investigate the property, and by their recommendation, the United States Bureau of Mines was authorized to put down a limited number of churn drill holes. The Bureau of Mines drilling carried on from November, 1943 to February, 1945. Seventeen holes were drilled, varying from 305 to 1990 ft. in depth.

The property was brought to the attention of Magma Copper Company in June, 1944, and an option agreement was made with the owners. Subsequently, a group of claims lying north of the original group and held by the Apex Lead Vanadium Mining Corporation, and a group to the east held by the Quarelli family, were optioned. A drilling program was laid out to conform to the Bureau of Mines pattern, and drilling started in December of 1944. San Manuel Copper Corporation was incorporated in September of 1945, and has carried on the exploration program to the present time.

GEOLOGY

General

The mineralized outcrop, chief copper mineral of which is chrysocolla, is a triangular area with a northeast-southwest base of 380 ft. and with the apex of the triangle 400 ft. to the southeast. Northwest of the base is Red Hill, so called because of the prominent gossan coloration. With a few exceptions, conglomerate and diluvium cover the rest of the property. The elevation varies from 2900 ft. to 3500 ft. above sea level. The area slopes gently to the east, with the exception of a small rugged and precipitous portion around the south side of Red Hill, and is cut by numerous dry washes with easterly courses toward the San Pedro River. The cover is sparse brush and cactii characteristic of this portion of the state.

Rocks

Relatively few rock types are found in surface exposures or are encountered in drilling. These formations were mapped by Dr. G. M. Schwartz of the United States Geological Survey, and the logging of all drill holes has conformed to his classification[3]. The rocks are quartz monzonite, monzonite porphyry, diabase, felsite, and felsite breccia, Gila conglomerate and recent alluvium.

The quartz monzonite found in the drilling area is granitic in texture, showing varying degrees of hydrothermal alteration. Quartz is abundant; the feldspars and biotite are extremely altered in most cases. Rutile is common, and the rock in general is sericitized and kaolinized.

The monzonite porphyry has a fine groundmass composed largely of a mosaic of quartz and feldspars. There is an abundance of biotite but less quartz than in the quartz monzonite. The feldspar phenocrysts are usually well altered, and the biotite is often bleached or chloritized. Secondary quartz flooding is fairly common, especially near the ore zone. A distinct phase of dark grey, fine-grained porphyry, containing an abundance of biotite in the form of phenocrysts recrystallized to aggregates of grains and much disseminated secondary hydrobiotite in the groundmass, is found in the hanging wall of the ore body to the south of the outcrop area.

Alteration products found in thin section in both the quartz monzonite and monzonite porphyry, as reported by G. M. Schwartz, include the following minerals: the hydromicas, allophane, epidote, leucoxene, montomorillonite, dickite, chlorite, potash clays, and calcite.

Diabase occurs as dikes cutting both the quartz monzonite and monzonite porphyry. The rock is well altered, grading from fine to coarse diabasic texture, and is mineralized with chalcopyrite and pyrite, or with chrysocolla and iron oxides in the oxidized zone.

The felsite, which is unmineralized and which cuts the diabase and the monzonites, is light grey to light cream in color, fine-grained, with occasional small quartz and feldspar phenocrysts in a finely crystalline groundmass.

The diabase occurs infrequently, and the felsite, while more abundant than diabase, is relatively unimportant in the overall rock distribution.

The Gila conglomerate consists of alluvial material interbedded with lava flows, breccias, and tuffs. The coarse conglomerate on San Manuel is composed of boulders of acid and basic volcanics cemented with clay. A phase of the Gila conglomerate, designated as granitic conglomerate and composed largely of fragments of relatively unaltered quartz monzonite, has been found in drilling to the southwest.

Structure

The structure at San Manuel, interpreted largely through drilling results, can only be generalized at the present time.

The Gila conglomerate, which covers the major part of San Manuel, strikes northwest and dips northeast at 20° to 45°. The San Manuel fault, striking northwest, more or less parallel to the strike of the conglomerate, and dipping southwest at 25° to 35°, forms the contact of the monzonite and the conglomerate. The San Manuel fault is in turn cut by two 60° to 75° northeast dipping faults striking northwest. The most westerly of these faults is designated as the west fault, and the most easterly as the east fault. (Fig. 1). This step faulting of the conglomerate is illustrated in Fig. 2, and has been substantiated by drilling to the northeast. Minor outcrops of hematite-stained, altered monzonite porphyry occur at intervals along the surface exposure of the most northeasterly segment of the San Manuel fault. Drilling northeast of these exposures indicates that the contact of the conglomerate with the old erosion surface dips northeasterly at 20° to 25°. The indicated vertical displacement of the west fault is in the neighborhood of 400 ft., and of the east fault, 200 ft. The east fault has been considered to be the southward extension of the Mammoth fault as mapped by Peterson[4] and others. A more complex fault system may be expected and is indicated by the drilling, but correlation of evidence of faulting is not possible from the churn drill results.

The outcrop area, as shown in plan in Fig. 1, is bounded on the southwest leg by the San Manuel fault and on the northeast leg by the west fault. The base, as indicated in cross section in Fig. 3, is controlled by decreasing copper mineralization, and is therefore, an assay boundary. A diabase dike, striking northeast and nearly coinciding with this cutoff of copper mineralization, was originally thought to be a diabase filled pre-Gila fault which abruptly cut off the northwestern extension of the ore body. Drilling northwest of this line has indicated a gradational decrease of copper mineralization in the projected ore zone rather than faulting.

The persistency of the San Manuel fault on both strike and dip is unusual, and it is difficult to visualize a low angle normal fault of this magnitude. The most feasable explanation, with the limited data at hand, can best be presented by this possible sequence of events:

1. Intrusion of the monzonite, and mineralization of the intrusive masses.
2. Oxidation and secondary enrichment.
3. Deposition of the Gila conglomerate. (Events 2 and 3 may be contemporaneous).
4. San Manuel fault formed, dipping 60° to 65° to the southwest.
5. Regional tilt of 25° to 35° to the northeast and development of the fault system, which strikes northwest, and dips to the east.

The San Manuel ore body has been described as a tabular mass, striking north 60° east, and dipping southeast at 50° to 60°; and is shown this way in Figs. 2 and 3. It must be remembered, however, that this strike and dip is largely due to an assay boundary. Any arbitrary cutoff figure selected would change the attitude of the ore body. The strong pyritic mineralization below the outlined ore body has not been bottomed by any drilling to date. The upper portion of the hanging wall rock is very lightly mineralized; alteration and mineralization increases at depth until the zone of better copper mineralization is encountered.

Copper mineralization has been proved by drilling for 5000 ft. in the northeast-southwest direction, and 1400 ft. in the northwest-southeast direction. Pyritic mineralization is known for 2200 ft.

northwest of the ore zone.

Mineralogy

In the oxidized zone the chief ore mineral is chrysocolla; cuprite is present locally; malachite and azurite are rare. The chrysocolla is generally found in joints and fracture planes.

Chalcocite is the predominate copper mineral in the secondary zone. Residual primary chalcopyrite, occurring chiefly as intergrowths with the secondary minerals, and secondary chalcopyrite are found. Some native copper is found as well as minor amounts of bornite and covellite. There is very conclusive evidence of one or more stages of partial oxidation of the secondary zone in parts of the ore body. This may be due to variations of the water table and regional tilting.

Chalcopyrite and minor amounts of chalcocite are the chief copper minerals of the primary zone. The proportion of chalcopyrite to pyrite determines the footwall of the ore body. Slight oxidation is found relatively deep in the primary zone, and is thought to coincide with fault planes. The sulphide minerals are well disseminated throughout the monzonite, as well as occurring as veinlets. Chalcopyrite and chalcocite are frequently found as films on pyrite. Molybdenite is present in sufficient amount to be of economic importance, and can be seen megascopically in a large proportion of samples in the primary zone. Gold and silver are found in small quantities throughout the deposit, but sufficient work has not been done toward determination of the gold and silver content to state the average assay at this time. Rutile is fairly abundant throughout, and is thought to be present as an alteration product of biotite.

Polished sections of the concentrates, selected at intervals in the sulphide zone, are prepared and examined by G. M. Schwartz of the United States Geological Survey.

CHURN DRILLING

General

A grid co-ordinate system, bearing 29°-50' west of true north, controls the churn drilling pattern. The orientation was set by the Bureau of Mines, and was based on the strike of the apparent northwesterly limit of copper mineralization of the outcrop. The drilling done by the Bureau of Mines and the early drilling by San Manuel Copper Corporation was spaced rather widely over the area to establish probable continuity of the ore body and to determine the required spacing of holes for future drilling. When intermediate holes were drilled and the general attitude of the ore zone became apparent, the present drilling pattern evolved. This pattern is based on a 400-ft. interval in the direction of strike, which is from east to west on the drilling grid, and a 200-ft. interval in the north-south direction. All holes since the beginning of exploration have been controlled by the grid co-ordinate system. The few exceptions are due to rugged terrain making the correct location impractical.

The drilling grid is extended from permanent reference points by transit and tape traverse; elevations are carried to the collar of each hole by a line of levels from established reference points. Elevation datum is from the United States Coast and Geodetic Survey bench marks. The drilling grid is tied to the San Manuel co-ordinate system, which is based on a true north meridian. Holes are spudded in as near the intersection of grid co-ordinate lines as practical, and the error in hole location is rarely more than one foot in either direction.

Statistics

At the present time 67 holes have been completed, and 11 are in progress for a total of 110,854 ft. of drilling since exploration of the property began. The Bureau of Mines drilled 15,824 ft., and San Manuel Copper Corporation has drilled 95,030 ft. The deepest hole drilled to date has been 2600 ft. All drilling is done on contract, with the contractor furnishing all equipment and tools.

The average drilling conditions at San Manuel are illustrated by the following tabulation of statistics for a three-month period. Drilling shifts refer to time actually spent in drilling; total shifts worked refer to drilling shifts plus the time spent moving and setting up on new locations, repairs, fishing, and miscellaneous lost time:

	Average	Best Drill	Poorest Drill
Elapsed Time	91 days	91 days	91 days
No. of Drills Operating	6	1	1
Total Footage Drilled	13296 ft.	3439 ft.	71 ft.
Drilling Shifts	698.6	116.5	13.8
Advance per Drilling Shift	19.0 ft.	29.5 ft.	5.1 ft.
Total Shifts Worked	825	133.8	23.7
Advance per Shift Worked	16.2 ft.	25.7 ft.	3.0 ft.

The average time required to move to a new location was 4.6 shifts. This includes pulling casing from the completed hole, moving, and rigging up preparatory to spudding in.

Equipment

The selection of churn drills for exploring this property was based on the record of accurate tonnage and grade estimates computed

from data obtained by churn drilling at other well-known dissemina-
ted copper deposits. Exploration by diamond drill was rejected because of probable low core recovery if the formations proved to be highly fractured.

Several types of churn drills are operating on the property; Bucyrus-Erie machines being in predominance. Models 24-W, 24-L, 29-W, 29-T, and 36-L, with drilling capacities ranging from 1500 ft. to 3600 ft. are represented. These are all-steel machines, very compactly built, and ideal for working in rough terrain. The space required for a set up is comparatively small, and the machines can be handled over fairly steep grades. There are four Ft. Worth Spudders in operation: Models Super D, F, Jumbo H, and Super J; having drilling capacities ranging from 2500 ft. to 5000 ft. These are larger machines of wood construction, and require considerably more room for a set up, as the engine is usually set back of the rig some 20 to 30 ft. Power transmission is by flat belt drive. They are more awkward to move, and take longer to set up and tear down than the Bucyrus-Erie machines.

The drilling contractors, operating under similar contracts, hire all help required to run the rigs. A crew usually consists of a driller, a tool dresser, and welder. Since all bits are built up by electric welding, the tool dresser is more of a general helper than his name implies. Some contractors work on a three 8-hr. shift basis; others on two 12-hr. shifts. All drills are now operating 24-hr. per day, and 7 days a week.

DRILLING

As the early drilling was comparatively shallow, holes 8-in.

in diameter were started, reduction to 6 and 4-in. holes then being possible. When it became evident that deeper drilling would be required, with the possibility of having to case and reduce size of hole several times before reaching bottom, the starting hole was increased to 10-in. and finally to 12-in. diameter. This permits running 10-in. casing followed by 8-in., 6-in., and 4-in. casing when necessary.

There has been considerable discussion regarding the advisability of starting holes with 12-in. bits. It was thought that the larger diameter hole and the greater shock produced by heavier tools would increase caving in fractured ground. The drill contractors preferred the 8-in. bit because a larger bit would probably slow the drilling speed in the upper portion of the hole, where contract prices per foot are relatively low. It has been our experience, however, that the larger sized hole does not decrease speed of drilling greatly, and that caving would be encountered at about the same place in the hole regardless of size of bit used. The larger hole gives one better assurance of being able to drill to the depth required. The 12-in. hole is never carried to more than 1200 ft., and casing is usually required before this depth is reached. The 10-in. hole is carried to 1500 or 1600 ft. if possible, allowing the hole to be completed with either an 8-in. or 6-in. bit. The deepest hole, which was 2600 ft., was finished with a 4-in. bit after having set a 400 ft. liner of 4 in. pipe at 2400 ft. Some of the ground seems to stand well, as three holes, the deepest of which was 2200 ft., have been drilled without the use of any casing.

Drill locations and access roads are constructed to meet the requirements of the type of machine that will occupy the site. The

Bucyrus-Erie machines dump the sludge on the left side, facing the machine, while the Ft. Worths dump on the right side; thus necessitating a different type of location. All roads and locations have been made by bulldozer and scarifier, on contract; no drilling and blasting have been required.

Fishing for lost tools is taken care of by the contractors, with the exception of some long difficult jobs below 1000 ft., in which case the company has assumed part of the burden of cost. This situation has not come up often.

Unless casing is ordered by the field engineer to shut off possible caving and the resultant contamination of samples, especially in or near the ore zone, its use is usually left to the discretion of the contractors. The contractor is required to make every effort to recover all of the casing, but there are times when several joints have to be cut off the bottom in order to salvage any. This is accomplished by setting off a bomb, fired electrically at a coupling near the bottom, or by using a "collar buster"; a device lowered on the string of tools to a predetermined depth, which punctures and slits the pipe until a collar is reached and cut. The bombs are not too satisfactory because they tend to swell the casing in one or more places, making withdrawal of the pipe difficult.

The use of any drilling muds or Aquajell is, in general, prohibited. The exceptions to this rule are to permit the use of Aquajell, plastered on casing couplings when being run into the hole to make later withdrawal easier, and during fishing operations in caving ground. In crooked holes it is occasionally necessary to drop surface rocks in the hole and redrill in order to straighten it. In any of these operations the driller is required to thoroughly clean the hole before sampling operations are resumed.

In order to accurately establish the depth from which samples are coming, the holes are measured frequently with a special measuring device consisting of a reel of 3/32 in. galvanized aircord marked with lead buttons every 10 ft. The 100 ft. marks are identified by a code of elongated buttons. The measuring cable was calibrated by attaching a 7-lb. lead weight to the zero end; lowering it down a vertical shaft; and marking off the units on surface. When measuring, a very definite jerk is felt when the weight is pulled off the bottom of the hole.

Frequency of measurement varies. Holes are measured when they near the contact of the conglomerate and monzonite, so this point can be closely determined. After that, measurements are made at about 200 ft. intervals, and again when the hole is completed.

SAMPLING

Equipment

Sampling equipment consists of a dump box, a 6-ft. launder, a sample splitter, and 5-gal. milk cans to catch the samples.

The dump boxes are built of 2 in. by 12 in. plank, lined with 1/4 in. steel plate welded at the joints. The boxes are 12 in. wide, 36 in. long, and 24 in. high--inside dimensions. The launder is constructed of 1/8 in. steel plate, and designed to fit securely, with a 3-in. overlap between the steel lining and wood exterior, at the open end of the dump box. The discharge end of the launder lies on the upper edge of the splitter unit. The slope of the launder is adjusted to insure an even flow of sludge to the splitter, which is a modification of the Ray Consolidated Company splitter[5]. It is, essentially, 3 or more Jones splitters arranged in series to facilitate gravity flow of the sludge through the successive individual units. The upper two tiers of slots of a four cut splitter are 1-1/4 in. wide, and the lower two tiers are 3/4 in. wide; the slots being staggered by 1/2. The sample portion of the sludge passes straight down and is discharged at the front. The rejects gather underneath and are discharged at the side.

Personnel

It is desirable to have as samplers young engineers or geologists. This type of help has not been available, so it has been necessary to employ less skilled men, which in turn has meant special training and supervision for the sampling crew. Every detail of catching, preparing, washing character samples, and panning for concentrates had to be taught in most cases. Sampling is supervised by shift bosses and engineers who visit the rigs periodically during sampling operations.

Technique

The churn drill holes are sampled at 5-ft. intervals, from the contact of the conglomerate and the monzonite, to the bottom of the hole. Character samples are taken at 20-ft. intervals in the conglomerate.

The sludge is dumped from the bailer into the dump box, and flows through the splitter. The driller is cautioned to ease the bailer into the box to avoid surge and splash. The sample portion is caught in a 5-gal. milk can and a bucket of rejects is caught; a portion of which is washed free of slimes and saved as a character sample. A uniform volume of rejects from each 5-ft. interval is panned to obtain a concentrate which is dried and sacked. An engineer examines both the character sample and concentrate to determine, megascopically, the rock type, alteration, kind, and relative amounts of mineralization. The character samples are filed for future reference, and the concentrate is sent to G. M. Schwartz of the United States Geological Survey for selected samples to be polished and examined by microscopic methods.

The sampler fills out a "Churn Drill Report", noting the depths at which the samples are caught, color of sludge, condition of hole, depth at which water was encountered, fault zones as evidenced by gouge, and any other pertinent data relative to the hole. The spaces for rock type and mineralization are filled in by the engineer who examines the character and concentrate samples.

The size to which the sample is cut depends largely on the size of hole being drilled, and if drilling is under water. A 12-1/2 in. hole may require a cut to 1/256 of the total volume of sludge bailed, and a 4 in. hole is cut to 1/8 or 1/4 of the original volume of sludge. The sample is cut so there is a minimum of about 15 lbs. of dry solids.

Drillers are required to bail holes clean. This is relatively simple above the water table, and takes about 3 or 4 trips into the hole. However, after the holes are under water, it is never possible to get a really clean hole, as there is always a certain amount of slimes in suspension. In this case, a few tests are made to determine how many bailings are required to pick up the largest part of the sample, and leave the hole relatively clean for the next run. On numerous occasions it has been possible to obtain samples of the slimes in suspension by carefully bailing a hole after it had been shut down for periods of 24 to 48 hrs. Assays of this material have agreed very closely with the assay of the last run made, so that no serious errors are introduced by leaving this material in the hole.

No attempt is made to shut the water off by casing.

Drying & Preparing Pulps

The samples caught in milk cans are gathered up, usually at the end of the shift, and hauled to a centrally located drying room. They are dried on a series of 9 heavy steel drying tables, each about 3 ft. square. Steam, which is generated to 20 lbs. gauge pressure in a manually-operated vertical fire tube boiler, using diesel oil for fuel, supplies the heat for the drying tables.

Other drying room equipment consists of a Jones dry splitter, 2 Braun type UA pulverizers, small platform scales, and a table for rolling pulps.

The operating personnel of the drying room consists of a foreman on day shift, with three dryers and grinders; and lead men on afternoon and graveyard shifts, with 2 or 3 helpers. The drying room operates 24 hrs. per day for 7 days a week.

As samples are brought in from the rigs, they are lined up in sequence and dried on the steam plates. Since there is such a large amount of sludge to be dried, the time of drying is more than an hour per sample, and may extend to 3 hrs. for exceptionally heavy, slimy samples. After drying, the sample is scraped off the table into a large pan and quarted by means of a Jones splitter. Three of these cuts are put in paper sacks; the fourth being set aside for pulverizing. Each of these cuts will weigh from 2-1/2 to 3 lbs. Paper tags are used, designating the sample number by hole as well as by footage. The cut which is pulverized and then thoroughly rolled, is divided between five different pulp sacks holding from 150 to 200 gms. each. One of these pulps is sent to the assay office of the St. Anthony Mining and Development Company for field control.

The other four are sent to the Magma Copper Company in Superior where one pulp is assayed directly for total and oxide copper; two are used in making up composites for total copper, oxide copper, gold, silver and molybdenum determinations. The fourth pulp is held in reserve.

Two of the three sacks of rejects are stored in tunnels at San Manuel, and one is stored at Superior. These are held in reserve for possible future examinations, or for further assay.

Records of the holes, listing each individual sample number, depth of footage, date of sample, weight of cut, number of splits made to obtain this cut, and the name of the sampler are kept in the bucking room. These records are all filed.

ASSAYING

The pulp sent to the St. Anthony Mining and Development Company is assayed for total and oxide copper. The method of assay used is a modified procedure of the short iodide method, wherein the end point of the starch-iodine blue was made much sharper, and gives results close enough for field control.

At the Magma Copper Company the total copper content is determined by standard electrolytic methods; oxide copper is determined by the long iodide method. Results of these assays check very closely with those of Ledoux & Company and Union Assay Office.

Gold, silver and molybdenum are determined from composites. These composites are made up of pulps representing portions of the hole of the same general mineralization or assay character, but do not usually exceed 100 ft. of hole.

If the average of individual assays of total copper checks within 0.03 percent with the total copper determination of the composite by Magma Copper Company and an umpire assayer, those values are accepted as being correct.

In the office at Superior, records of each hole are compiled showing all determinations made on individual and composite samples, the accepted assay, rock type, and mineralogy.

TONNAGE & GRADE

Churn drilling to May 1st has blocked out approximately 119,170,000 tons of ore, which will average 0.80 percent copper. This total contains 14,600,000 tons of low grade oxidized material which averages 0.65 percent total copper, 0.36 percent oxide; 29,640,000 tons of mixed oxidized and sulphide ore which averages 0.82 percent total copper, and 0.58 percent oxide copper; and 74,930,000 tons of sulphide ore which averages 0.82 percent total copper, and 0.05 percent oxide copper.

These tonnage and grade figures are of a preliminary nature, and are kept up to date with the drilling as closely as the required checking of assays allows.

The following procedure is used to compute the tonnage and grade:

The drilling area is divided into rectangles and triangles as the spacing of drill holes demand, with a drill hole at each corner of the rectangles, and at the apices of each triangle. Care is taken to arrange the pattern of geometric figures so that one drill hole is not a common corner for more figures than necessary. The area, calculated from the horizontal distance between holes, is multiplied by the average of the thickness of the columns of ore encountered in the holes making up the corners of the figures.

Twelve and one-half cu. ft. per ton is the factor used to convert the volume to tonnage. The grade for each block is the weighted average of the ore columns of the holes used.

The bottom sample, or in some case, more than one sample is thrown out as a precaution against salting of marginal material by higher grade samples above. The cut back at the bottom of an ore column depends on the condition of the hole, grade of ore, and whether there is a gradational change in copper content at the bottom of the column, or a sharp break. The tonnage is calculated from drill hole data with no allowances for an extension of the ore body beyond the boundaries of completed holes. This eliminates the necessity for constant revision of such an estimated extension of ore, due to the continually changing drilling pattern.

At intervals tonnage and grade calculations are computed by two other methods as checks. In the second method, the average area of adjacent cross sections is multiplied by the distance between the sections to compute the volume. The grade is computed from the weighted average of the ore columns of holes in the two sections. The ore columns are adjusted as in the first method.

The third method involves plotting the area of influence of each hole, and using the adjusted ore column for thickness, to compute a tonnage and grade figure for each area.

ACKNOWLEDGEMENT

Acknowledgement is due the officers of San Manuel Copper Corporation for permission to use the information presented.

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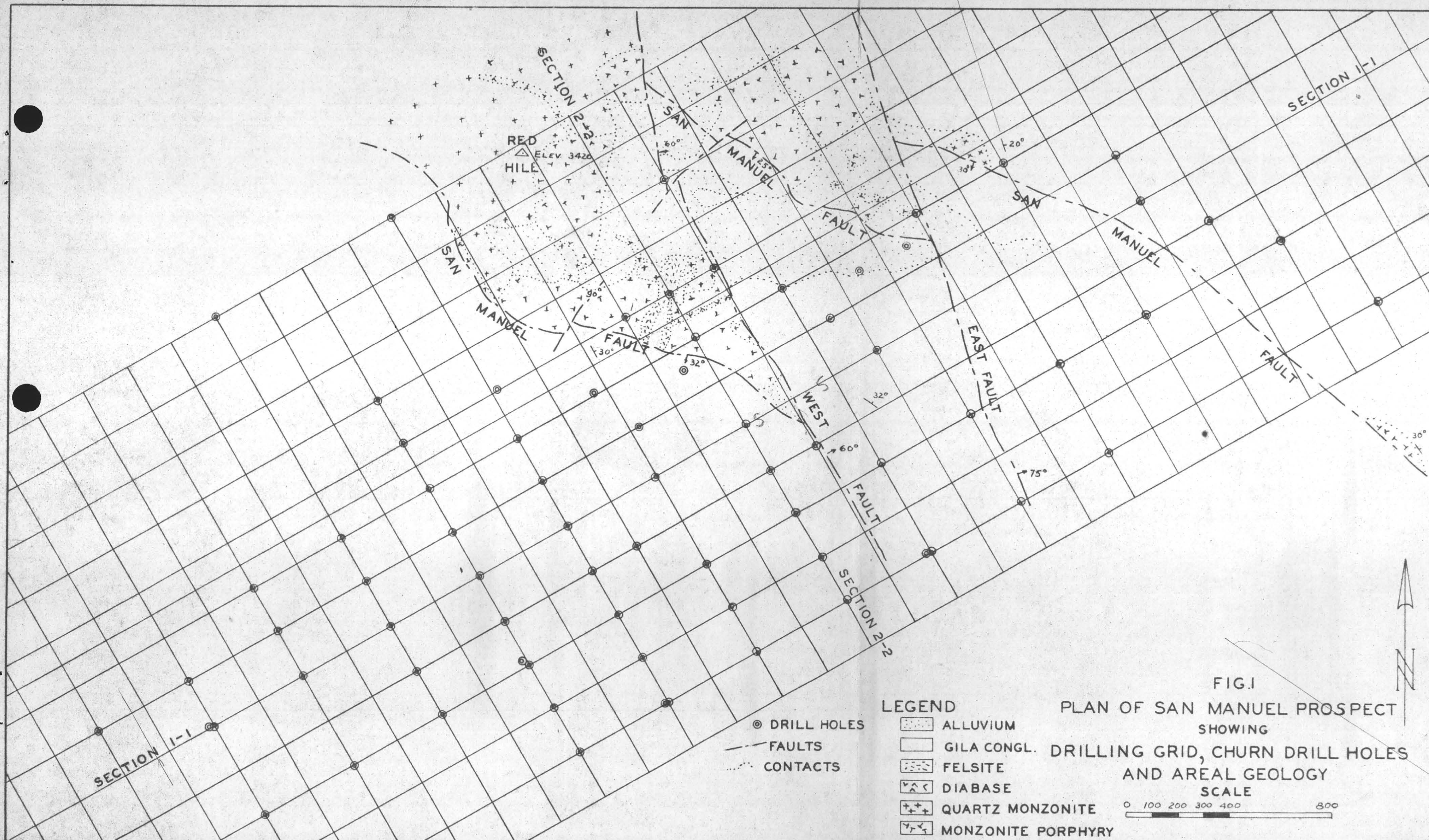

FIG.1
PLAN OF SAN MANUEL PROSPECT
SHOWING
DRILLING GRID, CHURN DRILL HOLES
AND AREAL GEOLOGY

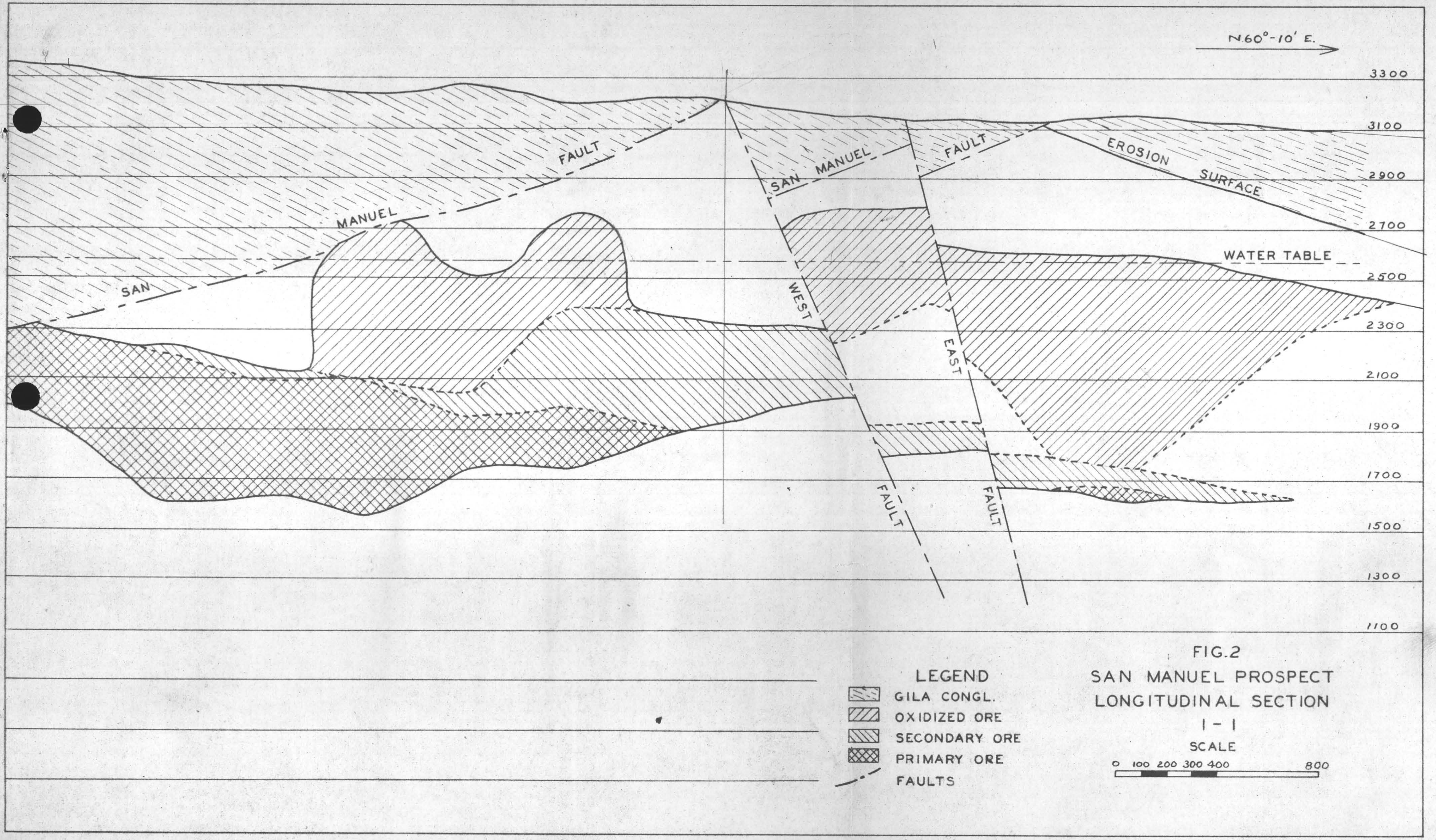

FIG. 2
SAN MANUEL PROSPECT
LONGITUDINAL SECTION
1 - 1

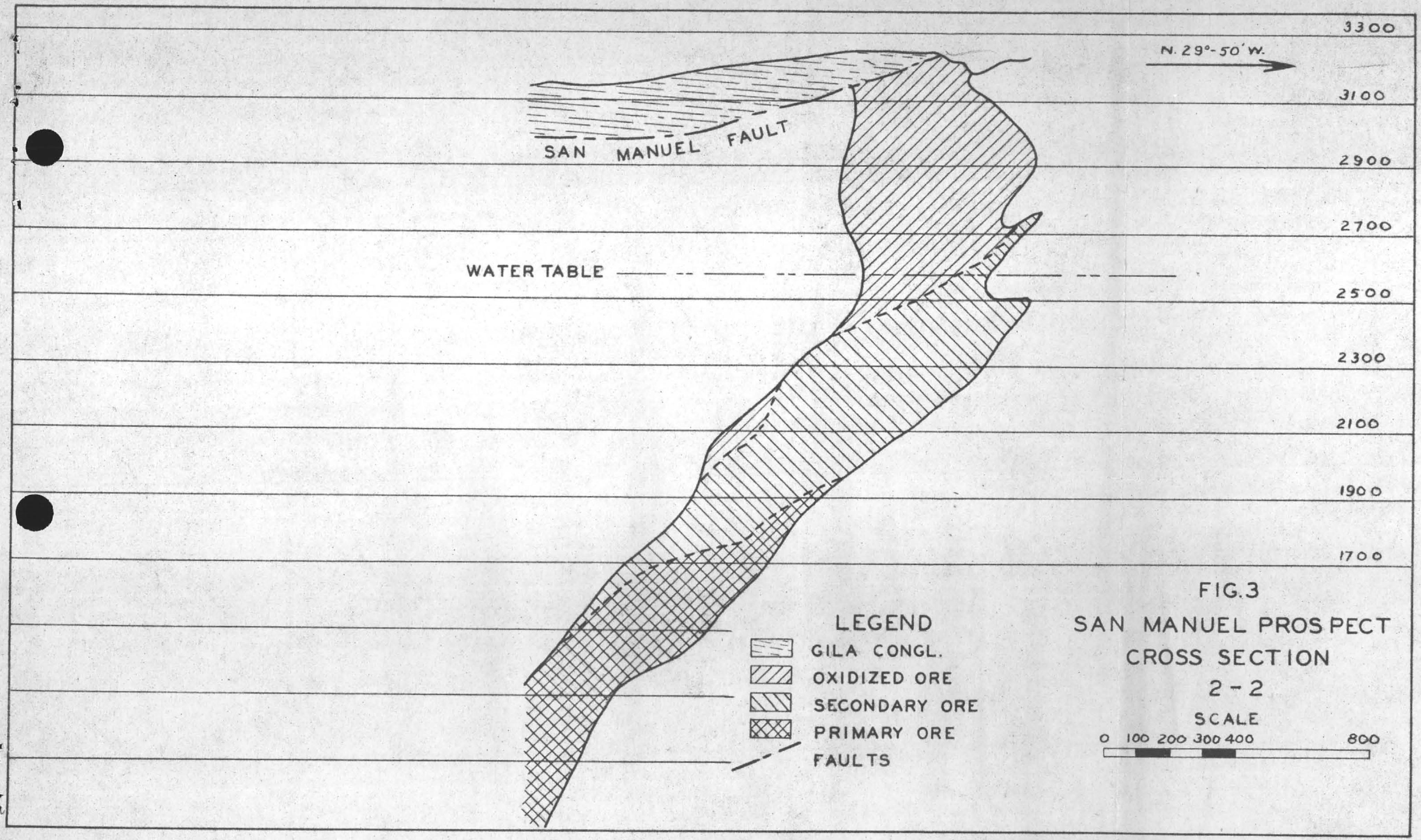

FIG. 3
SAN MANUEL PROSPECT
CROSS SECTION
2 - 2

San Manuel

SAN MANUEL PROSPECT

H. J. Steele and G. R. Rubly

Abstract

This paper describes the exploration by churn drilling of the San Manuel dissem-inated copper deposit in Arizona. The dis-cussion covers the generalized geology and mineralogy, tonnage and grade developed to date, and the drilling and sampling opera-tions.

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LOCATION AND HISTORY

The San Manuel property is located in townships 8-south and 9-south, range 16-east, Gila and Salt River Base and Meridian, State of Arizona. This area is in the Old Hat mining district, southern Pinal County, and is about 3-1/2 miles southwest of the town of Mammoth on the San Pedro River and one mile south of the Mammoth Mine at Tiger, Arizona. The property consists of over 150 contiguous lode claims.

The Old Hat district was prospected prior to the Civil War, but there was little or no production until 1881[1]. The chief producers have been the Mammoth and Mohawk Mines, now consolidated and operating as the St. Anthony Mining Development Company, Ltd. Production to 1936 was $5,200,000, of which 83% was gold[2]. Since 1940 the production has been chiefly lead and zinc, and some molybdenum and vanadium. There are a few small properties in the vicinity that have produced very minor tonnages of copper ore.

In the San Manuel group there are claims, located in 1906, that have been held continuously to the present time, and at least two churn drill holes were put down on or near the outcrop in 1917. No logs for these holes are available, but it is assumed that the grade of copper encountered was not sufficient to encourage further exploration.

A small amount of ore has been shipped from open cuts on the San Manuel outcrop area, but there is no record of the tonnage or grade. It is estimated that not more than 50 tons were mined. These cuts, plus a few shallow shafts and some short adits indiwere limited and unenthusiastic prospecting at San Manuel.

In 1942, through the efforts of James S. Douglas, [illegible] Gilvin, Victor Erickson, and Henry W. Nichols, owners of the San Manuel group, the Reconstruction Finance Corporation and War Production Board authorized the United States Geological Survey to investigate the property, and by their recommendation, the United States Bureau of Mines was authorized to put down a limited number of churn drill holes. The Bureau of Mines drilling carried on from November, 1943 to February, 1945. Seventeen holes were drilled, varying from 305 to 1990 ft. in depth.

The property was brought to the attention of Magma Copper Company in June, 1944, and an option agreement was made with the owners. Subsequently, a group of claims lying north of the original group and held by the Apex Lead Vanadium Mining Corporation, and a group to the east held by the Quarelli family, were optioned. A drilling program was laid out to conform to the Bureau of Mines pattern, and drilling started in December of 1944. San Manuel Copper Corporation was incorporated in September of 1945, and has carried on the exploration program to the present time.

GEOLOGY

General

The mineralized outcrop, chief copper mineral of which is chrysocolla, is a triangular area with a northeast-southwest base of 380 ft. and with the apex of the triangle 400 ft. to the southeast. Northwest of the base is Red Hill, so called because of the prominent [illegible] coloration. With a few exceptions, conglomerate and alluvium cover the rest of the property. The elevation varies from 2900 ft. to 3500 ft. above sea level. The area slopes gently to the east, with the exception of a small rugged and precipitous portion around the south side of Red Hill, and is cut by numerous dry washes with easterly courses toward the San Pedro River. The cover is sparse brush and cacti characteristic of this portion of the state.

Rocks

Relatively few rock types are found in surface exposures or are encountered in drilling. These formations were mapped by Dr. G. M. Schwartz of the United States Geological Survey, and the logging of all drill holes has conformed to his classification. The rocks are quartz monzonite, monzonite porphyry, diabase, felsite, and felsite breccia, Gila conglomerate and recent alluvium.

The quartz monzonite found in the drilling area is granitic in texture, showing varying degrees of hydrothermal alteration. Quartz is abundant; the feldspars and biotite are extremely altered in most cases. Rutile is common, and the rock in general is sericitized and kaolinized.

The monzonite porphyry has a fine groundmass composed largely of a mosaic of quartz and feldspars. There is an abundance of biotite but less quartz than in the quartz monzonite. The feldspar phenocrysts are usually well altered, and the biotite is often bleached or chloritized. Secondary quartz flooding is fairly common, especially near the ore zone. A distinct phase of dark grey, fine-grained porphyry, containing an abundance of biotite in the form of phenocrysts recrystallized to aggregates of grains and much disseminated secondary hydrobiotite in the groundmass, is found in the hanging wall of the ore body to the south of the outcrop area.

Alteration products found in thin section in both the quartz monzonite and monzonite porphyry, as reported by G. M. Schwartz, include the following minerals: the hydromicas, allophane, epidote, leucoxene, montmorillonite, dickite, chlorite, potash clays, and calcite.

Diabase occurs as dikes cutting both the quartz monzonite and monzonite porphyry. The rock is well altered, grading from fine to course diabasic texture, and is mineralized with chalcopyrite and pyrite, or with chrysocolla and iron oxides in the oxidized zone.

The felsite, which is unmineralized and which cuts the diabase and the monzonites, is light grey to light cream in color, fine-grained, with occasional small quartz and felspar phenocrysts in a finely crystalline groundmass.

The diabase occurs infrequently, and the felsite, while more abundant than diabase, is relatively unimportant in the overall rock distribution.

The Gila conglomerate consists of alluvial material interbedded with lava flows, breccias, and tuffs. The coarse conglomerate on San Manuel is composed of boulders of acid and basic volcanics cemented with clay. A phase of the Gila conglomerate, designated as granitic conglomerate and composed largely of fragments of relatively unaltered quartz monzonite, has been found in drilling to the southwest.

Structure

The structure at San Manuel, interpreted largely through drilling results, can only be generalized at the present time.

The Gila conglomerate, which covers the major part of San Manuel, strikes northwest and dips northeast at 20° to 45° . The San Manuel fault, striking northwest, more or less parallel to the strike of the conglomerate, and dipping southwest at 25° to 35°, forms the contact of the monzonite and the conglomerate. The San Manuel fault is in turn cut by two 60° to 75° northeast dipping faults striking northwest. The most westerly of these faults is designated as the west fault, and the most easterly as the east fault. (Fig. 1) This step faulting of the conglomerate is illustrated in Fig. 2, and has been substantiated by drilling to the northeast. Minor outcrops of hematite-stained, altered monzonite porphyry occur at intervals along the surface exposure of the most northeasterly segment of the San Manuel fault. Drilling northeast of these exposures indicates that the contact of the conglomerate with the old erosion surface dips northeasterly at 20° to 25°. The indicated vertical displacement of the west fault is in the neighborhood of 400 ft., and of the east fault, 200 ft. The east fault has been considered to be the southward extension of the Mammoth fault as mapped by Peterson[4] and others. A more complex fault system may be expected and is indicated by the drilling, but correlation of evidence of faulting is not possible from the churn drill results.

The outcrop area, as shown in plan in Fig. 1, is bounded on the southwest leg by the San Manuel fault and on the northeast leg by the West fault. The base, as indicated in cross section in Fig. 3, is controlled by decreasing copper mineralization, and is therefore, an assay boundary. A diabase dike, striking northeast and nearly coinciding with this cutoff of copper mineralization, was originally thought to be a diabase filled pre-Gila fault which abruptly cut off the northwestern extension of the ore body. Drilling northwest of this line has indicated a gradational decrease of copper mineralization in the projected ore zone rather than faulting.

The persistency of the San Manuel fault on both strike and dip is unusual, and it is difficult to visualize a low angle normal fault of this magnitude. The most feasible explanation, with the limited data at hand, can best be presented by this possible sequence of events:

1. Intrusion of the monzonite, and mineralization of the intrusive masses.
2. Oxidation and secondary enrichment.
3. Deposition of the Gila conglomerate. (Events 2 and 3 may be contemporaneous).
4. San Manuel fault formed, dipping 60° to 65° to the southwest.
5. Regional tilt of 25° to 35° to the northeast and development of the fault system, which strikes northwest, and dips to the east.

The San Manuel ore body has been described as a tabular mass, striking north 60° east, and dipping southeast at 50° to 60°; and is shown this way in Figs. 2 and 3. It must be remembered, however, that this strike and dip is largely due to an assay boundary. Any arbitrary cutoff figure selected would change the attitude of the ore body. The strong pyritic mineralization below the outlined ore body has not been bottomed by any drilling to date. The upper portion of the hanging wall rock is very lightly mineralized; alteration and mineralization increases at depth until the zone of better copper mineralization is encountered.

Copper mineralization has been proved by drilling for 5000 ft. in the northeast-southwest direction, and 1400 ft. in the northwest-southeast direction. Pyritic mineralization is known for 2200 ft northwest of the ore zone.

<u>Mineralogy</u>

In the oxidized zone the chief ore mineral is chrysocolla, cuprite is present locally; malachite and azurite are rare. The chrysocolla is generally found in joints and fracture planes.

Chalcocite is the predominate copper mineral in the secondary zone. Residual primary chalcopyrite, occurring chiefly as intergrowths with the secondary minerals, and secondary chalcopyrite are found. Some native copper is found as well as minor amounts of bornite and covellite. There is very conclusive evidence of one or more stages of partial oxidation of the secondary zone in parts of the ore body. This may be due to variations of the water table and regional tilting.

Chalcopyrite and minor amounts of chalcocite are the chief copper minerals of the primary zone. The proportion of chalcopyrite to pyrite determines the footwall of the ore body. Slight oxidation is found relatively deep in the primary zone, and is thought to coincide with fault planes. The sulphide minerals are well disseminated throughout the monzonite, as well as occurring as veinlets. Chalcopyrite and chalcocite are frequently found as films on pyrite. Molybdenite is present in sufficient amount to be of economic importance, and can be seen megascopically in a large proportion of samples in the primary zone. Gold and silver are found in small quantities throughout the deposit, but sufficient work has not been done toward determination of the gold and silver content to state the average assay at this time. Rutile is fairly abundant throughout, and is thought to be present as an alteration product of biotite.

Polished sections of the concentrates, selected at intervals in the sulphide zone, are prepared and examined by C. M. Schwartz of the United States Geological Survey.

CHURN DRILLING

General

A grid co-ordinate system, bearing 29°-50' west of true north, controls the churn drilling pattern. The orientation was set by the Bureau of Mines, and was based on the strike of the apparent northwesterly limit of copper mineralization of the outcrop. The drilling done by the Bureau of Mines and the early drilling by San Manuel Copper Corporation was spaced rather widely over the area to establish probable continuity of the ore body and to determine the required spacing of holes for future drilling. When intermediate holes were drilled and the general attitude of the ore zone became apparent, the present drilling pattern evolved. This pattern is based on a 400-ft. interval in the direction of strike, which is from east to west on the drilling grid, and a 200-ft. interval in the north-south direction. All holes since the beginning of exploration have been controlled by the grid co-ordinate system. The few exceptions are due to rugged terrain making the correct location impractical.

The drilling grid is extended from permanent reference points by transit and tape traverse; elevations are carried to the collar of each hole by a line of levels from established reference points. Elevation datum is from the United States Coast and Geodetic Survey bench marks. The drilling grid is tied to the San Manuel co-ordinate system, which is based on a true north meridian. Holes are spudded in as near the intersection of grid co-ordinate lines as practical, and the error in hole location is rarely more than one foot in either direction.

Statistics

At the present time 67 holes have been completed, and 11 are in progress for a total of 110,854 ft. of drilling since exploration of the property began. The Bureau of Mines drilled 15,824 ft., and San Manuel Copper Corporation has drilled 95,030 ft. The deepest hole drilled to date has been 2600 ft. All drilling is done on contract, with the contractor furnishing all equipment and tools.

The average drilling conditions at San Manuel are illustrated by the following tabulation of statistics for a three-month period. Drilling shifts refer to time actually spent in drilling; total shifts worked refer to drilling shifts plus the time spent moving and setting up on new locations, repairs, fishing, and miscellaneous lost time:

	Average	Best Drill	Poorest Drill
Elapsed Time	91 days	91 days	91 days
No. of Drills Operating	6	1	1
Total Footage Drilled	13296 ft.	3439 ft.	71 ft.
Drilling Shifts	698.6	116.5	13.8
Advance per Drilling Shift	19.0 ft.	29.5 ft.	5.1 ft.
Total Shifts Worked	825	133.8	23.7
Advance per Shift Worked	16.2 ft.	25.7 ft.	3.0 ft.

The average time required to move to a new location was 4.6 shifts. This includes pulling casing from the completed hole, moving, and rigging up preparatory to spudding in.

Equipment

The selection of churn drills for exploring this property was based on the record of accurate tonnage and grade estimates computed from data obtained by churn drilling at other well-known disseminated copper deposits. Exploration by diamond drill was rejected because of probable low core recovery if the formations proved to be highly fractured.

Several types of churn drills are operating on the property; Bucyrus-Erie machines being in predominance. Models 24-W, 24-L, 29-W, 29-T, and 36-L, with drilling capacities ranging from 1500 ft. to 3600 ft. are represented. These are all steel machines, very compactly built, and ideal for working in rough terrain. The space required for a set up is comparatively small, and the machines can be handled over fairly steep grades. There are four Ft. Worth Spudders in operation: Models Super D, F, Jumbo H, and Super J; having drilling capacities ranging from 2500 ft. to 5000 ft. These are larger machines of wood construction, and require considerably more room for a set up, as the engine is usually set back of the rig some 20 to 30 ft. Power transmission is by flat belt drive. They are more awkward to move, and take longer to set up and tear down than the Bucyrus-Erie machines.

The drilling contractors, operating under similar contracts, hire all help required to run the rigs. A crew usually consists of a driller, a tool dresser, and welder. Since all bits are built up by electric welding, the tool dresser is more of a general helper than his name implies. Some contractors work on a three 8-hr. shift basis; others on two 12-hr. shifts. All drills are now operating 24-hr. per day, and 7 days a week.

DRILLING

As the early drilling was comparatively shallow, holes 8-in.

in diameter were started, reduction to 6 and 4-in. holes then being possible. When it became evident that deeper drilling would be required, with the possibility of having to case and reduce size of hole several times before reaching bottom, the starting hole was increased to 10-in. and finally to 12-in. diameter. This permits running 10-in. casing followed by 8-in., 6-in., and 4-in. casing when necessary.

There has been considerable discussion regarding the advisability of starting holes with 12-in. bits. It was thought that the larger diameter hole and the greater shock produced by heavier tools would increase caving in fractured ground. The drill contractors preferred the 8-in. bit because a larger bit would probably slow the drilling speed in the upper portion of the hole, where contract prices per foot are relatively low. It has been our experience, however, that the larger sized hole does not decrease speed of drilling greatly, and that caving would be encountered at about the same place in the hole regardless of size of bit used. The larger hole gives one better assurance of being able to drill to the depth required. The 12-in. hole is never carried to more than 1200 ft., and casing is usually required before this depth is reached. The 10-in. hole is carried to 1500 or 1600 ft. if possible, allowing the hole to be completed with either an 8-in. or 6-in. bit. The deepest hole, which was 2600 ft., was finished with a 4-in. bit after having set a 400 ft. liner of 4-in. pipe at 2400 ft. Some of the ground seems to stand well, as three holes, the deepest of which was 2200 ft., have been drilled without the use of any casing.

Drill locations and access roads are constructed to meet the requirements of the type of machine that will occupy the site. The

Bucyrus-Erie machines dump the sludge on the left side, facing the machine, while the Ft. Worths dump on the right side; thus necessitating a different type of location. All roads and locations have been made by bulldozer and scarifier, on contract; no drilling and blasting have been required.

Fishing for lost tools is taken care of by the contractors, with the exception of some long difficult jobs below 1000 ft., in which case the company has assumed part of the burden of cost. This situation has not come up often.

Unless casing is ordered by the field engineer to shut off possible caving and the resultant contamination of samples, especially in or near the ore zone, its use is usually left to the discretion of the contractors. The contractor is required to make every effort to recover all of the casing, but there are times when several joints have to be cut off the bottom in order to salvage any. This is accomplished by setting off a bomb, fired electrically at a coupling near the bottom, or by using a "collar buster"; a device lowered on the string of tools to a predetermined depth, which punctures and slits the pipe until a collar is reached and cut. The bombs are not too satisfactory because they tend to swell the casing in one or more places, making withdrawal of the pipe difficult.

The use of any drilling muds or Aquajell is, in general, prohibited. The exceptions to this rule are to permit the use of Aquajell, plastered on casing couplings when being run into the hole to make later withdrawal easier, and during fishing operations in caving ground. In crooked holes it is occasionally necessary to drop surface rocks in the hole and redrill in order to straighten it. In any of these operations the driller is required to thoroughly clean the hole before sampling operations are resumed.

In order to accurately establish the depth from which samples are coming, the holes are measured frequently with a special measuring device consisting of a reel of 3/32 in. galvanized aircord marked with lead buttons every 10 ft. The 100 ft. marks are identified by a code of elongated buttons. The measuring cable was calibrated by attaching a 7-lb. lead weight to the zero end; lowering it down a vertical shaft; and marking off the units on surface. When measuring, a very definite jerk is felt when the weight is pulled off the bottom of the hole.

Frequency of measurement varies. Holes are measured when they near the contact of the conglomerate and monzonite, so this point can be closely determined. After that, measurements are made at about 200 ft. intervals, and again when the hole is completed.

SAMPLING

Equipment

Sampling equipment consists of a dump box, a 6-ft. launder, a sample splitter, and 5-gal. milk cans to catch the samples.

The dump boxes are built of 2 in. by 12 in. plank, lined with 1/4 in. steel plate welded at the joints. The boxes are 12 in. wide, 36 in. long, and 24 in. high--inside dimensions. The launder is constructed of 1/8 in. steel plate, and designed to fit securely, with a 3-in. overlap between the steel lining and wood exterior, at the open end of the dump box. The discharge end of the launder lies on the upper edge of the splitter unit. The slope of the launder is adjusted to insure an even flow of sludge to the splitter, which is a modification of the Ray Consolidated Company splitter[5]. It is, essentially, 3 or more Jones splitters arranged in series to facilitate gravity flow of the sludge through the successive individual units. The upper two tiers of slots of a four cut splitter are 1 1/4 in. wide, and the lower two tiers are 3/4 in. wide; the slots being staggered by 1/2. The sample portion of the sludge passes straight down and is discharged at the front. The rejects gather underneath and are discharged at the side.

Personnel

It is desirable to have as samplers young engineers or geologists. This type of help has not been available, so it has been necessary to employ less skilled men, which in turn has meant special training and supervision for the sampling crew. Every detail of catching, preparing, washing character samples, and panning for concentrates had to be taught in most cases. Sampling is supervised by shift bosses and engineers who visit the rigs periodically during sampling operations.

Technique

The churn drill holes are sampled at 5-ft. intervals, from the contact of the conglomerate and the monzonite, to the bottom of the hole. Character samples are taken at 20-ft. intervals in the conglomerate.

The sludge is dumped from the bailer into the dump box, and flows through the splitter. The driller is cautioned to ease the bailer into the box to avoid surge and splash. The sample portion is caught in a 5-gal. milk can and a bucket of rejects is caught; a portion of which is washed free of slimes and saved as a character sample. A uniform volume of rejects from each 5-ft. interval is panned to obtain a concentrate which is dried and sacked. An engineer examines both the character sample and concentrate to determine, megascopically, the rock type, alteration, kind, and relative amounts of mineralization. The character samples are filed for future reference, and the concentrate is sent to G. M. Schwartz of the United States Geological Survey for selected samples to be polished and examined by microscopic methods.

The sampler fills out a "Churn Drill Report", noting the depths at which the samples are caught, color of sludge, condition of hole, depth at which water was encountered, fault zones as evidenced by gouge, and any other pertinent data relative to the hole. The spaces for rock type and mineralization are filled in by the engineer who examines the character and concentrate samples.

The size to which the sample is cut depends largely on the size of hole being drilled, and if drilling is under water. A 12-1/2 in. hole may require a cut to 1/256 of the total volume of sludge bailed, and a 4 in. hole is cut to 1/8 or 1/4 of the original volume of sludge. The sample is cut so there is a minimum of about [illegible] lbs. of dry solids.

Drillers are required to bail holes clean. This is relatively simple above the water table, and takes about 3 or 4 trips into the hole. However, after the holes are under water, it is never possible to get a really clean hole, as there is always a certain amount of slimes in suspension. In this case, a few tests are made to determine how many bailings are required to pick up the largest part of the sample, and leave the hole relatively clean for the next run. On numerous occasions it has been possible to obtain samples of the slimes in suspension by carefully bailing a hole after it had been shut down for periods of 24 to 48 hrs. Assays of this material have agreed very closely with the assay of the last run made, so that no serious errors are introduced by leaving this material in the hole.

No attempt is made to shut the water off by casing.

Drying & Preparing Pulps

The samples caught in milk cans are gathered up, usually at the end of the shift, and hauled to a centrally located drying room. They are dried on a series of 9 heavy steel drying tables, each about 3 ft. square. Steam, which is generated to 20 lbs. gauge pressure in a manually-operated vertical fire tube boiler, using diesel oil for fuel, supplies the heat for the drying tables.

Other drying room equipment consists of a Jones dry splitter, 2 Braun type UA pulverizers, small platform scales, and a table for rolling pulps.

The operating personnel of the drying room consists of a foreman on day shift, with three dryers and grinders; and lead men on afternoon and graveyard shifts, with 2 or 3 helpers. The drying room operates 24 hrs. per day for 7 days a week.

As samples are brought in from the rigs, they are lined up in sequence and dried on the steam plates. Since there is such a large amount of sludge to be dried, the time of drying is more than an hour per sample, and may extend to 3 hrs. for exceptionally heavy, slimy samples. After drying, the sample is scraped off the table into a large pan and quarted by means of a Jones splitter. Three of these cuts are put in paper sacks; the fourth being set aside for pulverizing. Each of these cuts will weigh from 2-1/2 to 3 lbs. Paper tags are used, designating the sample number by hole as well as by footage. The cut which is pulverized and then thoroughly rolled, is divided between five different pulp sacks holding from 150 to 200 gms. each. One of these pulps is sent to the assay office of the St. Anthony Mining and Development Company for field control.

The other four are sent to the Magma Copper Company in Superior where one pulp is assayed directly for total and oxide copper; two are used in making up composites for total copper, oxide copper, gold, silver and molybdenum determinations. The fourth pulp is held in reserve

Two of the three sacks of rejects are stored in tunnels at San Manuel, and one is stored at Superior. These are held in reserve for possible future examinations, or for further assay.

Records of the holes, listing each individual sample number, depth of footage, date of sample, weight of cut, number of splits made to obtain this cut, and the name of the sampler are kept in the bucking room. These records are all filed.

ASSAYING

The pulp sent to the St. Anthony Mining and Development Company is assayed for total and oxide copper. The method of assay used is a modified procedure of the short iodide method, wherein the end point of the starch-iodine blue was made much sharper, and gives results close enough for field control.

At the Magma Copper Company the total copper content is determined by standard electrolytic methods; oxide copper is determined by the long iodide method. Results of these assays check very closely with those of Ledoux & Company and Union Assay Office.

Gold, silver and molybdenum are determined from composites. These composites are made up of pulps representing portions of the hole of the same general mineralization or assay character, but do not usually exceed 100 ft. of hole.

If the average of individual assays of total copper checks within 0.03 percent with the total copper determination of the composite by Magma Copper Company and an umpire assayer, those values are accepted as being correct.

In the office at Superior, records of each hole are compiled showing all determinations made on individual and composite samples, the accepted assay, rock type, and mineralogy.

TONNAGE & GRADE

Churn drilling to May 1st has blocked out approximately 119,170,000 tons of ore, which will average 0.80 percent copper. This total contains 14,600,000 tons of low grade oxidized material which averages 0.65 percent total copper, 0.36 percent oxide; 29,640,000 tons of mixed oxidized and sulphide ore which averages 0.82 percent total copper, and 0.58 percent oxide copper; and 74,930,000 tons of sulphide ore which averages 0.82 percent total copper, and 0.05 percent oxide copper.

These tonnage and grade figures are of a preliminary nature, and are kept up to date with the drilling as closely as the required checking of assays allows.

The following procedure is used to compute the tonnage and grade:

The drilling area is divided into rectangles and triangles as the spacing of drill holes demand, with a drill hole at each corner of the rectangles, and at the apices of each triangle. Care is taken to arrange the pattern of geometric figures so that one drill hole is not a common corner for more figures than necessary. The area, calculated from the horizontal distance between holes, is multiplied by the average of the thickness of the columns of ore encountered in the holes making up the corners of the figures.

Twelve and one-half cu. ft. per ton is the factor used to convert the volume to tonnage. The grade for each block is the weighted average of the ore columns of the holes used.

The bottom sample, or in some case, more than one sample is thrown out as a precaution against salting of marginal material by higher grade samples above. The cut back at the bottom of an ore column depends on the condition of the hole, grade of ore, and whether there is a gradational change in copper content at the bottom of the column, or a sharp break. The tonnage is calculated from drill hole data with no allowances for an extension of the ore body beyond the boundaries of completed holes. This eliminates the necessity for constant revision of such an estimated extension of ore, due to the continually changing drilling pattern.

At intervals tonnage and grade calculations are computed by two other methods as checks. In the second method, the average area of adjacent cross sections is multiplied by the distance between the sections to compute the volume. The grade is computed from the weighted average of the ore columns of holes in the two sections. The ore columns are adjusted as in the first method.

The third method involves plotting the area of influence of each hole, and using the adjusted ore column for thickness, to compute a tonnage and grade figure for each area.

ACKNOWLEDGEMENT

Acknowledgement is due the officers of San Manuel Copper Corporation for permission to use the information presented.

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STRUCTURE AND MINERALIZATION, SILVER BELL, ARIZONA

By

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AMERICAN SMELTING AND REFINING COMPANY

A paper to be presented at the annual meeting of
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ABSTRACT

Replacement-type ore bodies in tactite have accounted for the Silver Bell District's production of copper in the past. In the near future, substantial production will come from porphyry-type copper ores occurring in two deposits spaced two miles apart within a northwesterly trending zone of hydrothermal alteration several miles in length. This zone lies along a major regional fault which is believed to have formed initially in Paleozoic and Cretaceous sedimentary rocks, and subsequently to have been the locus of repeated Laramide igneous activity. Alaskite followed by dacite porphyry were intruded first. Then, after an erosional interval marked by basal conglomerate, a thick series of dacite flows and pyroclastics was deposited. Intrusions of small stocks of monzonite and related dikes were preceded and partly controlled by: (a) regenerative movement along the major structure and (b) development of cross-breaking fractures. Renewed development of cross-breaking joint systems along the main zone provided the principal control of ensuing hypogene mineralization. Post-mineral andesite dikes were emplaced parallel to the major structures. Lastly, enrichment by supergene chalcocite formed the two ore bodies.

Features considered significant: (a) The belt of alteration and copper mineralization coincides with the inferred position of the original major fault. (b) The systems of close-spaced parallel joints were most favorable to deposition of the primary chalcopyrite. (c) The intensity and extent of supergene enrichment are reflected by the quantity of limonite-after-chalcocite in outcrops. (d) The erosional interval between alaskite and monzonite may be a useful means in age-distinction of Cretaceous and Tertiary igneous rocks.

INTRODUCTION

Purpose:

At Silver Bell the mineralized zone and a number of structural features trend west-northwest. Yet, mineralization is controlled in detail by northeast, cross-trending fractures. The purpose of this paper is to present interpretations of these and other relationships.

Previous Work and Acknowledgments:

The first scientific study of the district was published in 1912 by C. A. Stewart (5). Considerable field and laboratory work has been done in more recent years by several groups and individuals, including the writers, all reporting privately to the American Smelting and Refining Company. Roland Blanchard conducted leached outcrop studies in a portion of the area. Harrison Schmitt with H. M. Kingsbury and L. P. Entwistle mapped structure and mineralization in the central part of the district. Paul F. Kerr studied the alteration features, and later published a comprehensive paper (3) on the district. Thomas Mitcham mapped structural features in the surrounding area. The writers have drawn considerably on unpublished data, particularly in compilation of the geologic map. The high quality and usefulness of the work of these men is gratefully acknowledged, but unfortunately it is not feasible to give specific individual credits.

Thanks are due the American Smelting and Refining Company for permission to give this paper.

Location:

Silver Bell is situated 35 airline miles northwest of Tucson, Arizona, in a small, rugged range rising above the extensive alluvial plains of this desert region. Its geographical relation to other porphyry copper deposits of the Southwest is shown on the inset map in the lower left corner of Plate 1. The climate is semi-arid. Altitudes range within 2000 and 4000 feet.

History:

Opening of the Boot Mine, later known as the Mammoth, in 1865 was the first event of note in the district's history. Oxidized copper ores containing minor silver-lead values were mined from replacement deposits in garnetized limestone and treated in local smelters. Copper production had approached 45 million pounds by 1909 when the disseminated copper possibilities in igneous rocks were recognized. Extensive churn drill exploration was carried out during the next three years and resulted in the partial delineation of two copper sulphide deposits, the Oxide and El Tiro. Although the then-submarginal tenor discouraged exploitation of these disseminated deposits, selective mining of ore bodies in the sedimentary rocks continued intermittently until 1930, providing a production total of about 100 million pounds of copper.

The American Smelting and Refining Company began exploratory and check drilling in 1948 and subsequently made plans for mining and milling the Oxide and El Tiro ore bodies at the rate of 7500 tons per day. Production will start during the second quarter of this year at a rate of about 18,000 tons of copper annually.

GENERAL GEOLOGY

Formations ranging in age from Pre-Cambrian to Recent are exposed in the Silver

Bell vicinity. The more erosion-resistant of these, Paleozoic limestone and Tertiary volcanics, predominate in the scattered peaks and ridges comprising the Silver Bell mountains. The porphyry copper deposits are located along the southwest flank of these mountains in hydrothermally altered igneous rocks. These are principally intrusives which cut Cretaceous and older sediments and are considered to be components of the Laramide Revolution.

For three-fourths of its length, the zone of alteration strikes west-northwest (Plate I). There now is no single structure which accounts for this alignment. Howevery, indirect evidence suggests that a fault representing a line of profound structural weakness existed in this position prior to the advent of Laramide intrusive activity. This line will hereinafter be referred to as the "major structure". It was obliterated by the Laramide intrusive bodies, but it affected a degree of control on their emplacement, as evidenced by their shapes and positions. The influence of fault structures on the shapes of intrusives in other porphyry copper districts has been noted by Butler and Wilson (2), and by others.

As shown on the inset map on Plate II, a fault of parallel trend and considerable displacement lies to the north. This fault is now marked by a line of small Laramide intrusive bodies. To the south is a third fault of large displacement. Evidence of its age in relation to the Laramide intrusions and mineralization is not recognized, but its conformance in strike with the other two major faults is significant. These three breaks establish a pronounced trend of regional faulting. They are high-angle, and the southerly one may be reverse. Stratigraphic separations on these faults are of the order of several thousand feet.

The local Paleozoic section is about 4000 feet thick. It is composed predominantly of limestone with a basal quartzite member. The Cretaceous section appears to exceed 5,000 feet. Conglomerates, red shales, and arkosic sandstones (the youngest) characterize the three principal members.

Intrusion of alaskite marked the beginning of Laramide igneous activity. It was emplaced as an elongate stock with one side closely conforming to the major structure line throughout a distance of nearly four miles. The alaskite was at one time regarded as a thrust block of pre-Cambrian rock (2); however, its intrusive relationship and consequent post-Paleozoic age has been established by inclusions of limestone found in outcrops north of El Tiro. It is believed also to be post-Cretaceous although conclusive evidence of this has not been found at Silver Bell.

The next event was the intrusion of a large stock of dacite porphyry into Paleozoic sediments and alaskite. The stock was some three miles in width and at least six miles in length in a northwesterly direction. It was sharply confined along its southwest side by the major structure line. A number of large pendants of moderately folded Paleozoic sediments occur within and along its southwest edge. Thus, the inferred, original major fault between Paleozoic and Cretaceous sediments became a contact between alaskite and Paleozoic sediments and then, a contact between dacite porphyry and alaskite.

Andesite porphyry may have been intruded later than the dacite porphyry, but relationships are not clear; it may be simply a facies of the latter.

The intrusive activity was at this stage interrupted by an interval of erosion. The erosion surface probably was rugged as there were local accumulations of coarse, angular conglomerate. Subsequently, a series of volcanic flows and pyroclastics several thousand feet in thickness was deposited. A similar unconformity has been recognized elsewhere in the Southwest, particularly in the Patagonia Mountains near the Flux mine, some 75 miles southeasterly. Here, as at Silver Bell, volcanics were deposited on an erosion surface cut in Cretaceous and older sediments which had been intruded by alaskite.

Though no evidence is offered which closely defines the age of this unconformity, and proper analysis of the problem is beyond the scope of this paper, it is interesting to speculate that it may mark the close of the Cretaceous Period and provide a distinction between Tertiary and Cretaceous igneous rocks within the Laramide Revolution.

Subsequent parallel faulting along the major structure line sliced the volcanics and Cretaceous sediments into horst and graben structures. These faults are remarkably persistent southeasterly, extending several miles beyond the map. It is not clear if they originally extended through the northwest part of the district; they may have terminated against the earlier east-west fault shown on the inset map on Plate II. The formation of these faults indicates at that time a still-existent, deep-seated zone of weakness along the major structure line.

Monzonite stocks and contemporaneous dikes were then emplaced along and near this line, obliterating portions of the faults described in the foregoing paragraph. The stocks are elongate parallel to the major structure line. The dikes are distributed along this line but trend across it, for the most part, with an average east-northeast strike. Systems of close-spaced, parallel fractures then developed. Like the dikes, these fractures are distributed along the major structure and strike across it. Alteration and sulphide mineralization then took place. The deposition of sulphides, particularly chalcopyrite, was controlled in detail by the cross-trending fractures. Although these were distributed along the major structure line as a narrow band, it is notable that throughout much of its length there are now no fault structures to account for this trend.

Post-sulphide dikes of andesite represent the last intrusive activity in the immediate district. Curiously, most of these dikes parallel the strike of the major structure, although it would seem that the cross-breaking fractures represented available lines of weakness. This serves to emphasize the major structure line as being a profound, deep-seated zone of weakness persisting through a long period of time.

Uplift and erosion of the region during late Tertiary or Quaternary time exposed the lean primary mineralization to processes of weathering and enrichment, resulting in the accumulation of the two chalcocite ore bodies.

Small plugs and flows of basaltic lava occur in the flats surrounding the Silver Bell range. These are later in age than the Gila conglomerate and mark one of the more recent events in the geologic history of the region.

STRUCTURAL CONTROL OF HYPOGENE MINERALIZATION

As in the majority of porphyry copper deposits, the principal primary sulphide minerals at Silver Bell are pyrite and chalcopyrite. Although occurring as disseminated grains, they are more abundant as narrow veins or seams which are usually near-vertical in attitude and persistently parallel. Varying in thickness from paper-thin to several inches and, in spacing, from inches to several feet, these thin sulphide sheets occur as groups of various sizes throughout the narrow, northwest-trending zone of hydrothermal alteration. (Due to the small scale, a single line in the pattern of "Mineralized Fissures" on Plate I usually represents a large number of parallel structures, rather than an individual.) In detail the average individual fissure appears as a thin quartz-sulphide seam encased by a rather uniform band of sericite. The fissures are predominantly oriented in the northeast quadrant; a small proportion strike northwest and a few are random. From a broad viewpoint there are, among these systems, or groups, no intersections of consequence. Within groups, changes in strike occur gradually and result in curving trends. As noted earlier, these groups of mineralized fissures are distributed along the major structure line, and it is assumed they were formed in response to deep-seated, uniform stress related to this line.

At least a few hundredths of one per cent copper is present nearly everywhere in the altered zone; better values occur where there are mineralized fissures; and the best values, where the fissures are close-spaced. The two comparatively large groups of these close-spaced structures coincide with the positions of the two ore bodies (Plate I). However, the actual structural, mineralogical, and lithological distinctions among these and other, smaller groups are minor, and the factors that controlled the position and size of these two groups are not clearly evident. The strong east-west fault which terminates in the Oxide area may have influenced the concentration of fracturing there, and at El Tiro the sharp bend in the alteration zone and the group of northeast-striking dikes likewise may indicate a cross-trending line of weakness that localized stresses. Nonetheless, the importance of these structural conditions is not clearly demonstrated, and no good evidence is found to explain the structural cause of the more intense fracturing which localized the two ore bodies in their present positions in preference to other locations along the major structure line.

Outside of the zone of alteration the dacite porphyry is finely fractured and jointed throughout most of its large exposed area. In sharp contrast to the systems of parallel fissures in the alteration zone, these breaks in the dacite porphyry are almost completely disoriented; parallelisms are rare and traceable for only a few inches or feet. They appear to be pre-mineral where they are found in the alteration zone in the westerly and southwesterly portions of the dacite porphyry. It would seem that in physical aspect this formation was exceptionally well prepared to be mineralized---perhaps better than the rocks of the ore zone proper. The fact that it was mineralized only to a minor degree may be accounted for by the absence of systematic fractures. That is, only the systems of parallel fractures were connected with the deep-seated source of mineralization, and the pervasive breaking of the dacite porphyry did not alone qualify it for mineralization.

Excepting the post-mineral andesite dikes, all igneous rocks within the narrow northwest-trending zone shown on Plate I are hydrothermally altered. Variations in the intensity or in the completeness of the process, have been subdivided by Kerr (2) into five stages. His analysis demonstrated, among other things, that the known ore bodies occur within the more strongly altered areas.

The area outlined on Plate I includes all degrees of alteration, but no differentiation is made It merely represents the areal extent of bleached-appearing, igneous rocks showing evidence in the leached outcrops of pre-existing disseminated sulphides---principally pyrite. The transition to relatively fresh rock is quite sharp in many places, particularly along the contact with sedimentary rocks and on the faults in the southeast portion. However, along most of the southwest margin the transition is gradational, and the limit is an arbitrary line.

Tactite, composed essentially of garnet, quartz and lime-silicate minerals, is confined to a narrow belt along the southwest margin of the limestone pendants, except in the vicinity of the Mammoth and Union mines where it has replaced the full width of the sedimentary block. It has been suggested by Stewart (1) that the dacite porphyry and monzonite are responsible for this "contact metamorphism". The areal distribution of this tactite is such that, if it were to be considered strictly as a contact phenomenon, the alaskite would be as related to it as the other intrusives. Without going into the problem in detail, it is worth noting that the tactite occurs along the major structure line in such a manner as to indicate a close genetic connection with it. Supporting evidence in the form of well-defined structural controls of individual pods of tactite is not recognized. An occasional mineralized fissure cuts the tactite in the Mammoth and Union deposits, although the primary chalcopyrite ore bodies have little obvious structural control. Elsewhere, fissures in igneous rocks terminate abruptly at tactite margins.

SUPERGENE ENRICHMENT

The two ore deposits consist of rudely tabular accumulations of chalcocite from one to two hundred feet in thickness. Lying beneath about one hundred feet of leached capping, they were formed by two- to threefold enrichment of the copper contained in the primary mineralization. Typical ore is composed of altered rock and sulphides in a ratio of about 10:1 by weight.

Most of the capping over the ore bodies contains less than one-tenth of one per cent copper as cuprite, or other oxidation products, mingled with the limonite. Occasionally, somewhat higher values occur where copper has been precipitated as silicates and carbonates by reactive gangue material present in less altered rock. Within the ore bodies, where alteration is strong and the gangue is non-reactive, the upper limit of the sulphide zone (or, the base of oxidation) appears on open-cut faces as a sharply defined, highly irregular line. Only rarely is there a transition zone of mixed sulphide and oxidized minerals. In general shape the base of oxidation conforms to modern topography, even though local relief exceeds 200 feet. The water table for the most part now is well below the chalcocite zone.

Some of the irregularities of the base of oxidation are caused by displacement on post-chalcocite faults, but most are due to variations in rock permeability. This is evidenced by the dense siliceous character of a few sulphide remnants occurring well up in the leached zone, and by leached indentations of the sulphide zone along some of the fissures.

It is significant that the base of oxidation shows general conformance to the topography, but that in detail it is a highly irregular, sharply defined "front". Its present shape may have been produced by modification of a pre-existing base---one which was established during relatively moist climatic periods of the past. Under such conditions the water table would have oscillated at uniformly shallow depths and thus would have served to limit the depth of oxidation, thereby determining the shape of its base to some extent. Otherwise, under conditions involving depression of the water table---principally those of dryer climates---it appears that the oxidation process proceeded in the vadose zone independent of the water table, and that it advanced downward on a sharply defined front whenever oxygen-charged meteoric water reached it.

Opinions vary as to the role of the water table in the deposition of chalcocite and as to the reason for the chalcocite's distribution through a considerable vertical range. At Silver Bell pyrite and, preferentially, chalcopyrite are only partially replaced by chalcocite immediately below the line at the base of oxidation as well as on down through the zone of enrichment. This condition appears to be an argument favoring the theory that chalcocite is deposited at or below the water table. That is, the dissolved copper on its downward course by-passed available chalcopyrite and pyrite until it reached the water table where it formed chalcocite. The partial replacement of primary sulphides by chalcocite and its vertical distribution, as now existing, may then be explained as originating through the numerous cyclic fluctuations of the water table position.

LEACHED OUTCROPS

In the formation of most disseminated chalcocite deposits the enrichment process takes place progressively---copper is repeatedly dissolved, carried downward and precipitated. It has been well established by Blanchard (1), Locke (4) and others that under these conditions "limonites" of certain colors and textures are left behind in the leached capping as evidence of the pre-existing chalcocite.

The Silver Bell district provides exceptionally good examples of this phenomenon, but limonites of chalcocite derivation are not confined to the outcrops over the ore bodies. They are widely dispersed through the zone of alteration. Proper interpretation of their significance in respect to ore possibilities rests mainly on quantitative rather than qualitative appraisal. Mapping of the Silver Bell outcrops on this basis provided a valuable guide in exploration drilling. Results have demonstrated conclusively that the pattern of relatively strong copper mineralization at depth is reflected in the outcrops by the distribution and abundance of diagnostic limonites.

It may be of interest at this point to mention the ancient excavations which are numerous in the outcrops of the mineralized zone at Silver Bell. There is evidence indicating they are several centuries old. These shallow open cuts invariably follow close-spaced, parallel fissures containing the dark maroon limonite-after-chalcocite. Since there are no precious metals or visible copper in these fissures, it is plausible to assume that this limonite with its particular hue was considered valuable in the past as a pigment, perhaps for pottery or war paint. Thus, in the history of leached outcrop investigations, it seems that some early Arizona Indian tribe deserves at least honorable mention.

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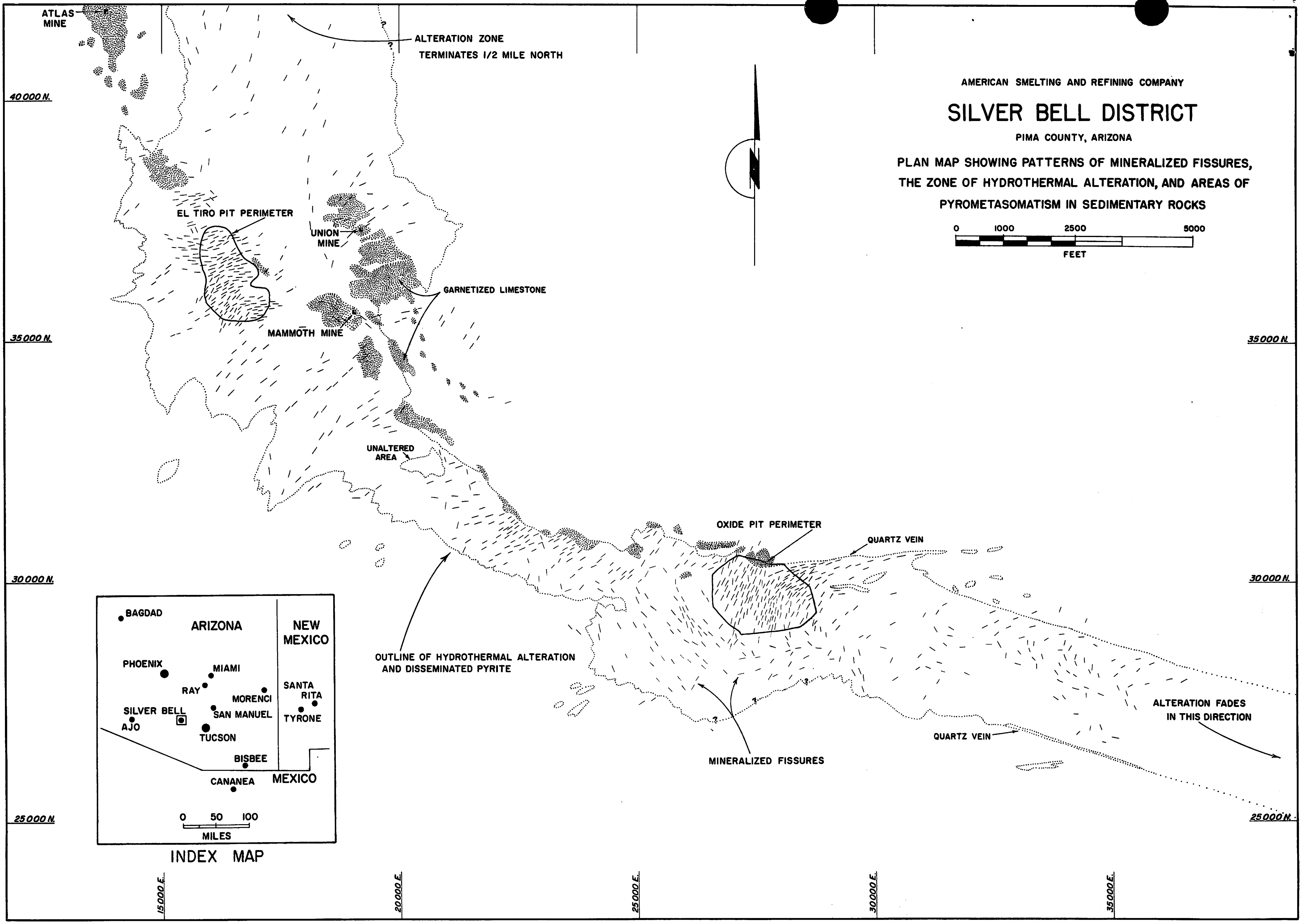
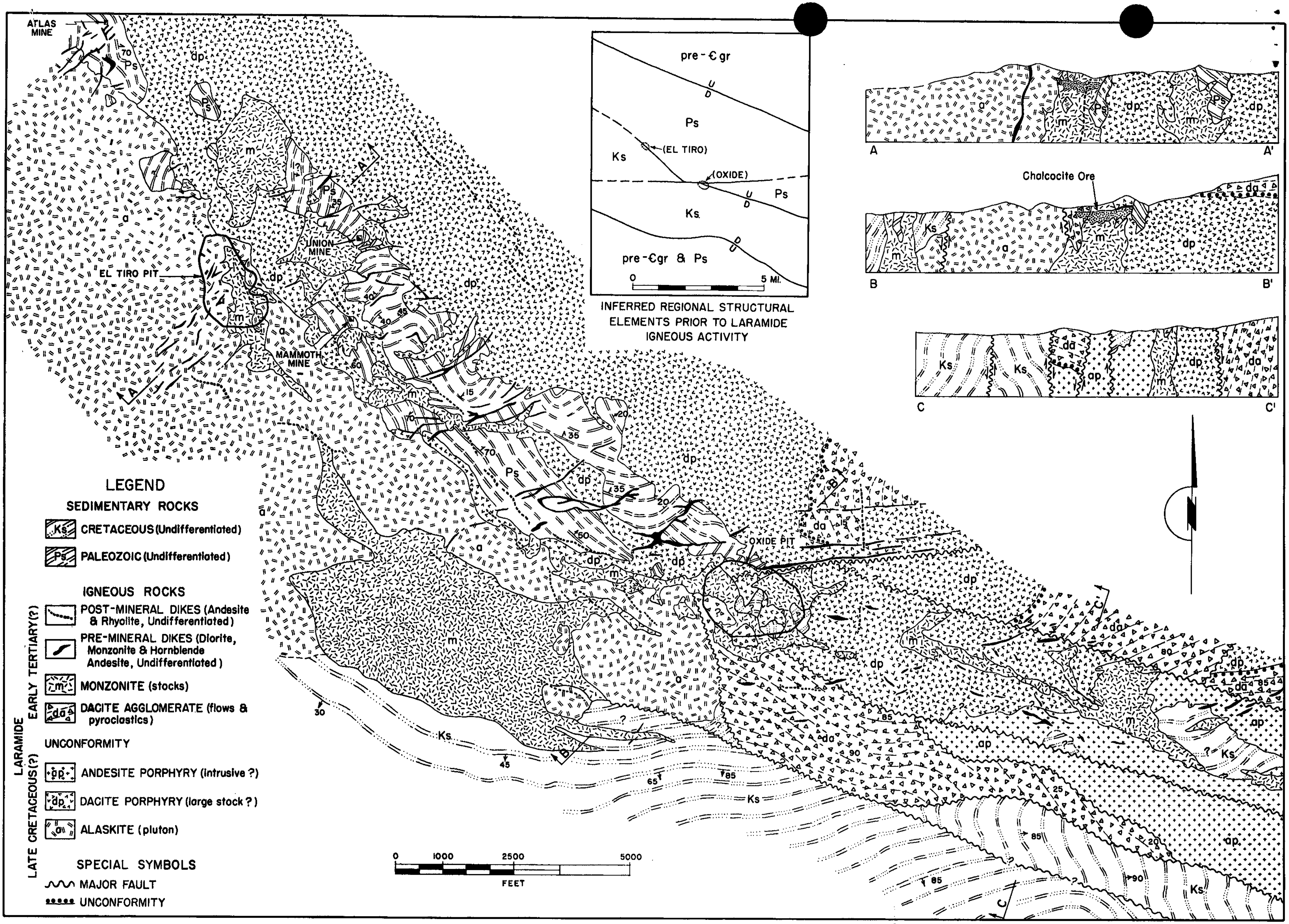

AMERICAN SMELTING AND REFINING COMPANY
SILVER BELL DISTRICT
PIMA COUNTY, ARIZONA
PLAN MAP SHOWING PATTERNS OF MINERALIZED FISSURES, THE ZONE OF HYDROTHERMAL ALTERATION, AND AREAS OF PYROMETASOMATISM IN SEDIMENTARY ROCKS
0
1000
2500
5000
FEET
ATLAS MINE
ALTERATION ZONE TERMINATES 1/2 MILE NORTH
EL TIRO PIT PERIMETER
UNION MINE
GARNETIZED LIMESTONE
MAMMOTH MINE
UNALTERED AREA
OUTLINE OF HYDROTHERMAL ALTERATION AND DISSEMINATED PYRITE
OXIDE PIT PERIMETER
QUARTZ VEIN
MINERALIZED FISSURES
QUARTZ VEIN
ALTERATION FADES IN THIS DIRECTION
40000 N.
35000 N.
30000 N.
25000 N.
15000 E.
20000 E.
25000 E.
30000 E.
35000 E.
BAGDAD
ARIZONA
NEW MEXICO
PHOENIX
MIAMI
RAY
MORENCI
SANTA RITA
SILVER BELL
AJO
SAN MANUEL
TYRONE
TUCSON
BISBEE
MEXICO
CANANEA
0
50
100
MILES
INDEX MAP

PLATE I



GEOLOGIC MAP, SILVER BELL DISTRICT, ARIZONA

PLATE II

Silver Bell
JE Kinnison
(for the Wilson Vol)

STRUCTURE AND MINERALIZATION AT SILVER BELL, ARIZ.

by

Kenyon Richard
and
James H. Courtright

INTRODUCTION

This material was originally published (12) in November, 1954. Exploration and mining during subsequent years have provided additional information; accordingly, a number of revisions of text and plates are included herein. Basic concepts, however, remain essentially the same as originally presented.

Watson, (16) is now preparing a doctoral dissertation based on detailed mapping in the Silver Bell Mountains. Mauger, et. al., (9) are making potassium argon age determinations of most of the igneous rocks in the district. These two lines of research should, among other things, materially improve upon the knowledge of certain age relationships which are only briefly noted herein.

Silver Bell is situated 35 airline miles northwest of Tucson, Arizona, in a small, rugged range rising above the extensive alluvial plains of this desert region. Its geographical relation to other porphyry copper deposits of the Southwest is shown on the inset map in the lower left corner of Plate 1. The climate is semi-arid. Altitudes range within 2000 and 4000 feet.

Opening of the Boot mine, later known as the Mammoth, in 1865 was the first event of note in the district's history. Oxidized copper ores containing minor silver-lead values were mined from replacement deposits in garnetized limestone and treated in local smelters. Copper production had approached 45 million pounds by 1909 when the disseminated copper possibilities in igneous rocks were recognized. Extensive churn drill exploration was carried out during the next three years and resulted in the partial delineation of two copper sulphide deposits, the Oxide and El Tiro. Although the then-submarginal tenor discouraged exploitation of these disseminated deposits, selective mining of ore bodies in the sedimentary rocks continued intermittently until 1930, providing a production total of about 100 million pounds of copper.

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GENERAL GEOLOGY

Formations ranging in age from Pre-Cambiran to Recent are exposed in the Silver Bell vicinity. The more erosion-resistant of these, Paleozoic limestone and Tertiary(?) volcanics, predominate in the scattered peaks and ridges comprising the Silver Bell mountains. Porphyry copper mineralization occurs along the southwest flank of these mountains in hydrothermally altered igneous rocks. These are principally intrusives which cut Tertiary(?), Cretaceous, and older sediments and are considered to be components of the Laramide Revolution.

For three-fourths of its length, the zone of alteration strikes west-northwest (Plate I). There now is no single structure which accounts for this alignment. However, indirect evidence suggests that a fault representing a line of profound structural weakness existed in this position prior to the advent of Laramide intrusive activity. This line will hereinafter be referred to as the "major structure." It was largely obliterated by the Laramide intrusive bodies, but it effected a degree of control on their emplacement, as evidenced by their shapes and positions. The influence of fault structures on the shapes of intrusives in other porphyry copper districts has been noted by Butler and Wilson (2).

As shown on the inset map on Plate II, a fault of parallel trend and considerable displacement lies to the north. This fault is now marked by a line of small intrusive bodies. To the south is a third fault of large displacement. Evidence of its age in relation to the Laramide intrusions and mineralization is not recognized, but its conformance in strike with the other two major faults is significant. These three breaks establish a pronounced trend of regional faulting, and it has been suggested (11) that they be named, from south to north, the Waterman thrust, the Silver Bell fault zone, and the Ragged Mountains fault. The two northerly ones are high-angle, and the southerly one may be reverse. Stratigraphic separations on these faults are on the order of several thousand feet.

The local Paleozoic section is 4400 feet thick (10). It is composed predominantly of limestone with a basal quartzite member. The Cretaceous section appears to exceed 5000 feet, but this figure is not a result of careful measurement. Conglomerates, red shales, and arkosic sandstones characterize the lithology. Volcanics and sediments of early Tertiary(?) age aggregate over 2000 feet in thickness. Three units are recognized by the writers (14): (a) the Claflin Ranch (earliest) --- conglomerates and coarse sandstones made up largely of igneous fragments and containing a few pyroclastic interbeds; (b) the Silver Bell --- andesite porphyry breccia, principally of mud flow origin; and (c) the Cat Mountain* --- pyroclastics, composed mainly of ash flows (16).

Intrusion of alaskite marked the beginning of Laramide igneous activity. It was emplaced as an elongate stock with its northeast side closely conforming to the major structure line for a distance of nearly four miles. The alaskite was at one time regarded as a thrust block of Pre-Cambiran rock (6); however, clear evidence of its intrusive relationship with both Paleozoic limestone and Cretaceous(?) arkose has since been found.

The intrusive activity was at this stage interrupted by an interval of erosion, resulting in partial exposure of the alaskite stock, followed by deposition of the Claflin Ranch, Silver Bell, and Cat Mountain units. (These three units are grouped as Tertiary(?)* volcanics and sediments on Plate II herein, and were termed "dacite agglomerate" on Fig. 2, reference (12).) A similar sequence has been recognized by the writers elsewhere in the Southwest (14).

The next event was the intrusion of a large stock or sill of dacite porphyry some three miles in width and at least six miles in length in a northwesterly direction.

*K-Ar ages of 56 to 70 m.y. have been obtained for various Cat Mountain Rhyolite occurrences by Damon, et. al., (3). According to Holmes (5) the beginning of Tertiary time is 70$\pm$ 2 m.y.

its main mass lies outside and along the northeast edge of the mineralized zone. Although its southwesterly side consists of irregular stocks, sills, and dikes extending into the mineralized zone, these apophyses of the dacite porphyry are limited in this direction by the major structure line. A number of large pendants of folded and faulted Paleozoic sediments occur within the southwest edge of the dactie porphyry. Thus, it is inferred, the original major fault between Paleozoic and Cretaceous (?) sediments became a contact between alaskite and Paleozoic sediments; and then, a contact between dacite porphyry and alaskite.

Andesite porphyry may have been intruded later than the dacite porphyry, but relationships are not clear; it may be simply a facies of the latter.

Subsequent parallel faulting along the major structure line sliced the volcanics and Cretaceous (?) sediments into horst and graben structures. These faults are remarkably persistent southeasterly, extending several miles beyond the map. They probably extended through the northwest part of the district, but there is little direct evidence. The formation of these faults indicates at that time a still-existent, deep-seated zone of weakness along the major structure line.

Monzonite stocks and contemporaneous dikes were then emplaced along and near this line, obliterating portions of the faults described in the foregoing paragraph. The stocks are elongate parallel to the major structure line; but the dikes trend across it, for the most part, with an average east-northeast strike. The dikes are elements of an extensive swarm having a general northeasterly trend and occurring throughout the Silver Bell Mountains.

Systems of close-spaced, parallel fractures then developed. These systems are distributed along the major structure line and generally strike across it.

Alteration and sulphide mineralization took place next. The deposition of sulphides, particularly chalcopyrite, was controlled in detail by the cross-trending fractures. Although these are distributed along the major structure line as a narrow band, it is notable that throughout much of its length there are now no fault structures to account for the trend of this zone.

Post-sulphide dikes of andesite and rhyolite represent the last intrusive activity in the immediate district. Curiously, most of these andesite dikes are parallel to the major structure, although it would seem that the cross-breaking fractures represented available lines of weakness. This serves to emphasize the major structure line as being a profound, deep-seated zone of weakness persisting through a long period of time.

Uplift and erosion of the region exposed the lean primary mineralization to processes of leaching and enrichment, resulting in the accumulation throughout the district of a thin blanket of chalcocite. Two open pit ore bodies occur within this blanket.

Remnants of flows of andesite and basalt occur in the flats surrounding the Silver Bell range. In at least one locality to the east these flows are nearly flat and overlie conglomerate which dips about 25^{o} and contains boulders and fragments eroded from completely leached capping of the mineralized zone. Damon (3) has determined an age of 27.9 m.y. for these flows. This is particularly interesting because it indicates that, prior to that date, there existed an environment permitting formation of leached capping and, presumably, a chalcocite zone.

STRUCTURAL CONTROL OF HYPOGENE MINERALIZATION

As in the majority of porphyry copper deposits, the principal primary sulphide minerals at Silver Bell are pyrite and chalcopyrite. Although occurring as discrete grains, they are more abundant, accompanied by quartz, in systems of veinlets or seams which are usually near-vertical in attitude and persistently parallel. Varying in thickness from paper-thin to several inches and, in spacing, from inches to several feet, these thin sulphide sheets occur as groups of various sizes throughout the narrow, northwest-trending zone of hydrothermal alteration. (Due to the small scale, any single line in the pattern of "Mineralized Fissures" on Plate 1 diagrammatically represents a large number of parallel veinlets, rather than an individual.) In detail the average individual fissure appears as a thin quartz-sulphide seam encased by a rather uniform band of sericite. The fissures are predominantly oriented in the northeast quadrant; a small proportion strike northwest and a few are random. From a broad viewpoint there are, among these systems or groups, no intersections of consequence. Within a group, changes in strike occur gradually and result in curving trends. As noted earlier, these groups of mineralized fissures are distributed along the major structure line, and it is assumed they were formed in response to deep-seated, uniform stress related to that line.

At least a few hundredths of one per cent copper is present nearly everywhere in the zone of disseminated sulphides; better values occur where there are veinlets; and the best values, where the veinlets are close-spaced. The two comparatively large groups of these close-spaced structures coincide with the positions of the two ore bodies (Plate 1). However, the actual structural, mineralogical, and lithological distinctions among these and other, smaller groups are minor, and the factors that controlled the position and size of these two groups are not clearly evident. A strong east-west fault which terminates in the Oxide area may have influenced the concentration of fracturing there, and at El Tiro the sharp bend in the alteration zone and the group of northeast-striking dikes likewise may indicate a cross-trending line of weakness that localized stresses. Nonetheless, the importance of these structural conditions is not clearly demonstrated, and no good evidence is found to explain the structural cause of the more intense fracturing which localized the two ore bodies in their present positions in preference to other locations along the major structure line.

Outside of the zone of alteration the dacite porphyry is finely fractured and jointed throughout most of its large exposed area. In sharp contrast to the systems of parallel fissures in the alteration zone, these fractures in the dacite porphyry are almost completely of random orientation; parallelisms are rare and traceable for only a few inches or feet. They are pre-mineral in age where they are found in the alteration zone in the westerly and southwesterly portions of the dacite porphyry. It would seem that in physical aspect this formation was exceptionally well prepared to be mineralized --- perhaps better than the rocks of the ore zone proper. The fact that it was mineralized only locally may be accountable, in part, by the absence of <u>systematic</u> fractures. That is, only the systems of parallel fractures were connected with the deep-seated source of mineralization, and the pervasive breaking of the dacite porphyry did not alone qualify it for mineralization.

Excepting the post-mineral andesite dikes, all igneous rocks within the narrow northwest-trending zone shown on Plate 1 are hydrothermally altered. Variations in the intensity, or in the completeness of the process, have been subdivided by Kerr (6) into five stages. His analysis demonstrated, among other things, that the known ore bodies occur within the more strongly altered areas. The area outlined by the writers on Plate 1 includes all degrees of alteration, but no differentiation is made. It merely represents the areal extent of bleached-appearing, igneous rocks showing evidence in the leached outcrops of pre-existing disseminated sulphides --- principally pyrite. The transition to relatively fresh rock is quite sharp in many places, particularly along the contact with sedimentary rocks and on the faults in the southeast portion. However, along most of the southwest margin the transition is gradational, and the limit is an arbitrary line.

Tactite, composed essentially of garnet, diopside, other lime-silicate minerals, and quartz is confined to a narrow belt along the southwest margin of the limestone pendants, except in the vicinity of the Mammoth and Union mines where it has replaced the full width of the sedimentary block. There, portions of the tactite contain sufficient disseminated chalcopyrite to be classed as low grade ore. As in the Mission deposit (13), this mineralized tactite is regarded by the writers as having been formed by the same processes which altered and mineralized the intrusive rocks. Thus, it is a product of hydrothermal metasomatism, rather than contact metamorphism caused by the dacite porphyry and the monzonite as proposed by Stewart (15).

SUPERGENE ENRICHMENT

The two ore deposits consist of rudely tabular accumulations of chalcocite from one to two hundred feet in thickness. Lying beneath about one hundred feet of leached capping, they were formed by two- to threefold enrichment of the copper contained in the primary mineralization. Typical ore is composed of altered rock and sulphides in a ratio of about 10:1 by weight.

Most of the capping over the ore bodies contains less than one-tenth of one per cent copper as cuprite, or other oxidation products, mingled with the limonite. Occasionally, somewhat higher values occur where copper has been precipitated as silicates and carbonates by reactive gangue material present in less altered rock. Within the ore bodies, where alteration is strong and the gangue is non-reactive, the upper limit of the sulphide zone (or, the base of oxidation) appears on open pit bench faces as a sharply defined, highly irregular interface. Only rarely is there a transition zone of mixed sulphide and oxide copper minerals. Some of the irregularities of the base of oxidation are caused by displacement on post-chalcocite faults, but most seem to be due to variations in rock permeability. This is evidenced by the dense, siliceous character of a few sulphide remnants occurring well up in the leached zone, and by leached indentations of the sulphide zone along many of the fissures.

The present-day water table at Silver Bell is well below the chalcocite zone, a condition which exists in many of the porphyry copper districts (4). This indicates that the Silver Bell chalcocite zone now is in an environment of oxidation, and it should be undergoing leaching rather than enrichment. This current climatic cycle may have been relatively short and dry; and may have caused only minor modifications of the chalcocite blanket.

The base of oxidation conforms in general shape to modern topography, even though local relief exceeds 200 feet. This rude conformance would seem to require a relatively wet climate with the water table being no more than a few tens of feet below the ground surface as the modern physiography developed.

In the early days at Morenci, Lindgren (7) observed that oxidation and leaching had in some instances penetrated along fissures down through the chalcocite into underlying primary sulphides; also, that erosion of Chase Creek Canyon had left the principal chalcocite zones stranded high above the canyon bottom, indicating that the chalcocite formed originally about an ancient water table several hundred feet above the present water table. Although erosion at Silver Bell has not penetrated as deeply as at Morenci, its chalcocite zone currently is in a similar unbalanced environment of oxidation with no appreciable enrichment now taking place. Reshaping of the upper surface of chalcocite zones in both districts to conform to the existing ground surface appears, then, to have occurred during formation of modern topography, but at some time prior to the current, dry climatic cycle.

LEACHED OUTCROPS

In the formation of many disseminated chalcocite deposits the enrichment process is presumed to have taken place progressively --- copper having been repeatedly dissolved, carried downward, and precipitated. It has been well established by Blanchard (1), Locke (8) and others that under these conditions "limonites" of certain colors and textures are left behind in the leached capping as evidence of the pre-existing chalcocite. The Silver Bell district provides exceptionally good examples of this phenomenon, but limonites of chalcocite derivation are not confined to the outcrops over the ore bodies. They are widely dispersed through the zone of alteration. Proper interpretation of their significance in respect to ore possibilities has rested mainly on quantitative rather than qualitative appraisal. Mapping of the Silver Bell outcrops on this basis has provided a valuable guide in exploration drilling of the past 15 years. Results have demonstrated that the pattern of relatively strong chalcocite at depth is reflected in the outcrops by the distribution and abundance of diagnostic limonites.

It may be of interest at this point to mention the ancient excavations which are numerous in the outcrops of the mineralized zone at Silver Bell. There is evidence indicating they are several centuries old. Since there are no precious metals or visible copper in these cuts, it is plausible to assume that the limonite and clay minerals were considered valuable, perhaps for pottery or war paint. Thus, in the history of leached outcrop investigations, it seems that some early Arizona Indian tribe deserves at least honorable mention.

Previous Work and Acknowledgments:

The first scientific study of the district was published in 1912 by C. A. Stewart (15). Considerable field and laboratory work has been done in more recent years by several groups and individuals, including the writers, all reporting privately to the American Smelting and Refining Company. Roland Blanchard conducted leached outcrop studies in a portion of the area. Harrison Schmitt with H. M. Kingsbury and L. P. Entwistle mapped structure and mineralization in the central part of the district. Paul F. Kerr studies the alteration features, and later published a comprehensive paper (6) on the district. Thomas Mitcham mapped structural features in the surrounding area. The writers have drawn considerably on these and other unpublished data, particularly in compilation of the geologic map. The high quality and usefulness of this material is gratefully acknowledged, but unfortunately it is not feasible to give specific individual credits.

Thanks are due the American Smelting and Refining Company for permission to publish this paper.

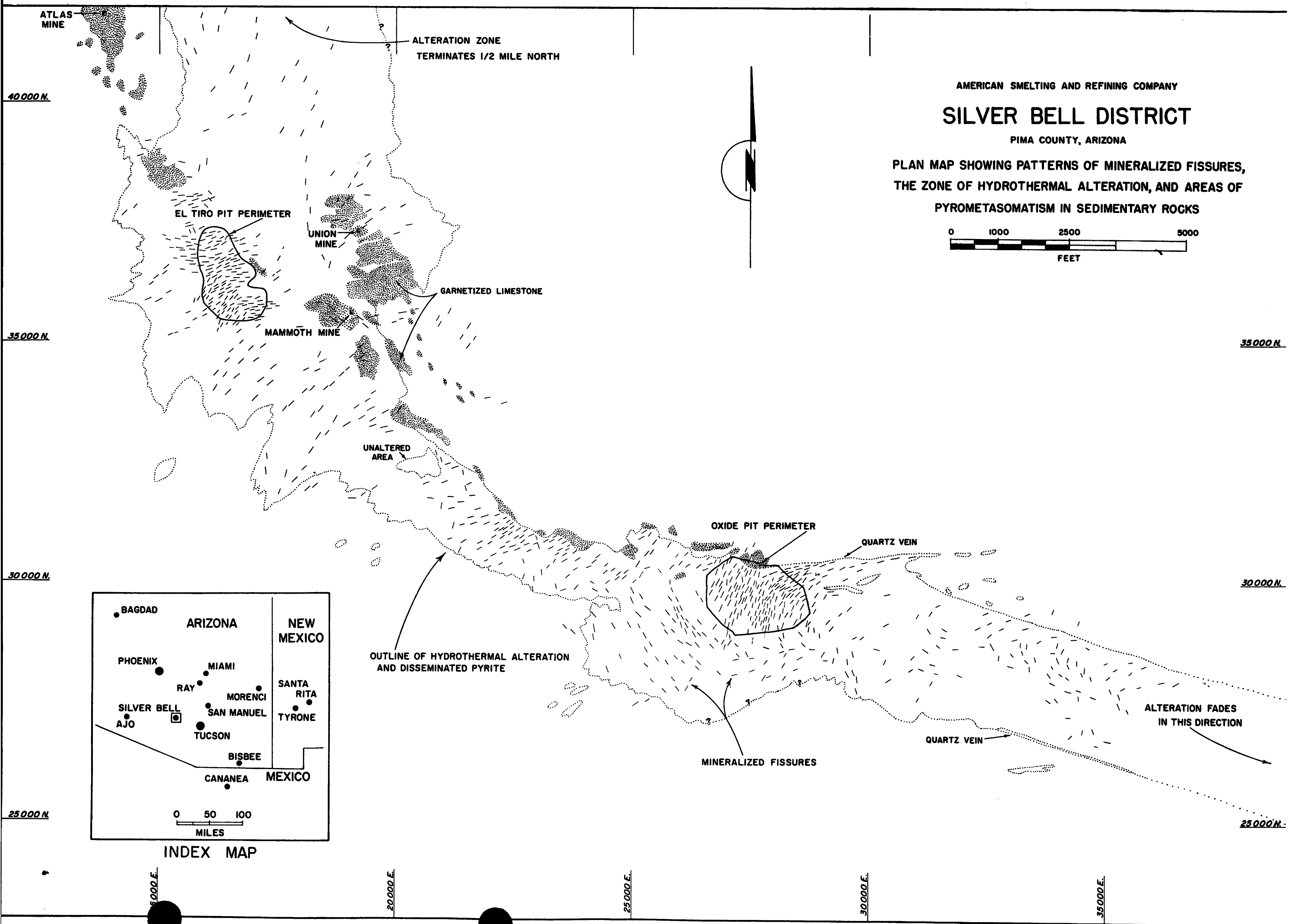
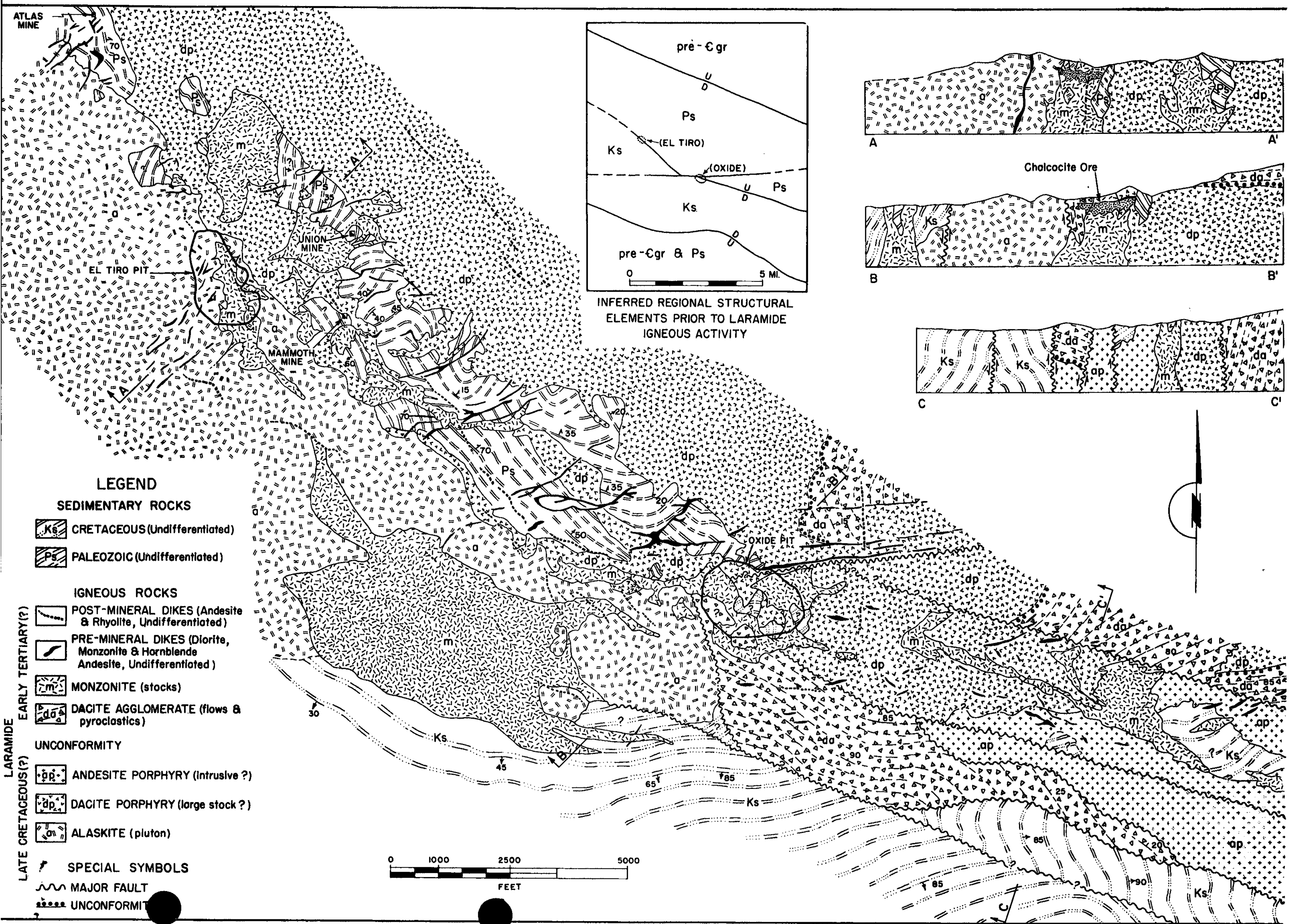

AMERICAN SMELTING AND REFINING COMPANY
SILVER BELL DISTRICT
PIMA COUNTY, ARIZONA
PLAN MAP SHOWING PATTERNS OF MINERALIZED FISSURES, THE ZONE OF HYDROTHERMAL ALTERATION, AND AREAS OF PYROMETASOMATISM IN SEDIMENTARY ROCKS
0 1000 2500 5000
FEET
ATLAS MINE
ALTERATION ZONE TERMINATES 1/2 MILE NORTH
EL TIRO PIT PERIMETER
UNION MINE
GARNETIZED LIMESTONE
MAMMOTH MINE
UNALTERED AREA
OXIDE PIT PERIMETER
QUARTZ VEIN
OUTLINE OF HYDROTHERMAL ALTERATION AND DISSEMINATED PYRITE
MINERALIZED FISSURES
QUARTZ VEIN
ALTERATION FADES IN THIS DIRECTION
40000 N.
35000 N.
30000 N.
25000 N.
15000 E.
20000 E.
25000 E.
30000 E.
35000 E.
BAGDAD
ARIZONA
NEW MEXICO
PHOENIX
MIAMI
RAY
MORENCI
SANTA RITA
SILVER BELL
SAN MANUEL
TYRONE
AJO
TUCSON
BISBEE
CANANEA
MEXICO
0 50 100
MILES
INDEX MAP

PLATE 1



GEOLOGIC MAP, SILVER BELL DISTRICT, ARIZONA

PLATE I

SILVER BELL

~~577~~ 325-6029 Briscoe

HISTORY

History of mining in the Silver Bell district possibly dates back as far as Precolumbian times when Indians in the area dug shallow trenches along fracture zones and andesite dikes searching for turquois, hematite and clay. Large saguaro cacti growing in some of these workings indicate they are at least 200 years old.

The area first came to the attention of the white man in 1865 when prospectors located a small pod of enriched silver ore in the altered sedimentary rocks near the present southeast corner of El Tiro pit. Early efforts to mine silver in this area failed, probably due to the fact that Silver Bell has only weak sporadic occurances of silver mineralization...

Well organized mining activity began in 1899 with the organization of the Silver Bell Copper Company, which evolved into the Imperial Copper company in 1903. The Southern Arizona Smelting Company or SASCO, built a smelter near the northern end of the Silver Bell mountains giving rise to the small smelter town of Sasco, the ruins of which are still visable today. The Arizona Southern Railway hauled ore between the mines at Silver Bell and the Sasco smelter, both the railway and the smelter being subsidiaries of the Imperial Copper Company.

By 1910 the Company or its predecessors had done some 20.8 miles of underground work in removing about 700,000 tons of ore averaging about 3.7% copper. Yet even by accounting all profits including those from the smelter, the railroad, and company store back to the mine, the company only showed a profit one year. Production ceased in 1910 with the company going into receivership, and later purchase by the American Smelting and

and Refining Company in 1917.

ASARCO operated the mine on a marginal basis until 1919 when all large scale mining was halted, sporradic small scale production continuing until 1930. Although the possibilities of disseminated enriched chalcocite ore was recognized in 1909, an extensive drilling program indicated that the tenor was then sub-economic.

In the early forties the area was again scrutinized by ASARCO, but WW II precluded definite action. In the late forties the company under-took a program of geologic mapping and exploratory and check drilling under the direction of Kenyon Richard and Harold Courtright. This resulted in the delineation of the Oxide and El Tiro enriched chalcocite ore bodies, production from which began in 1952.

The sedimentary rocks which had accounted for the early day production from the district were largely ignored during the first part of the open pit development. This was mainly due to the apparently small amount of mineralized sediments available for open pit operations. In addition, the early miners being interested only in the high grade pods of chalcopyrite, considered anything below 3% copper as waste rock, giving the erroneous impression on old maps that the sediments contained widely scattered pods of high grade material in barren rock.

During a search through old records late in the 1950's, Mr. Steve Von Fay found assay records indicating areas designated as waste ran up to 2% copper. Also found was an old drill log showing mineralized sediments lying below poorly mineralized dacite between the El Tiro fault and the outcropping mineralized sediments to the east. A detailed surface and subsurface mapping and sampling program was undertaken. This program was completed with favorable results and a drilling program was initiated. After three years of close spaced drilling, an ore zone of primary chalcopyrite, mineable by open pit methods was delineated.

GEOLOGY

SLIDE 1 Generalized geology of the Silver Bell alteration zone, pointing out the location of El Tiro Pit and the sediments and dacite relationship.

SLIDE 2 Generalized geology of the El Tiro pit

The El Tiro pit exposes all rocks typical of the alteration zone except for the syenodrorite porphyry the early phase of the monzonite, porphyry. The main geologic features in the pit area are the mafic-free alaskite on the southwest and the dacite intruding Paleozoic sediments to the northeast. These two features are generally separated by the northwest trending El Tiro fault, a wide breccia zone which cuts all Laramide rocks in the pit, and is probably closely related to Richard and Courtrights ancestral "Major Struture". The fault zone appears to have been an important conduit for hydrothermal fluids during the period of mineralization, massive sulfides or strong alteration effects occurring throughout its length. Post mineral movement on the fault is indicated by brecciated and slickensided sulfides.

Two other northwest trending faults indicating recurrent movement along the northwest zone of weakness are the defined by post-mineral andesite dikes. These dikes are Mid-Tertiary in age, similar ones being seen throughout length of the alteration zone.

The sediments to the east of the pit are intruded by the dacite in a silt-like manner. Drill hole data indicates the outcropping sediments are floored by the dacite, while the dacite just to the northeast of the El Tiro fault is underlain by sedimentary blocks. Several of these blocks are exposed in the southeastern corner of the pit and along the El Tiro fault zone, and more will be exposed as the pit is deepened.

Two stocks of monzonite porphyry are exposed in the pit. The stock to the southwest of the El Tiro fault is surrounded by alaskite, while the stock to the northeast of the fault intrudes the dacite containing large blocks of sediments and it is essentially bounded on the east, south and southwest sides by these sediments. The two stocks are connected by easterly trending dikes, and are undoubtedly connected in depth to a parent monzonite pluton. These two bodies, inspite of their genetic relationship, are quite differently altered and mineralized. The stock to the southwest of the El Tiro fault is strongly altered showing moderate to strong clay, sericite, secondary potassium feldspar, and silicification along with disseminated pyrite, chalcopyrite and molybdenite and enriched chalcocite blanket. Moving easterly across the El Tiro fault the alteration becomes perceptably weaker in the monzonite dikes the stock itself being only weakly argillized with sparse to trace amounts of pyrite giving rise to scant limonite staining. There is no chalcocite enrichment and the rock contains only trace amounts of primary copper. Easterly trending dikes radiating out from this stock, which cut the sediments, are occasionally so weakly altered that twinning of the plagioclase can be seen on a freshly broken surface. This lack of alteration of the monzonite I feel to be due to the fact that it is surrounded by reactive sediments. I theorize that the hydrothermal fluids that so strongly effected the monzonite stock to the southwest of the El Tiro fault were completely absorbed by and reacted with the limy sediments surrounding the stock to the northeast of the fault, leaving the monzonite almost entirely uneffected by hydrothermal alteration.

The presence of the sediments had a similar effect on the dacite, so that poorly altered and mineralized dacite may be underlain by sediments containing primary chalcopyrite ore.

SLIDE 3 Crossectinn through the El Tiro pit showing the subsurface relationships of the alaskite, dacite, sediments, and monzonite. Note dip of the sediments in the Union Ridge area under the dacite.

ALTERATION AND MINERALIZATION OF THE SEDIMENTS

Although the sediments have been intruded by three different Laramide igneous rocks, namely the alaskite, the dacite and the monzonite, the effects of these intrusions are hard to evaluate. The dacite was relatively cool and gas charged at the time of intrusion and had apparently little metamorphic effect on the sediments. The alaskite and monzonite intrusions may have marbleized the limes and hornfelzed the shaley rocks to some extent. These effects are almost entirely obliterated however, by the later intense effects which accompanied the hydrothermal mineralization.

In the igneous rocks to the southwest of the El Tiro fault innumerable parallel, easterly trending fractures localized and and formed the plumbing for the hydrothermal solutions. This northeastealy direction of tension also controlled the earlier emplacement of monzonite dike swarms in the El Tiro and Oxide pit areas. This same easterly trending tension direction appears to be the structural control for emplacement of ore fluids into the sedimentary rocks.

The ore fluids which permeated the sediments along the northeasterly trending plumbing system carried silica, iron, sulfur, possibly some potassium, alumnium, and magnesium, along with copper, zinc, molybdenum and minor lead and silver, these last two elements possibly being late stage or even Mid-Tertiary in age.

SLIDE 4 El Tiro pit geology showing the Metasediments broken into quartzite, Hf, Tf, ls

The hydrothermal fluids altered the sediments to quartzite, marble, hornfels and tactite. The terms quartzite and marble are used in the normal sense and indicate an indurated and silicified sandstone and a recrystallized probably originally rather pure limestone. The terms hornfels and tactite are more ambiguous and have been defined for use at Silver Bell as follows:

Hornfels is a fine textured rock consisting of varying proportions of lime-silicates such as diopside, epidote, chlorite, feldspar and quartz along with occasional garnet. It is derived from shales, from thinbedded argilaceous limestones and from mudstones and siltstones.

Tactite is a medium textured rock composed of a number of lime-silicate minerals with predominate garnet. It is usually considered to be derived from impure limestones

In a broad sense the hornfels and tactite units reflect different stratigraphic units, however, locally they are intermingled within individual horizons.

Generally speaking the impure limes and limy argilaceous rocks appear to be more receptative to metasomatism and are therefore good hosts for mineralization.

Garnet, diopside, tremolite, Wollastonite $CaSiO_3$, chlorite and hydrobiotite are the most important gangue minerals.

Slide 5-Photo showing coarsely crystalline greenish grossalarite garnet surrounding a patch of coarse wollastonite.

Garnet in the ore bearing areas is usually brown in color. Chemical analyses indicate it is compossed of equal parts of calcium bearing grossularite garnet and iron rich andradite garnite. This appears to represent iron metasomatism and is contrasted with the greenish garnet, probably mainly calcium rich grossularite, which isn't usually associated with ore grade mineralization.

Diopside may represent silica metasomatism of dolometic limes, or merely recrystallization, with the aid of hydrothermal solutions, where sufficient silica as sand was already present.

Wollastonite ($CaSiO_3$), represent silica metasomatism of limestone. In wollastonite hornfelses it probably represents reaction of the lime and silica already present, assisted by the presence of the hydrothermal fluids.

Slide 6-Showing intergrown hydrobiotite and chalcopyrite.

Increasingly large amounts of metamorphic rock composed mainly of hydrobiotite and chlorite are being found in the pit. This is particularly true along the El Tiro fault and other major hydrothermal channelways, where crystalls of hydrobiotite up to two inches across can occasionally be seen. In some places the massive mica-rock (~~slide~~)---is richly intergrown with chalcopyrite. The presence of biotite or chlorite appears to be a fairly good ore guide. The alteration is thought to represent iron, potassium and possibly aluminum metasomatism in a water rich environment.

Chalcopyrite is the only important sulfide copper mineral in the sediments. In the areas in the orebody shpalerite is closely associated with the chalcopyrite. In some cases the chalcopyrite being found in solid solution with the sphalerite. As no zinc is recovered, where the two minerals are found in solid solution, the sphalerite acts as a diluent because no clean separation can be made between it and the chalcopyrite in the mill.

Molybdenite occurs in the sediments as disseminations, (as "paint" along fractures) and with quartz veins, in about the same quantity as occurs in the igneous rocks.

Iron as hematite and magnetite, magnetite being most important appears to be closely associated with the copper mineralization. The occurrance of magnetite varies from disseminated grains to massive pods of the mineral cut by veins of chalcopyrite. This close association with chalcopyrite has made the magnetometer a very useful tool in the search for ore.

Slide 7-Photo of sample of massive pyrite and intergrown magnetite

Pyrite, though occuring ubiquitously through the metasediments in minor amounts, appears spatially segregated from the chalcopyrite when it occurs in massive form. Drill holes have encountered as much as 100 feet of massive intergrown pyrite and magnetite.

Small occurrances of galena, sometimes quite argentiferous, have been seen, but these are not economically significant. They are either late mineral or may be associated with the Mid-Tertiary activity.

Slide 8-Parallel quartz veins cutting sediments.

As mentioned previously, the introduction of the hydrothermal fluids was accomplished along easterly trending structures. Most of the disseminated chalcopyrite is associated with small quartz veins, with chalcopyrite disseminating out from the central conduit.

All graduations, from mineralization confined to the vein, to blebs of chalcopyrite disseminated through the rock but associated with vein conduits, to more intense mineralization where most of the gangue minerals have been replaced by sulfides, can be seen in the ore body. Even the massive replacement type mineralization appears to be associated with easterly trending structures, though this relationship is sometimes obscure.

Slides 9-11 -Showing dissemented ore. #9 weekly oxidized chalcopyrite veins cutting hornfels with disseminated material occuring between.
#10 Chalcopyrite veins cutting tactite with disseminated chalcopyrite in between the veins.
#11 Close up of the above slides. Note brown blebs of androdite garnet in dropsicle chlorite hornfels.

Slide 12 Showing coarse marble with garnet veins.

Argillaceous or dirty limestone horizons appear to be particularly favorable for the deposition of ore, where these occur along an ore fluid conduit. Pure limes and of course quartzite horizons are unfavorable for ore deposition, however, along fissures marble will be metasomatized to garnet and carry some chalcopyrite.

OXIDATION OF SEDIMENTS AND THE OXIDIZED OUTCROP AS A GUIDE TO ORE

The mineralized sediments which outcrop have been oxidized to varying degrees. That is, oxidation may extend to a depth of inches or fractions of an inch or to a hundred feet or more, dependent mainly on permeability due to faulting fracturing. In most cases, sulfides may be found close to the surface, at least locally.

Because of the high carbonate content of even the most intensely altered rocks, the copper from oxidizing sulfides is almost immediately precipitated in the form of copper carbonates, and therefore, there is no enriched chalcocite blanket. This is important in that copper values found at or near the surface are indicative of the values to be expected in the sulfide zone, providing there is no change in the chemical favorability of the rock.

Important oxide minerals are the black copper oxides, tenorite, and melaconite, the brown amorphous iron-copper complex known as copper pitch, and the copper carbonates malachite and azurite.

Slide 13-Showing the oxidation of chalcopyrite to copper pitch to malachite.

Chalcopyrite undergoing oxidation usually first alters to the brown copper pitch. This further reacts with the surrounding carbonate to form malachite. In many cases all that remains of the original chalcopyrite is copper pitch and some malachite, although the copper content of the rock does not change with the oxidation.

Slide 14-Showing the oxidized outcrop of the tactite ore, note Cuox in fissure.

The ozidized outcrops of the orebearing metasediments are usually black and lava-like in appearance, with white quartz veins which were the conduit for the mineralizing solutions standing in relief. In many cases copper minerals are not visable except in protected crevices or fissures. The dark coloration is due to manganese and hematite, probably derived mainly from the oxidation of sulfides, but possibly due in part to hydrothermal hematite, and breakdown of iron rich garnet.

Slide 15-~~Centrast~~ the outcrop with the previous outcrop. This shows greenish granulation iron poor tactite which carries no ore. Note the absence of black color and strong quartz veins.

Slide 16-Aerial view of Lluron Hill showing black outcrop of ore bearing sediments.

Slide 17-What the oxidized outcrop looks like on a freshly broken surface. Note blebs of remaining chalcopyrite, oxidizing for copper pitch and tenorite which in turn goes to melachite.

Slide 18-Geologic map of El Tiro pit showing the breakdown of the sediments into quartzite, Ks, tactite and hornfels. Note location of crossection B-B'

On breaking into the rock copper pitch, malachite and possibly even remanent chalcopyrite may be seen.

Stratigraphic sequence in the Union Ridge area.

Because of the complex structure and intense alteration of the sediments in the El Tiro area, all attempts to work out their stratigraphy by early workers proved fruitless.

The intensity of the alteration is exemplified by the fact that the early workers thought that the Bolsa quartzite, which crops out to the north of the pit, was merely an intensely silicified igenous rock.

The stratigraphy was worked out by Mr. Joy Merz in 1967, as his Masters thesis problem at the U. of A.

Using the idea that specific sedimentary rock types when altered would yield specific metamorphic equivalents and working from the numerous drill logs from holes in the area, Mr. Merz was able to piece together a logical stratigraphic sequence.

His work shows that the pure monomineralic rocks such as quartzite and pure limestone were poor hosts for metasometric and copper mineralization, the best host rocks being impure limestone and limy siltstones.

The stratigraphic sequence in the union ridge area is the Lower Paleozoic sequence of the Bolsa through the limestone. Because of their impure thinbedded argillaceous nature, the lower Abrigo, the Upper Abrigo, and the Lower Martin limestones are the best hosts for ore, while the Bolsa quartzite, the more pure Middle Abrigo, and the Escabrosa limestone are relatively unmineralized.

SUMMARY

In summary, the Lower Paleozoic sediments in the El Tiro area have been altered and mineralized by the same hydrothermal fluids that altered and mineralized the Laramide igenous rocks.

Although easterly trending structural conduits were important, the mineralizing solutions preferentially metasomatized and mineralized thin bedded units of the Lower and Upper Abrigo formation and the lower part of the Martin limestone. The mineralized sediments form an orebody amenable to open pit mining.

This alteration and mineralization appears typical of limy sediments which are adjacent to bodies of copper bearing porphyrys, similar exmaples being seen at Santa Rita, New Mexico; Ely, Nevada;Bisbee, Arizona the Pima district south of Tucson, and elsewhere.

SILVER BELL

John E. Kinnison
1968
Tucson
1263 W. La Osa Dr.

UPDATING THE GEOLOGY AND STRUCTURAL ORE CONTROLS AT SILVER BELL, ARIZONA

by Barry N. Watson
ASARCO Geologist

A talk to be presented to the Mining Geology Division of the Arizona Section of A.I.M.E. on May 20, 1968.

One of the more complete stratigraphic sections in southern Arizona can be pieced together in the Silver Bell area. Much of the geology has been worked out by ASARCO geologists, while a few important areas have been mapped by students as thesis problems. Other portion s of the Silver Bell area have yet to be mapped in any kind of detail, and some of this yet-uncharted geology could well be critical to a better understanding of the complex Mesozoic and Cenozoic stratigraphy.

It is my strong belief that a knowledge of certain of the stratigraphic units in the Silver Bell area--their lithologic characters and structural settings--would be of considerable help to field geologists dealing with similar phenomena elsewhere in southern Arizona. Parts of the Silver Bell stratigraphic section are accessible only by washes or somewhat obscure truck trails, and other portions of the section are on, or readily reachable only by passage through, private property owned by ASARCO.

In the following, I will attempt to briefly describe the geologic history of the Silver Bell area, with particular emphasis on the Mesozoic Era. My knowledge of the area has been greatly enhanced through field excursions and conversations with Harold Courtright, Kenyon Richard, Jim Briscoe, Craig Clarke, Chuck Haynes, Nick Nuttycombe, Joy Merz, Fred Graybeal and Dr. Willard Lacy. I must take, however, the responsibility for the interpretations drawn herein.

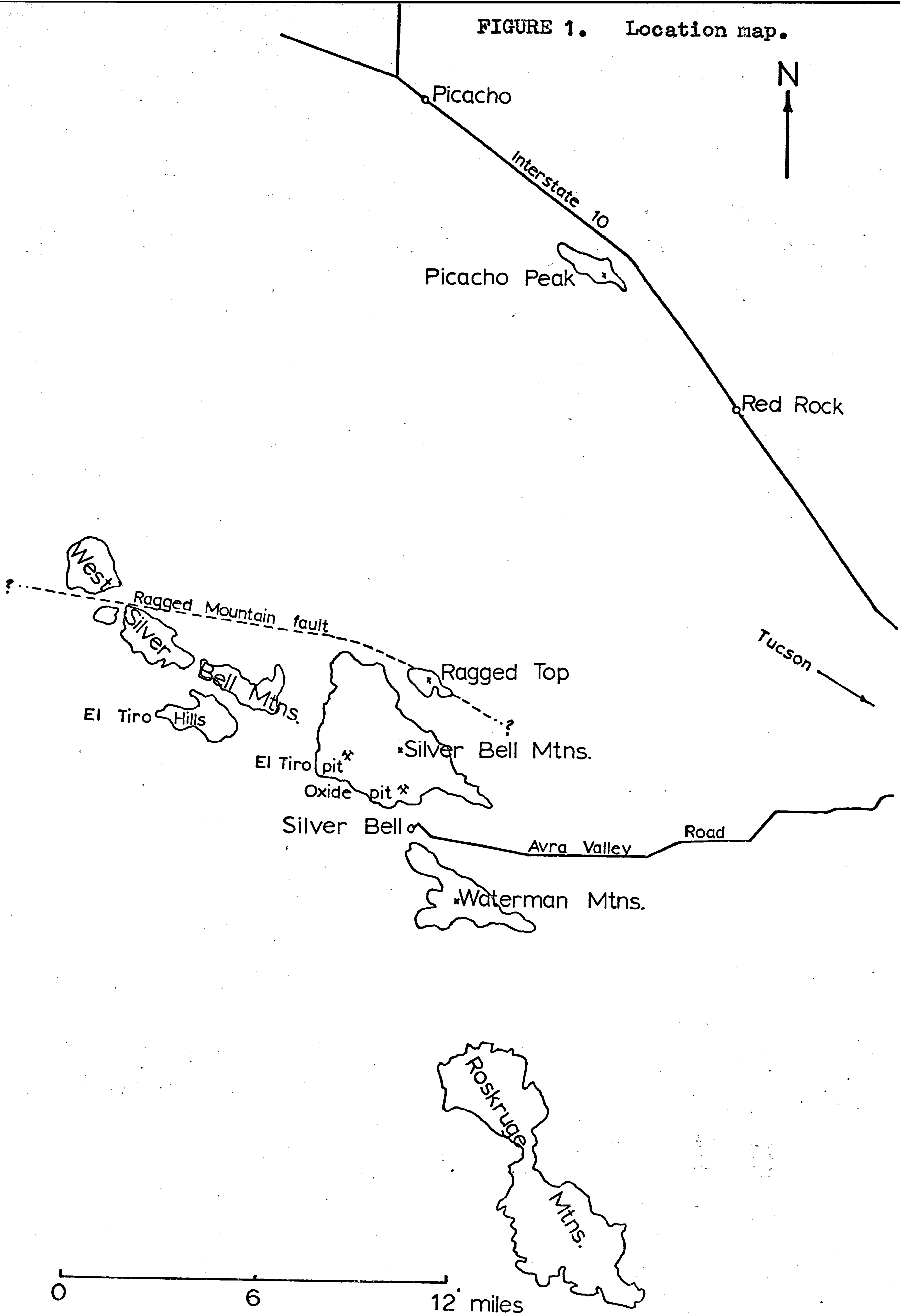
Figure 1 is a location map showing the principal topographic features mentioned below. Figure 2 is my diagrammatic representation of the Silver Bell stratigraphic column.

PRECAMBRIAN

Pinal Schist

The only outcrop of the basement Pinal Schist known to the author in the Silver Bell vicinity straddles the El Paso Natural Gas pipeline road about two miles east of Ragged Top. Relationships with other rock units are obscured by cover, except on the south where the schist is bounded by a mid-Tertiary dike filling the major WNW-trending Ragged Mountain fault.

FIGURE 1. Location map.



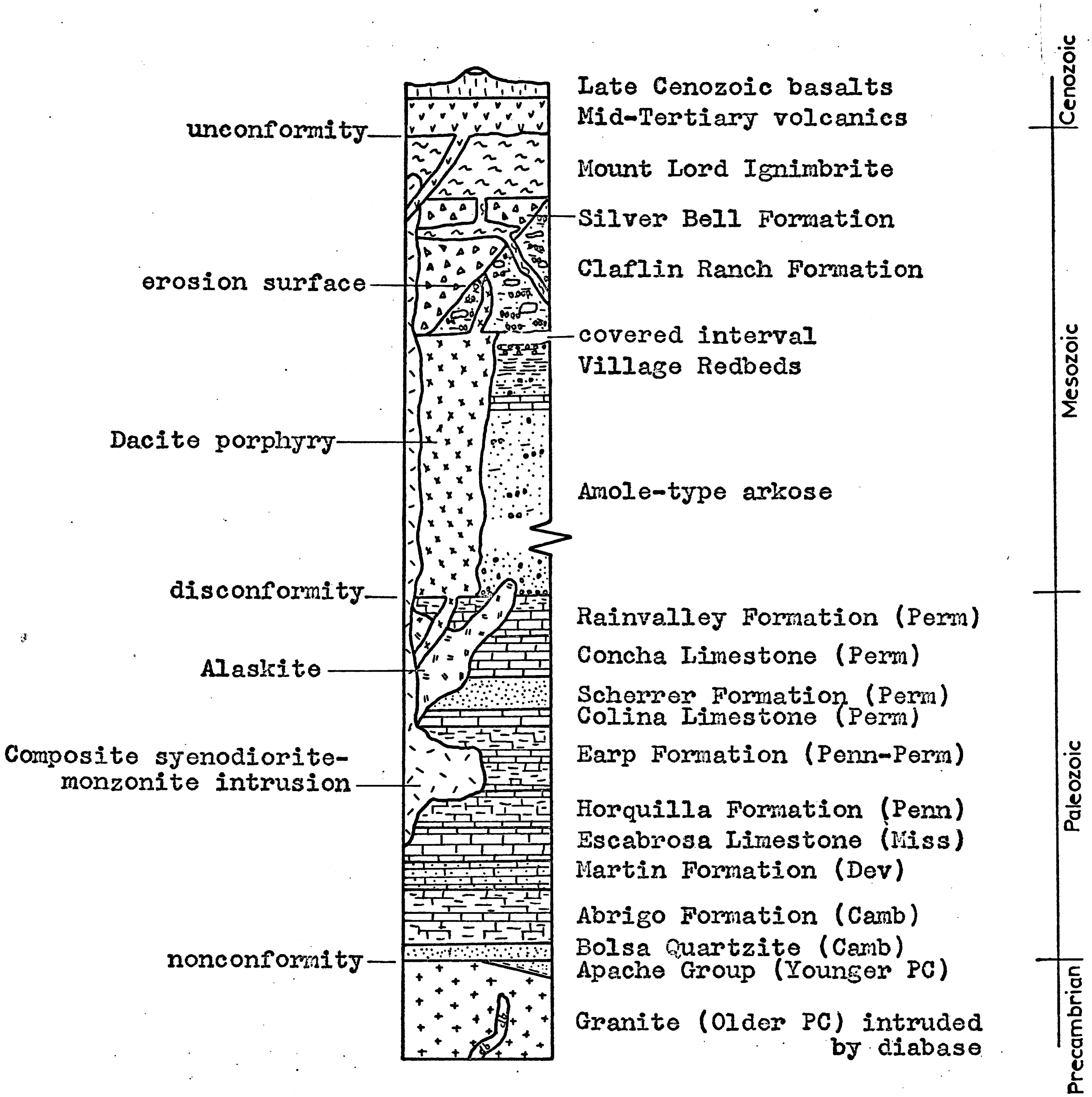


FIGURE 2. Diagrammatic geologic column of the Silver Bell area. Maximum known thicknesses for Paleozoic and Mesozoic rocks are shown. Scale of column: 1"=2000'.

Many fragments (ranging up to boulder size) of Pinal-like schist are seen in Cretaceous sediments just south of Ragged Top, indicating the presence of a considerable area of that schist at the surface in the near vicinity during the Laramide igneous activity.

Granite

A coarse-grained granite is found extensively to the north of the Ragged Mountain fault. Large and numerous quartz grains--frequently.25 inch in diameter--are set among pinkish crystals of feldspar and clumps and books of biotite. In many places orthoclase porphyroblasts up to an inch in length are common. This granite megascopically resembles the Precambrian Oracle granite seen near the town of Oracle.

Paleozoic sediments in the Waterman Mountains southeast of Silver Bell are also underlain by porphyroblastic granite.

Apache Group

Younger Precambrian Apache Group metasediments lie on granite just northeast of Ragged Top. Locally more than 200 feet thick, these south-dipping beds are sharply cut off to the south by the Ragged Top intrusive which wells up along the Ragged Mountain fault. The Apache Group stratigraphy here is not well worked out, but it appears as if a few tens of feet of probable Pioneer Formation (mixed sandy and shaly beds) are overlain by 2-3 feet of Barnes Conglomerate, which is in turn overlain by thin-to moderately thick-bedded quartzites of the Dripping Springs Quartzite.

Apache Group metasediments are missing in the Waterman Mountains where McClymonds (1957) notes Cambrian Bolsa Quartzite to conformably overlie basement granite.

Diabase

Well-altered diabase of possible Precambrian age irregularly intrudes the granite on the northern slopes of Ragged Top. As it is found only within granite, it's relative age cannot be stated with certainty. The principal period of Precambrian diabase intrusion in southern and central Arizona is post-Apache Group.

PALEOZOIC ERA

The Paleozoic stratigraphy of the Waterman Mountains has been deciphered by McClymonds (1957) and Ruff (1951) who mapped a well-faulted pile of limestones, quartzites, siltstones, and shales amounting to a thickness of 4,400+ feet. In the Silver Bell Mountains, Paleozoic stratigraphy was unravelled by Kingsbury, Entwistle and Schmitt in 1941 in a private report to the American Smelting and Refining Co. Merz (1967) undertook the difficult study of the altered and mineralized Paleozoic sediments on Union Ridge east of ASARCO's El Tiro pit. The alteration and mineralization of these Union Ridge sediments will be described in the next paper this morning.

The Paleozoic section in the Silver Bell Mountains is well faulted, locally intensely altered, and generally inundated by various Laramide intrusive units. Although each of the Paleozoic periods represented in the Waterman Mountains also show in the Silver Bell range, the section in the latter is obviously incomplete. A brief tabulation of units with thickness estimates is presented below:

Permian quartzites, limestones, shales	550 ft. approx.
Pennsylvanian Horquilla Limestone	220 ft. max.
Mississippian Escabrosa Limestone	275 ft. max.
Devonian Martin Formation	300 ft. max.
Cambrian Abrigo Formation	430 ft. max.
Cambrian Bolsa Quartzite	230 ft. min.
Total	2,005± ft.

In the El Tiro Hills section of the West Silver Bell Mountains, Clarke (1965) mapped 1,200+ feet of uppermost Permian sediments. Approximately 300 feet of quartzites and dolomitic limestones belonging to the Scherrer Formation are overlain by ±420 feet of Concha Formation Limestone and +550 feet of Rain-valley Formation limestone and argillite. These Permian rocks protrude from alluvial cover and are overlain by Mesozoic sediments.

MESOZOIC ERA

Amole-type arkose

A clearly exposed contact between Mesozoic and Paleozoic sediments is found in the El Tiro Hills where Clarke (1965) has mapped an estimated 5,000+ feet of probable Cretaceous Amole-type sediments overlying Permian Rainvalley rocks. The basal Amole-type units, lying on a disconformity, is a massive arkosic conglomerate containing rounded quartzite cobbles up to several inches in diameter. This unit of the Cretaceous (?) is several feet thick; the remainder is generally more thinly bedded.

Hayes and Drewes (1968) consider the Amole Arkose of the Tucson Mountains to be more or less a time-equivalent of the lower Middle Cretaceous Bisbee Group sediments. If the Amole-type materials in the El Tiro Hills can be considered correlative with the Amole Arkose, then Clarke's basal quartzite pebble conglomerate qualifies as a far-western equivalent of the basal Bisbee Glance Conglomerate. The presence of Cretaceous (?) beds lying disconformably on the uppermost Permian Rainvalley certainly suggests that the Silver Bell area did not experience, at least locally, the degree of structural unrest manifested farther to the east.

Another interpretation suggested by the near-conformable nature of the Paleozoic-Mesozoic contact related to recent U.S. Geological Survey recognition of Triassic sediments in southern Arizona. Possibly the hiatus between Permian and Mesozoic deposition is not as great as might be thought, and the lowermost Amole-type sediments are of Triassic age?

A few tuffaceous beds are scattered through the Amole-type arkoses, indicating periodic volcanic activity in the general region. Red-colored shales and conglomerates are found here and there through the sequence and are most prevalent in the upper portions. A 20-30-foot thick sandy limestone occurs near the top of the exposed older Cretaceous beds.

The Amole-type sediments are overlain in angular unconformity by interbedded tuffs and coarse clastic sediments of the Claflin Ranch-type. A similar mid-to late Cretaceous unconformity has been noted elsewhere across southeastern Arizona. It is felt that this unconformity reflects initial upheaval related to Laramide deformation.

Amole-type arkoses, conglomerates and sandstones also crop out in the valley between the Waterman and Silver Bell Mountains. Immediately overlying the arkoses near the southeast corner of the older Silver Bell tailings dam is a limestone unit probably exceeding 200 feet in thickness. Donald Bryant of the University of Arizona was able to identify recrystalized pelecypods here as of definite Cretaceous age. Outside of the Bisbee Group Mural Limestone, this localized unit is probably the thickest Cretaceous limestone known in southcentral Arizona.

Village Redbeds and red conglomerates

A sequence of red-colored clastics is found overlying the limestone unit and Amole-type arkoses south of the Silver Bell tailings dams. These clastics, which also underlie Silver Bell village, are locally several hundreds of feet thick, but faulting and alluvial cover prevent thickness determinations. The author originally considered this unit to be an equivalent of the Recreation Redbeds of the Tucson Mountains. However, detailed mapping plus radiometric age-dating have recently proven the Recreation Redbeds to be of pre-Amole age, and evidence is now overwhelming that red coloration represents restricted environmental conditions that could, and do, appear at various times throughout the Mesozoic. Consequently, I am here designating the Cretaceous redbeds and red conglomerates near the Silver Bell townsite the "Village Redbeds".

In places redbeds and light-colored Amole-type arkoses are found interbedded, suggesting a somewhat gradual transition from the Amole to the Village environment. Several hundred feet of red silts, sands and arkoses occur in the lower portions of the Village Redbeds and are seen to grade upward to red conglomerates. At first these conglomerates contain only sedimentary detritus. Higher in the sequence igneous materials begin to appear, however, and in the uppermost known portions the red conglomerate consists almost entirely of purple andesitic fragments set in a detrital matrix. Deformation of an ancient Silver Bell landscape and a gradual increase in volcanic activity is readily evidenced in the continuing deposition of the redbeds and red conglomerates. Thus the transition from normal Cretaceous subaerial sedimentation to coarse and rapid Laramide accumulation is not always marked by an obvious stratigraphic break.

The Village red conglomerates are cut off by a major WNW-trending fault in the tailing pond area, and their relation to overlying units is not presently known.

Claflin Ranch Formation

The Claflin Ranch Formation is something of a catch-all term, and the rocks it represents are not limited to any one specific time of deposition. The formation represents a type of sedimentation associated with a terrane undergoing volcanic upheaval and rapid erosional deformation. Thus, in the Silver Bell Mountains where Richard and Courtright first used the name (1960), the conglomerates, mudflows, landslide blocks, aeolian tuffs, water-lain tuffs and pyroclastic layers included within the Claflin Ranch Formation have ambiguous relationships with associated volcanic units. They are pre-dacite and post-dacite, pre-Silver Bell andesite and post-Silver Bell andesite. In the West Silver Bell Mountains Claflin-like conglomerates are interbedded with pyroclastics and overlie earlier Cretaceous sediments by angular unconformity.

The thickest continuous Claflin Ranch sequence in the Silver Bell Mountains--approximately 1800 feet--occurs southwest of Ragged Top. This accumulation is, at least in good part, pre-dacite porphyry (the earliest of the Laramide volcanic and sub-volcanic rocks in the Silver Bell range). Coarse, greenish clastic materials megascopically identical with parts of the Claflin Ranch Formation are found as a matrix of the Tucson Mountain Chaos in the Tucson Mountains. Claflin Ranch-type rocks also are seen in roadcuts north of Sonoita along Arizona State Highway 83.

It seems reasonable to expect that the Claflin Ranch-type of surface accumulation of detrital and volcanic debris might be found throughout southern Arizona wherever Laramide volcanic piles exist. Such depositional sequences--seemingly thickest in earlier Laramide time--would run the gamut from fairly thin-bedded sands to chaotic masses of landslide-block accumulations.

Alaskite

Richard and Courtright (1966), in accounting for the WNW-striking zone of alteration at Silver Bell, conclude that "indirect evidence suggests a fault representing a line of profound structural weakness existed in this position prior to the advent of Laramide intrusive activity." This line is referred to as the "major structure." They go on to note that this major structure "was largely obliterated by the Laramide intrusive bodies, but it effected a degree of control on their emplacement, as evidenced by their shapes and positions."

The first indication of activity along the Silver Bell fault zone came in early Laramide time with the intrusion of a coarsely granitoid alaskite along the southwest side of the major structure. This alaskite, which contains a very low ferromagnesian mineral content, intrudes Paleozoic sediments and Cretaceous Amole-type arkoses in the El Tiro area. Aplite dikes are found through the alaskite, and, locally, fine-grained border phases of alaskite are found in contact with other rock units.

The alaskite is one of the principal hosts for the later porphyry copper mineralization. This coarse-grained felsic rock locally shows high chalcopyrite-to-pyrite ratios.

Dacite porphyry

The dacite porphyry is a sub-volcanic rock characterized by numerous rounded or triangular quartz "eyes" set in a very fine-grained matrix. Orthoclase and sanidine phenocrysts, vague but consistent flow structure, and up to 20% of xenoliths are also commonly seen. Chemically, the dacite porphyry is more accurately a quartz latite porphyry.

The dacite occurs extensively northeast of the major structure in the form of sills and dikes within Paleozoic and Mesozoic sediments. The largest body of the porphyry--a sill ± 3,400 feet thick--occupies the stratigraphic interval in the Silver Bell range proper where Amole-type arkose should occur. This sill is floored by Paleozoic sediments and roofed by an 1800-foot sequence of Claflin Ranch materials. The dacite-Claflin Ranch contact is gradational over several feet, but dikes of dacite porphyry are found locally in the overlying Claflin Ranch beds.

An explosive history for the dacite porphyry is strongly suggested by the numerous xenoliths, the large fragments of quartz, and the shards of former glass in the matrix. The nature of the rock is believed to reflect an emplacement by fluidization in the following manner:

The gas-and fragment-charged dacite porphyry magma (actually quartz latite in composition, suggesting greater viscosity and more explosive potential) rose along the Silver Bell fault zone into Paleozoic strata. The higher the porphyry magma ascended, the more the confining pressure decreased, causing exsolution of gases and thus lending an explosive and dilative nature to the intrusive material.

Its extension to the southwest blocked by the large body of alaskite, the dacite porphyry welled up, sending small dikes and sills northeastward into the Paleozoic beds. Damp Amole-type Cretaceous (?) sediments were reached and more gas evolved. The magmatic material, expanding constantly, spread laterally to the northeast in the weak Cretaceous (?) sediments. Dilation occurred, as did the incorporation of fragments broken by churning gas action.

The dacite porphyry probably surfaced in one or more places, venting gases as it did. Gas also escaped laterally through the just-formed sill and vertically into overlying Claflin Ranch sediments. The heat and vapor action altered the immediately overlying quartzo-felspathic clastic sediments, giving rise to the gradational contact seen today.

The dacite porphyry was a poor host rock for porphyry copper mineralization because of its flinty, "tight" nature.

Silver Bell Formation

The Silver Bell Formation (Richard and Courtright, 1960) consists of laharic, autobrecciated, and intrusive andesitic to dacitic breccias, andesitic to dacitic flows, and andesitic intrusions. These materials overlie Claflin Ranch sediments and dacite porphyry in the Silver Bell Mountains. The rugged nature of the basal Silver Bell contact and the fact that it locally lies on unroofed dacite porphyry points to a period of rapid uplift and erosion following intrusion of the dacite porphyry sills.

Purplish Silver Bell-type breccias are seen to be interlayered in places with overlying Mount Lord Ignimbrite. Such a transition from andesitic activity to more felsic and explosive volcanism is seen throughout the world and is commonplace in the Laramide rocks of southern Arizona and southwestern New Mexico.

It is believed that the Silver Bell Formation is roughly correlative with the Demetrie Formation of the Sierrita Mountains, the Picacho Peak volcanics (Briscoe, 1967), the Owl Head volcanics, and that portion of the Cloudburst Formation north and east of the San Manuel mine.

Mount Lord Ignimbrite

A welded ignimbrite lithologically similar to, and stratigraphically a time-equivalent of, the Cat Mountain Rhyolite of the Tucson Mountains overlies the Silver Bell Formation in the Silver Bell Mountains. This quartz latitic ignimbrite is up to 800 feet thick, including an 80-foot thick cap of lithic vitric tuff. As Silver Bell Peak was formerly known to residents of the area as "Mount Lord" and since the peak is composed of the pyroclastic unit, the name "Mount Lord Ignimbrite" has been given to this Cat Mountain-type unit.

Intrusive ignimbrites--genetically related to the Mount Lord Ignimbrite, and megascopically and petrographically identical with it--occur as dikes and sills in the underlying Silver Bell Formation and dacite porphyry. These feeder materials once en route to the surface spread along bedding and formational contacts, apparently when vents became choked.

The Cat Mountain Rhyolite of the Tucson Mountains evinces an average age of 68 million years (Damon, 1968), and it is felt that the Mount Lord Ignimbrite is of similar age.

Syenodiorite porphyry

The syenodiorite porphyry is an early and somewhat extensive pyroxene-bearing phase of the composite intrusive thought to be related to the copper mineralization at Silver Bell. Later phases of this composite intrusive are monzonitic and quartz monzonitic. The syenodiorite porphyry is found principally in the southeastern portion of the Silver Bell Mountains. It occurs as massive bodies in Oxide pit (where it was previously called both "andesite" and "dacite") and east of Oxide pit along the major structure, and is found as east-trending dikes north of Oxide pit in the mountain range.

The syenodiorite porphyry is the best host rock in Oxide pit. It shows the highest primary copper sulfide content of any of the igenous rocks at Silver Bell and has allowed precipitation of a substantial chalcocite blanket.

Only occasional dikes of syenodiorite porphyry are seen in El Tiro pit.

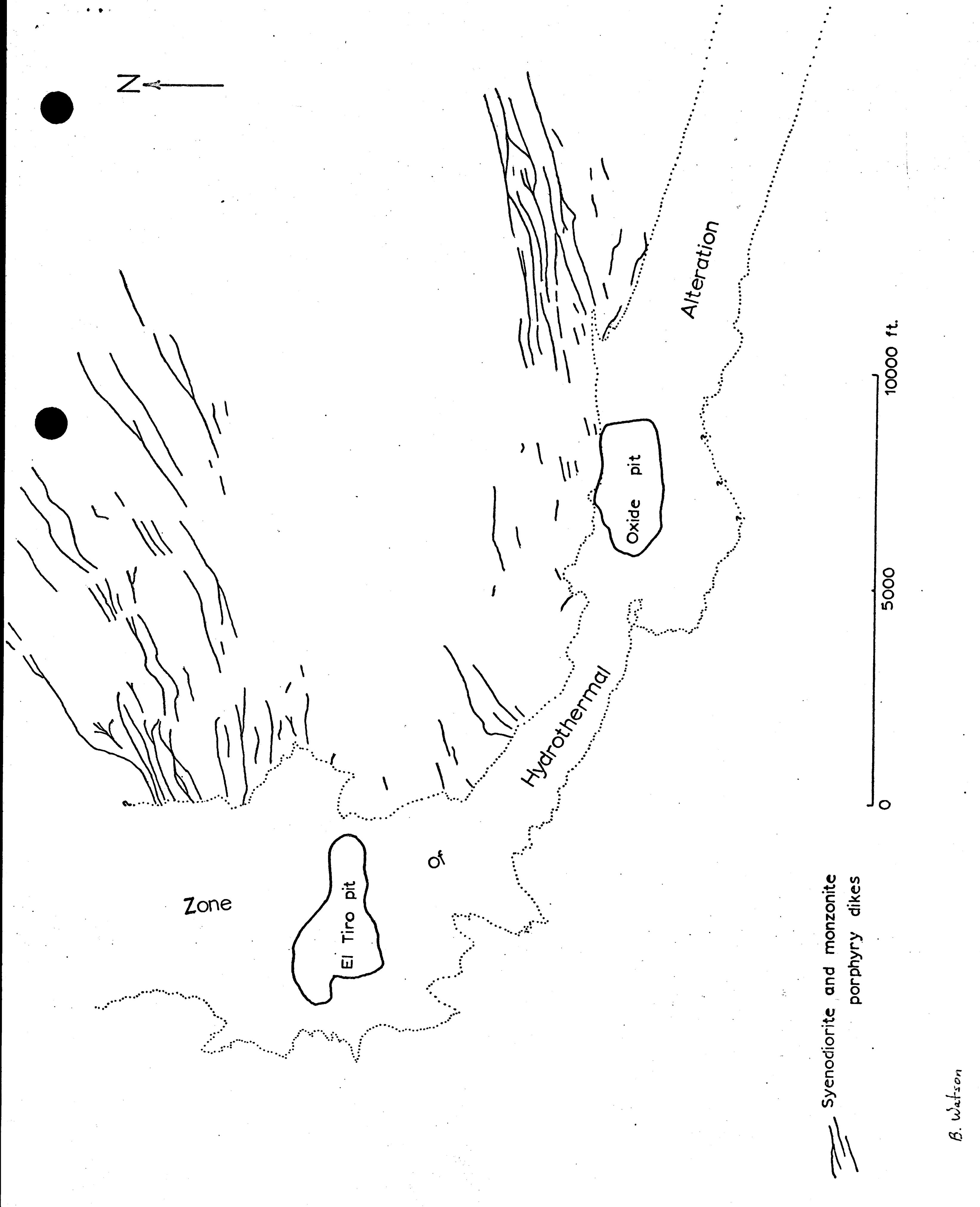
Monzonite porphyry

The later monzonitic and quartz monzonitic phases of the composite intrusion are found as massive bodies scattered along the major structure. They occur also as generally east-trending dikes in the mountain range to the northeast of the major structure.

The principal porphyry copper mineralization followed emplacement of the monzonite porphyry, and a zone of alteration was superimposed on the major structure. K-Ar age-dating (Mauger, Damon and Giletti, 1965) has shown that the solidification of the monzonite porphyry and the subsequent hydrothermal alteration occurred at approximately 65 million years and within a short enough time span so that, considering the limits of error of the age-dates, the two events are radiometrically indistinguishable. I do not mean to imply here that the Silver Bell deposits are to any great extent syngenetic as has been suggested recently (Mauger, 1966). It may be that a small amount of chalcopyrite became trapped as discrete grains in the monzonite magma at the time of solidification. The great preponderance of copper mineralization, however, was emplaced in the various host rocks through veins, veinlets, and hairline fractures with values diffusing into wallrocks, possibly with the aid of a certain amount of igneous rock recrystallization.

It is interesting to note that both the Oxide and El Tiro orebodies occur at structural intersections (see Figure 3). Oxide pit is located at the junction of the WNW-trending major structure with an ENE-trending swarm of syenodiorite and monzonite porphyry dikes. Similarly, El Tiro pit exists at the junction of the major structure with a northeast-trending swarm of monzonite porphyry dikes.

FIGURE 3. Dike swarms related to mineralization at Silver Bell



CENOZOIC ERA

It is preferred here to set the Mesozoic-Cenozoic time boundary at 63 million years as defined by Folinsbee, Baadsgaard, and Lipson (1961). This allows the Silver Bell mineralization to fall at the end of the Cretaceous Period.

Regional northeasterly tilting of 20°-30° occurred sometime between the emplacement of the composite Laramide intrusion and the mid-Tertiary volcanism. It probably was a result of late Laramide upheaval. This tilting, shown by the present orientation of Laramide depositional units, appears to have taken place by rotation of WNW-elongate, fault-bounded blocks in the Silver Bell area.

The mineralized rocks at Silver Bell were exposed to weathering and probably supergene enrichment in early Tertiary time. This is strongly suggested 3 miles east of Oxide pit where pieces of leached capping were found in a conglomerate immediately underlying an andesite flow dated at 28 million years (Damon and Mauger, 1966). A mid-Tertiary period of rhyolitic to andesitic volcanism evinced widely over southern Arizona probably covered and thus preserved the Silver Bell mineralization. This mineralization has been exhumed in more recent times and is presently undergoing destruction through weathering processes.

North-northwest-trending quartz latite porphyry and andesite porphyry dikes of the mid-Tertiary volcanic epoch cut all earlier rock units in the Silver Bell Mountains. The quartz latite dikes have a strangely discontinuous line of outcrop which is caused not by faulting, as has been previously suggested by Schmitt (1941), but by intrusion into a very broken and faulted terrane. A few of the andesite porphyry dikes are conspicuous in El Tiro pit where they are locally collectors of green copper oxide.

The Ragged Top Latite Porphyry dated at 25±1.0 million years (Mauger, Damon and Giletti, 1965) intruded the prominent Ragged Mountain fault which had dropped Laramide rocks on the south some 5,000-7,000 feet against Precambrian granite. Andesitic and rhyolitic flows of probably similar age are seen several miles west of Ragged Top in the northeastern part of the West Silver Bell Mountains.

A late and minor lead-silver-copper mineralization is found in the Silver Bell range. North-trending epithermal veins carrying galena, native silver and cerargyrite with a barite-quartz-calcite-fluorite gangue were mined in the early days. Copper stain is seen on the old dumps. This later period of mineralization has been superimposed very locally on the porphyry copper deposits to the south. On the other hand, a mid-Tertiary quartz latite porphyry dike cuts one of the epithermal veins, thus establishing a general minimum date to this mineralization.

Quaternary-Tertiary basalt cones and flows are found north of the Ragged Mountain fault.

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Yerington

GEOLOGY

of the Yerington Mine

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Ray

HISTORY AND GEOLOGY OF THE RAY COPPER DEPOSIT

RAY, ARIZONA

Talk to be given at the Arizona AIME Open-Pit Mining Subsection May 16, 1966.

HISTORY AND GEOLOGY OF THE RAY COPPER DEPOSIT

Ray, Arizona

INTRODUCTION

The Ray copper deposit is located in east central Arizona 75 miles east-southeast of Phoenix, and 70 miles north of Tucson in the Mineral Creek Mining District of Pinal County. It lies in the valley of Mineral Creek five miles north of the Gila River between the Tortilla Mountains on the west and Dripping Spring Range on the east.

Although the copper showings attracted the attention of the Indians who mined chrysocolla with large diabase hammers such as these (show artifact), the first written record of them was made in 1846 by members of Kearny's Army of the West, who named Mineral Creek for the numerous mineral deposits found along its banks.

Development of the district, though, was hampered by its inaccessibility and the danger presented by raiding Apaches. These were gradually overcome and mining activity began in 1870 with the location of a mining claim by a prospector who, as legend has it, named it after his sister. The name, Ray, was immortalized by the ensuing mining companies and townspeople, who applied it to the corporate names as well as the community.

In 1880 the first attempt at production, albeit a short one, was made by the Mineral Creek Mining Company, which erected a five-stamp mill on the Mineral Creek claim located near the eastern limit of what is now the Pearl Handle Pit.

The silver-bearing copper prospects had also attracted the attention of a pair of Tucson merchants, Louis Zeckendorf and Albert Steinfeld, in the by the Ray Central Copper Company), and the Gila Copper Company. The communities of Ray, Sonora, Barcelona and the temporary Indian camp, Vitoria, began to take shape. (The Town of Kearny was founded in 1958 mainly to replace Ray and Sonora which will be displaced by the mining operations.) [Slide 1, claim map of district 1/1/12 (Ransome, 1919, p. 101]

The Gila Copper Co. had been organized in 1907 to buy a number of claims which the English company had declined to sell until certain requirements were met. In 1910 nearly all the stock of the Gila Copper Company was exchanged for Ray Consolidated stock. The Arizona Hercules property, too small and difficult to be mined for itself, was acquired in 1927. By then all of these, including Ray Consolidated, had been acquired by the Nevada Consolidated Copper Company. The last corporate change of note in Ray's history took place when Nevada Consolidated was merged into Kennecott Copper Corporation in 1933.

A list of the men associated with the Ray mine during this period reads like a "Who's Who" of large scale mining - Seely Mudd, Henry Krumb, Daniel Jackling, and Louis Cates - only a few testifying to the cliche that mines are, in fact, made and not found.

With the completion of a 5,000 ton mill at Hayden, 25 miles away, the first ore was shipped in 1911. Mining was done by a combination of shrinkage and block caving methods and large scale operations increased Ray's production to 50,000 tons of copper per year by 1942.

However, caving properties and grade of the ore in many areas of the mine were somewhat less than ideal. In 1948, after considerable additional exploration drilling and study, it was decided that the Ray orebody could better be mined by open pit methods. The transition from underground to surface mining was completed in 1955. This step was followed by an expansion program resulting in the construction of a smelter and other facilities at Hayden and an increase in the mine's production from 15,000 tons of ore daily to its present rate of over 24,000.

Ore is presently mined from two open pits, the Pearl Handle and West Pits, separated by Emperor Hill. Exploration drilling in recent years, however, has disclosed an extension of the orebody east of Mineral Creek and mining operations are advancing in that direction.

Since 1911 Ray (Ray Consolidated including Ray Hercules) has produced more than one and a half million tons of copper, 40,000 ounces of gold and four million ounces of silver. Some copper has also been produced by leaching of caved workings and waste dumps, bringing the gross value of all production to well over a half billion dollars.

The growth of the property from one which spasmodically produced 250 tons a day at the turn of the century to one currently producing one hundred times that amount has necessitated a more complete understanding of the controlling geologic features, thus facilitating development and exploitation. Toward this end a program of detailed geologic mapping and study was begun at Ray as at other Kennecott properties. During the course of this investigation a number of old problems have been solved and several new ones arisen which, like the nebulous "hydrothermal solution", will require a bit of time for a complete understanding. Among other things, the results of this study have emphasized the importance of structure and lithology in controlling copper mineralization. The writer is indebted to Kennecott Copper Corporation for permission to make some of these findings public at this time.

REGIONAL GEOLOGIC SETTING

The Ray deposit is situated near the wetsern edge of the Mexican Highland Section of the Basin and Range physiographic province in a series of north-northwest trending mountain ranges which was referred to by Ransome as the Mountain Region of Arizona. The eastern boundary of the Sonoran Desert lies about twenty miles to the west, and the southern edge of the Colorado Plateau Province some eighty air line miles to the north.

More specifically, the district occupies the valley and adjacent slopes between the Tortilla and Dripping Spring Mountains. (Slide 2) Relief is fairly high with elevations ranging from less than 2000 feet in the valley of Mineral Creek to over 5000 feet at the top of Scott Mountain northeast of Ray. Generally, it may be said that these mountains are of typical basin and range structure with major fault systems paralleling the length of the range and the valley between having been filled in varying degree by detritus from the adjacent uplifted blocks.

Southeast of Ray the two ranges are separated by the valleys of Mineral Creek and the Gila River (Slide 3); to the north they coalesce into a ruggedly dissected plateau (Slide 4).

The Tortilla Mountains are composed essentially of Precambrian schist and granite (Slide 5). The Dripping Spring Range, (Slide 6) however, comsists primarily of younger Precambrian and Paleozoic sediments which dip moderately to the south. Both ranges also contain Precambrian and Laramide (?) intrusives and are covered in part by Tertiary volcanics and sediments.

DISTRICT GEOLOGY

As is apparent from the District Geologic Map, (Slide 7) Ray is endowed with an abundance of rock types ranging in age from Lower Precambrian to Quaternary and running the gamut of composition. The relative orderliness of surrounding areas disappears here because of faulting, unconformities, intrusions, or combinations of all three.

ROCK TYPES

The next slide (Slide 8) shows the normal stratigraphic (if not the field) relationships of formations in the Ray district. The Lower Precambrian basement rocks are overlain by more than 2500 feet of Upper Precambrian sediments, mainly quartzites and shales but including, however, the Mescal dolomitic limestone and vesicular basalt flow. An incomplete section of about 500 feet of Paleozoic limestones is present above the former, and well over 1100 feet of Tertiary and Quaternary terrestrial conglomerates and volcanics are also found in the district. Economic interests for the purpose of this slide can be restricted, however, to the formations below the Mescal limestone, which host the copper ores, and the post-ore Tertiary and Quaternary rocks which conceal a portion of the mineralization.

Illustrated here (slide 9) in somewhat simplified manner, are the intrusive relationships of the plutonic rocks at Ray. The Madera diorite and Ruin granite are both Lower Precambrian rocks which intrude the Pinal schist. The diabase, whose age is somewhat controversial, intrudes only the Precambrian rocks older than the Troy quartzite. It occurs primarily as thick sills in the sediments and low angle dikes in schist, often intruding along fault surfaces. Diabase with this intrusive relationship outside the district has been dated isotopically at 1000-1200 million years. Other workers report evidence of a Tertiary age for diabase. However, definite evidence of a Tertiary age has not been observed anywhere in the Ray area, and, therefore, a Precambrian age for the diabase seems acceptable here.

The next youngest igneous activity is represented by a series of Laramide or early Tertiary intrusives: quartz diorite, diorite, porphyry, the Granite Mountain quartz monzonite porphyry, andesite, Teapot Mountain quartz monzonite porphyry, and quartz diorite porphyry in that order. Of these the Granite Mountain porphyry is the most important, being the youngest pre-ore rock.

STRUCTURE

Structure within the Ray District is virtually as varied as its rock types. Faulting, however, has been the major type of structural deformation, with folding playing only a very minor part. As is fashionable for porphry coppers, Ray has also been endowed with a breccia pipe and several pebble dikes which occur in the northeastern part of the district. (Slide 10)

Several types of faults occur: normal, reverse, thrust, and others which cannot be typed because they cut only one rock type, namely the Pinal schist, whose outcrops cover so much of the district. Their attitudes, likewise, are quite variable, although they may be divided into several sets which roughly parallel the regional schistosity, such as the Rustler Fault and Porphyry Break, and those which roughly parallel the mountain ranges. Their dips vary from vertical to horizontal. They range in age from pre-diabase (probably Precambrian), such as the Diabase and Rustler Faults, to post-Gila conglomerate, such as the School Fault. Most of these have undergone more than one age of movement, sometimes in different directions. The Diabase Fault is an interesting example of the latter case. (Slide 11)

Pre-diabase movement is evidenced by the fact that diabase intrudes this fault zone a couple of hundred feet south of the outcrop shown in this slide. The obvious displacement as shown by the outcrop is in the reverse direction with Lower Precambrian Pinal schist in the hanging wall and Upper Precambrian Dripping Spring quartzite in the footwall. Drill hole and other information, however, indicated subsequent movement in both directions (normal and reverse) along the same fault which offsets flat-lying diabase intrusives that continue across the district to the east as well as the overlying Whitetail conglomerate. The net throw as shown by Stratigraphic evidence is still in the neighborhood of two thousand feet.

The outstanding example of thrusting in the district is the Emperor Fault whose trace circumnavigates the Pearl Handle Pit (Slide 12). Here Upper Precambrian Pioneer shale and Dripping Spring quartzite are exposed in its footwall. A vertical thickness of more than 400 feet of lower Precambrian Pinal Schist overlies these in the hanging wall of the fault. At present, the full significance, direction, age and extent of the thrusting are not known or understood, though it seems safe to assume that at least several thousand feet displacement have occurred along the Emperor Fault.

Because of its similar attitude and appearance, the recently discovered Empress Fault is also considered to be a thrust; the Bishop and Broken Hill Faults show normal movements and the West End and North End Faults are probably also normal faults.

One of the main controlling structures in the district, the Porphyry Break, is a very subtle, highly fractured zone of weakness up to 2000 feet wide which has been intruded by the Granite Mountain porphyry.

The School Fault, a reverse fault whose net displacement is similar to that of the Diabase Fault, probably had little to do with controlling primary mineralization; it did, however, serve to localize small amounts of exotic copper oxides.

The Calumet Breccia Pipe (Slide 13), the only feature of its kind known in the district, consists of fragments of Pinal schist, Scanlan conglomerate, Pioneer shale and diabase. Its maximum surface dimensions are 200 feet by 600 feet and it has a minimum depth of over 800 feet. Spatial distribution of the fragments, which range in size up to twelve feet in diameter, indicates a collapse origin. The breccia is weakly mineralized with copper oxides occurring near the surface and iron, copper, and molybdenum sulfides at depth in the interstices of the breccia.

As mentioned before, one of the occurrences of pebble dikes in the district is observed cutting the Calumet breccia. An interesting feature of these is that they contain fragments of Granite Mountain porphyry. No porphyry is known to occur within a quarter of a mile of the pebble dikes. Therefore, it may be inferred that prophyry exists at considerable depth below the breccia pipe. A similar relationship has been observed in an adit in upper Rustler Gulch where other pebble dikes are cut by Teapot Mountain porphyry.

OREBODY GEOLOGY

Size and Shape

The copper mineralization at Ray occurs within an area bounded by the West End Fault to the west, the Broken Hill Fault on the east, the North End Fault on the north and less sharply by the contact between Precambrian granite and Pinal schist to the south.

The ore presently being mined in the Pearl Handle and West Pits has been a product of supergene enrichment. It occurs as an irregular blanket up to several hundred feet thick. Copper oxides are present in the eastern portion of the Pearl Handle Pit and generally become more abundant to the east.

Hypogene Sulfide Minerals

Hypogene sulfide minerals in the deposit are limited to pyrite, chalcopyrite, minor bornite and molybdenite, and traces of galena and sphalerite. Pyrite is ubiquitous as veins and disseminated grains and is relatively abundant in most of the ore. As discussed further below, the chalcopyrite content in primary mineralization tends to be considerably higher in diabase than in schist and porphyry. Molybdenite, which occurs in small amounts, is not being recovered from the ore at present. Equipment for molybdenite recovery is now being installed and will be in operation later this year. Galena and sphalerite are present in minor amounts in the outlying parts of the district and traces occur in the pit and in drill holes in the orebody area.

Secondary Mineralization

Chalcocite has been the main copper mineral in ore from the Ray deposit. It is most abundant in schist of the enriched zone but is also present in some porphyry and diabase. Minor amounts of covellite are also present.

Native copper, cuprite and chalcotrichite, brochantite, chalcanthite, malachite, and azurite are present locally in the oxidized zone of the deposit, and native silver has been found on the west side of the Pearl Handle Pit with secondary sulfides and various copper oxides. Much of the chalcocite ore has been slightly oxidized on grain surfaces and leach-precipitate-float process is used to treat that ore.

Chrysocolla and other copper silicates are relatively abundant in parts of the diabase, quartzite and schist to the east of the Ray Fault and in the upper levels of the Pearl Handle Pit. These bodies of oxidized mineralization appear to have resulted from oxidation of either primary or enriched sulfide ore with some leaching and lateral migration of copper.

Host Rocks

All intrusive rocks older than the quartz diorite porphyry as well as the Pinal schist and the Apache group may carry ore, and portions of the Whitetail conglomerate contain exotic copper minerals. No copper mineralization is known in the Paleozoic rocks but they do not occur in the area of the orebody.

Pinal schist: Nearly all the past production has been from supergene enriched ore in the Pinal schist. Grade is quite erratic but may go as high as

10% copper in areas such as the Bishop Fault zone in the southwest part of the Pearl Handle Pit where there is almost complete replacement of pyrite veins by chalcocite. In the West Pit, the replacement is generally less complete and the over-all grade is lower.

Protore grade in schist of the mine area averages between .1% and .2% copper. Thus, with at least 500 feet of leached capping known to exist, and more presumably once present, it is apparent that most of the present supergene orebody could have evolved from protore of the same tenor. Higher grade veins and fractures control of the enriching solutions were probably responsible for the resulting high-grade lenses which occur in the enriched zone.

Granite Mountain porphyry: A rather unusual feature of the Ray orebody is the fact that only a very small percentage of the ore occurs in the quartz monzonite porphyry itself. This ore may contain chalcocite, chalcopyrite and molybdenite as ore minerals and is usually found near the margins of the intrusive bodies in the Pearl Handle Pit, under Ray Hill, and east of Mineral Creek. Internal portions of these intrusives are usually very low-grade or barren.

Diabase: Almost the opposite can be said of the diabase. Whereas ore intercepts in diabase were at one time dismissed as unreliable or deleted from ore reserve calculations, the diabase is now recognized as having been the most important primary host in the district. In the Pearl Handle Pit and areas east of Mineral Creek primary chalcopyrite ore occurs in diabase near Granite Mountain porphyry intrusives or important pre-mineral faults, although none may be found in adjacent schist or quartzite. It is not uncommon for a drill hole to pass through two or more bodies of ore-grade diabase with the intervening material virtually barren of copper mineralization.

Supergene enrichment in the diabase is negligible, although in the shallower portions of the orebody copper silicates and oxides are found (Slide 14). Some are of this type also occurs in the Apache group quartzites and porphyry. A pilot plant is presently under construction to investigate methods of treating the silicate ore.

Tenor of ore within a diabase sill or series of sills exhibits a vertical gradation. The grade in any given sill is generally highest at the top and decreases gradually with depth. Where a series of diabase bodies occur in a vertical column, the uppermost will contain the highest grade mineralization, the next somewhat lower grade, and so on dropping off to only trace amounts of copper in the lowest.

ALTERATION

The predominant alteration types associated with the ore are quartz veining, silicification, biotitization, sericitization, and argillization. These are dependent upon the character of the host rock. For example, biotitization is expecially intense in the diabase and parts of the schist as well as the porphyry. Sericitization and argillization, believed to be largely supergene in origin are heaviest in areas of secondary sulfide enrichment in schist and porphyry and, where the original pyrite content was high, in diabase.

Silicification is heaviest in the rocks which had a fairly high silica content originally and is most obvious in the Apache group shales and quartzites, Granite Mountain porphyry, and schist in ore areas. There is no silicification in diabase which is commonly, however, reticulated with quartz veinlets.

The areas of sulfide enrichment were overlain by capping heavily stained with limonite and, occasionally, copper oxides. Remnants of this capping can be seen on Emperor Hill and the north wall of the Pearl Handle Pit. Other supergene alteration products are calcite (in diabase), alunite, and gypsum, as well as the oxide copper minerals mentioned previously.

MINERALIZATION RELATED TO STRUCTURE AND LITHOLOGY

The structural framework mentioned above played an essential part in the deposition of hypogene minerals and, to some degree, has influenced supergene enrichment.

Although there are several fault systems in the district which predate the intrusion of the Granite Mountain porphyry, the Porphyry Break, apparently a very deep seated structure, is most closely associated with it. The Porphyry Break's surface expression is very subtle and it shows only as an intensely shattered zone intricately intruded by very irregular masses, as well as small dikes and sills of porphyry, all having very erratic contacts with the country rock. The general northeast strike of the porphyry intrusive bodies was altered somewhat in the Mineral Creek-Ray-Diabase Fault zone, where it spread out in the direction of these structures.

The hypogene mineralization which followed the crystallization of the Granite Mountain porphyry used its contact zones as conduits, mineralizing fluids traveling along the porphyry contacts and the intersecting major structures. The fluids also migrated along the upper contacts of the diabase sills. To a lesser degree, they traveled through the Calumet Breccia Pipe depositing minor amounts of copper and molybdenum sulfides in the interstices of the breccia. Father away from the center of mineralization they formed sulfide veins.

Some of these faults had definitely limiting effects upon the mineralization. Copper values terminate abruptly near the West End (Slide 15) and North

End Faults at the western end of the orebody and in a similar manner at the eastern end of the district. In the latter case, as will be shown on a cross-section, diamond drilling has indicated a north-south striking intrusion of Precambrian granite in the Pinal schist. There seems to be a relation between the copper values in the overlying rocks and this contact, which is roughly perpendicular to the regional schistosity. It may be that the granite to the east acted as a barrier to the mineralizing fluids or it may have simply limited the extent of the fracturing in that direction.

Although it is generally conceded that a genetic relationship exists between the Granite Mountain porphyry and the mineralization, very little ore is found in the porphyry itself, and then usually only near the margins of the intrusion. Similarly, very little primary ore occurs in the Pinal schist, protore rarely containing more than 0.2% copper, and secondary enrichment was necessary to make the mineralization economic.

As I have already mentioned, structure was important in the secondary enrichment process as well. The most obvious example is the Emperor Fault (Slide 16, 17). Rocks in the hanging wall have been completely oxidized and leached of all sulfides, whereas those in the footwall contain high grade supergene enriched ore. The Bishop Fault, which cuts the Emperor, has carried the oxidation as well as the supergene enriching solutions to a greater depth. This has resulted in a high grade zone of steely chalcocite replacing pyrite in veins several inches across. Assays as high as ten percent copper have been obtained in this area and small amounts of native silver have also been observed. (Slide 18)

By far, the most important host rock in the district has been the diabase. Whereas at one time ore intercepts in diabase were dismissed as "unrealistic" or "unreliable", they are now known to be more extensive in the primary zone than in any other rock. The sill-like masses of diabase which extend for miles to the north, south, and east of Ray are, however, intensely mineralized within the district. The grade of copper mineralization in them is higher near the porphyry contacts and major structures previously mentioned and decreases outwardly. As in the other rock types, a pyritic halo extends for a considerable distance outside the copper mineralization.

As regards the vertical configuration, grade is highest at the top of the diabase intrusives and gradually diminishes with depth. Where several diabase sills occur in a column, the uppermost sill will generally carry the highest grade ore, those below gradually decreasing in grade. The intervening material, whether it be quartzite, schist or porphyry, is virtually barren of copper. A drill hole in such an area might, for example, collar in diabase bearing copper oxides and then pass through a section of Dripping Spring quartzite containing only pyritic mineralization. Upon entering a deeper diabase sill, it would show a marked increase in chalcopyrite as well as pyrite content which might render assays as high as two percent copper (a very high grade area!), decreasing with depth. Upon penetrating this diabase sill, entering a say, Pioneer shale, the copper content would immediately drop off, as would the pyrite, until a second diabase sill was encountered. Assays in the upper portion of this second diabase body might run, for example, one percent copper and again decrease with depth, until this sequence was interrupted by penetration of the diabase sill, our hypothetical drill hole then entering more shale or, perhaps, Pinal schist (Slide 19). This material would show only pyritic mineralization with very minor, or trace amounts, of chalcopyrite. Upon entering a third diabase body at still greater depth, copper values might jump to seven or eight tenths percent, again gradually decreasing with depth to two-tenths percent and less.

Thus it appears that not only was the diabase much more reactive to the mineralizing fluids by precipitating out greater amounts of chalcopyrite than the adjacent rocks, but it must have been more permeable as well. The fluids must have traveled not only vertically through the diabase, but laterally along the upper surfaces of these sills for a greater distance than in any of the other rocks.

SUMMARY

The many and varied geologic events and processes which have taken place at Ray necessarily give it some features that appear to be unique among porphyry coppers. Noticeable are the irregularity of the quartz monzonite porphyry intrusives and the fact that they contain so small a percentage of the orebody. The largest outcrops of the Granite Mountain porphyry occur outside the district and are essentially barren. Another singular feature is the importance of the diabase over any other host rock; the analogy might well be drawn, however, between the diabase and a favorable limestone bed in a mineralized area. Factors related to the formation of the copper silicates east of the Diabase Fault are unusual, if not unique. Structurally it is one of the most complex of the porphyry coppers.

In many ways, though, Ray is very similar to other porphyry copper deposits. The importance of old, recurrently active geologic structures, and the obvious genetic relationship of the ore to quartz monzonite porphyry fall right into line with the other deposits. This structural framework was essential in controlling the intrusion of the phorphyry and providing conduits through which the later mineralizing fluids could be disseminated through the host rock. With the exception of the diabase, however, most of the primary mineralization is sub-economic. As in most of the other deposits, supergene enrichment was necessary to make mining practicable.

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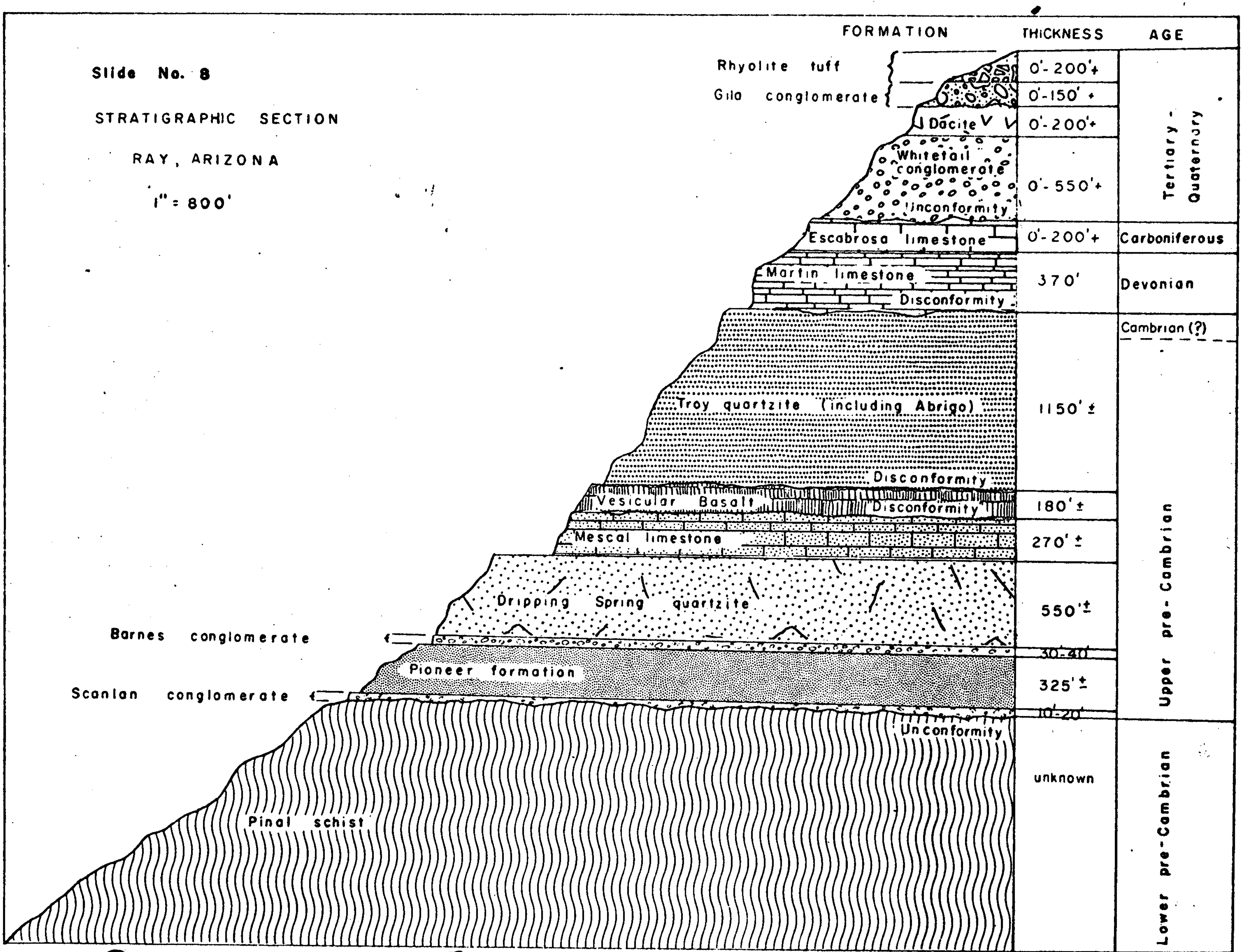
Slide No. 8

STRATIGRAPHIC SECTION

RAY, ARIZONA

1" = 800'



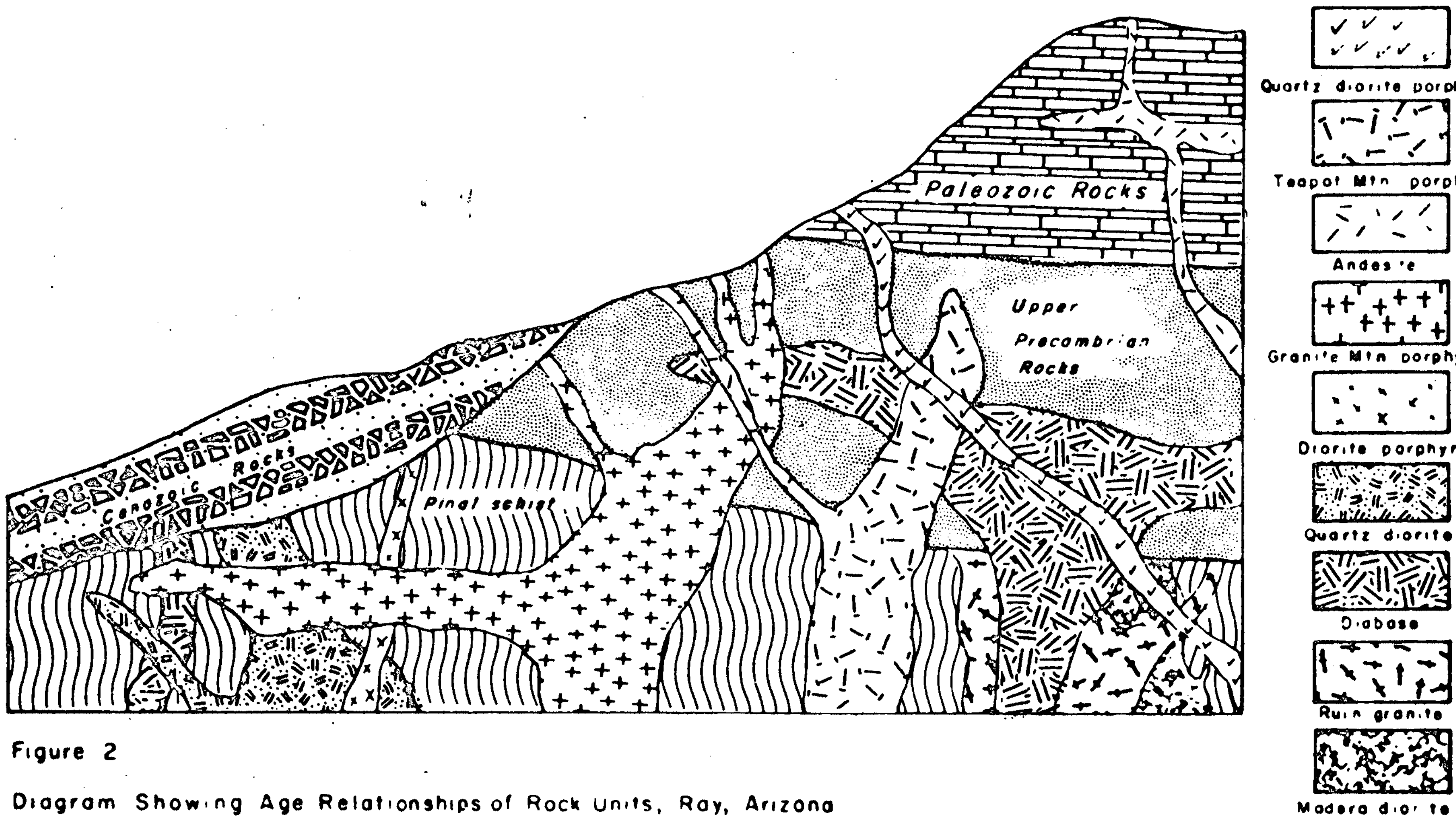
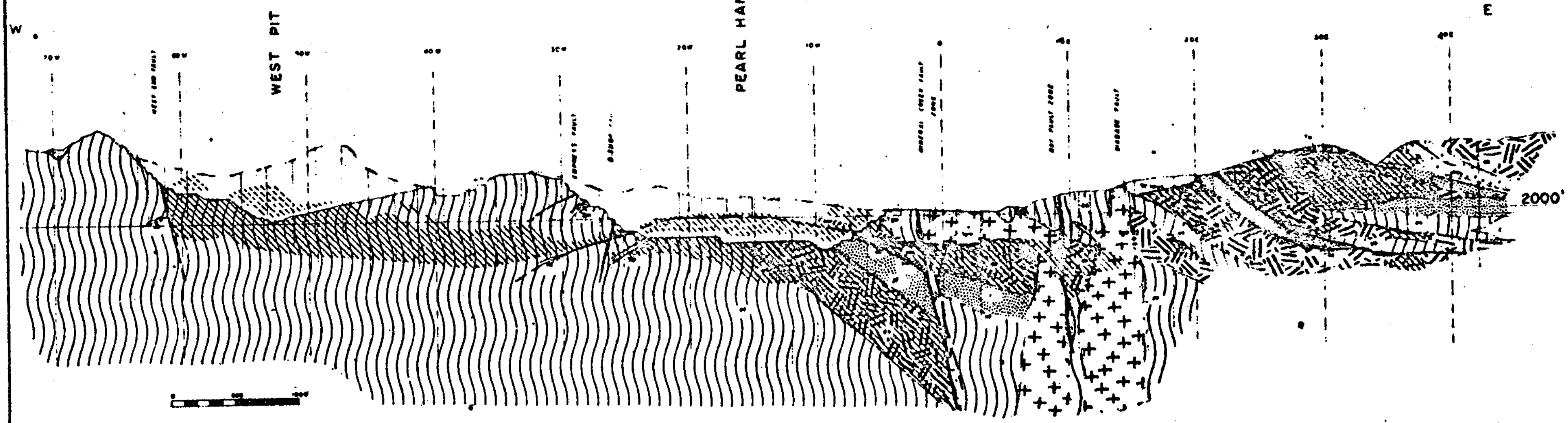


Figure 2

Diagram Showing Age Relationships of Rock Units, Ray, Arizona



GEOLOGIC CROSS SECTION
1200 North

Similar to Slide No. 18

LEGEND:

- Original Surface
- Copper Mineralization
- Copper Mineralization above present surface

GEOLOGY OF THE SAN MANUEL MINE

R O C K S

The San Manuel orebody is a disseminated copper deposit in quartz monzonite, monzonite porphyry, and diabase.

Quartz monzonite, which is Pre-Cambrian[1] in age, is exposed in an area including No. 1 and No. 4 shafts and extending about 2,400 feet southeast from No. 1 shaft. It is also exposed in the bottom of No. 2 shaft and in a zone roughly 500 to 1,200 feet southeast of No. 2 shaft having its long dimension along a northeast-southwest axis. Churn drilling has shown all these exposures to be parts of a contiguous mass of quartz monzonite lying within and beneath the ore zone.

Late Cretaceous[2] monzonite porphyry comprises the bulk of the remaining rock encountered below the conglomerate. In general, the porphyry occurs in two large masses that are separated by a projection of quartz monzonite south of No. 2 shaft. The porphyry masses converge to the east. The north area of porphyry is a sheet-like[3] mass lying above quartz monzonite. The south area has not been bottomed by any drilling south of the orebody and may be a stock.[4] Monzonite porphyry also occurs as dikes cutting quartz monzonite. These dikes become more numerous with proximity to the larger masses of porphyry and generally trend northeast-southwest.

Several diabase dikes, intrusive into quartz monzonite and monzonite porphyry, have been exposed in the mine openings. All the diabase dikes are mineralized similarly to the rocks they intrude.

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[1] References and notes appear at the end of the paper.

Andesite porphyry dikes have been noted in a few instances. Some of these dikes are unmineralized while others are lightly mineralized with pyrite. The mineralization and hydrothermal alteration in all cases are of a different character than that of the intruded rock. Andesite porphyry is probably, as Schwartz[5] suggests, the intrusive equivalent of the lava flows of the Cloudburst formation, the mineralization being of a later age than the ore mineralization.

The Cloudburst formation was cut by No. 3A and No. 3B shafts and by drifting on the westernmost part of the 1475 Level. This formation contains two members. The upper member is a conglomerate made up mainly of quartz monzonite fragments but containing some fragments of all the older rocks in the area. The matrix tends to be arkosic, but granitic sand and gravel are not uncommon. The conglomerate is poorly cemented but relatively well sorted compared with the overlying Gila(?) conglomerate, having beds of sand and gravel alternating with beds of larger boulders. Slickensides are frequently seen on bedding planes. Tuff beds are found in the conglomerate and in the underlying member which is composed of interbedded flows, flow breccias, and conglomerate. Where not distorted by drag adjacent to the San Manuel fault, the average strike of the conglomerate is N 5° W and the average dip is 30° to the east.

The contact of the Cloudburst formation with the overlying Gila(?) conglomerate in No. 3A shaft was an unconformity. In No. 3B shaft the contact was marked by an irregular tuff bed but here, and in the exposures of this contact on the 1475 Level, the bedding of the two formations is parallel or very nearly parallel and, in the 1475 Level exposures, it was not possible to pin-point the exact contact due to the similarity of the two formations.

A small tuff bed near the bottom of 3A shaft was mineralized with pyrite and a trace of chalcopyrite. This mineralization is later in age than the ore mineralization since the Cloudburst formation is not mineralized where it is seen in depositional contact with mineralized porphyry on the surface.

Rhyolite dikes were intersected in several places on all the levels of the mine. Rhyolite is not mineralized by hypogene copper minerals but is occasionally stained by migratory chrysocholla where the dike is in, or close to, the zone of oxidation. Chlorite was noted coating joint faces of several rhyolite dikes. Rhyolite dikes are known from surface exposures to intrude the Cloudburst formation but do not intrude Gila(?) conglomerate.

Gila(?) conglomerate was cut in the upper parts of shafts Nos. 2, 3A, and 3B, and on the 1475 Level southwest of No. 2 shaft. Fragments composing the upper portion are derived mainly from basic flow rocks while the lower beds are derived from granitic rocks. The Gila(?) conglomerate contains no hypogene mineralization or alteration. The average strike is N 50° W and the average dip is 35° to the northeast.

S T R U C T U R E

The oldest of the important post-mineral faults is the San Manuel fault. In its underground exposures, this fault has an average strike of N 66° W and an average dip of 26° to the southwest.

Typically, there are from one to three feet of red gouge and slickensides on the fault surface. On the footwall side, immediately beneath the red slickensides, are from five to fifteen feet of gray gouge with irregular slick faces aligned more or less parallel to the fault and sometimes containing harder fragments with slightly rounded edges. Beneath the gouge, the underlying rock is badly fractured and grades into less fractured, normal rock about 50 to 100 feet below the fault surface.

The conglomerate found in the hanging wall in exposures east of the Hangover fault is not badly disturbed but contains a few small slips close to the fault surface. West of the Hangover fault, besides showing small slips adjacent to the San Manuel fault, the Gila(?) and Cloudburst conglomerates show considerable drag for a distance of 300 feet above the plane of the San Manuel fault.

There are a number of faults which strike N 20° W to N 25° W and dip steeply to the east. These faults exhibit varying amounts of normal fault movement and are younger in age than the San Manuel fault. The most important of these are known as the East fault, the West fault, and the Hangover fault, the latter being in reality a zone of faulting.

A large reverse fault lying between the north and south limbs of ore was intersected by drifting on the 1475 and 1415 Levels. This fault, which is known as the Vent Raise fault, strikes N 59° E and has a dip which varies from vertical to about 70° to the southeast. On the 1475 Level, the Vent Raise fault cut the East fault or a branch of the East fault and is therefor considered to be younger than the northwesterly striking, easterly dipping system of faults.

MINERALIZATION AND HYDROTHERMAL ALTERATION

The ore lies within a mineralized zone having a width on the order of 8,000 to 9,000 feet and a known length in excess of 9,300 feet. To define ore, an arbitrary assay cut-off of 0.50% copper is used.

The upper and western portions of the orebody are separated into two branches by an area of lean, weakly altered hanging wall rock. These two branches converge at depth so that, in cross section, they may be likened to a "U" or "V" leaning to the northwest. The northwesterly limb of ore is referred to as the North orebody and the southeasterly limb as the South orebody.

The North orebody has a strike of about N 60° E and dips approximately 50° to the southeast. The western portion of the South orebody has a strike very nearly parallel with that of the North orebody, or N 60° E, which gradually swings about to the east where the strike is approximately N 45° E. The dip of the South orebody is variable, the upper portions dipping southeast, and the lower portions arching under to the northwest and joining the North orebody. To the east, the central area of lean material gradually diminishes to a core and then disappears as the two limbs join to form a single mass of ore.

The main primary minerals are chalcopyrite, pyrite, and quartz, with minor amounts of molybdenite. These minerals are distributed quantitatively into three zones which are known as the ore zone, the hanging wall zone, which lies between the North and South orebodies, and the footwall zone, which surrounds the ore and hanging wall zones.

The ore zone, which averages approximately 0.80% copper, contains most of the chalcopyrite, quartz veinlets, and molybdenite. Pyrite is present in about equal proportions to chalcopyrite. The yellow sulfides are finely disseminated through the rock but also appear as veinlets or, more often, scattered on fractures. Molybdenite usually forms a slick coating on fractures or accompanies quartz veinlets and is present in sufficient quantity to be recovered metallurgically. The ore zone is altered by a "sericite-pyrite-chalcopyrite"[6] type alteration which is recognized in underground exposures by the moderate gray color of the rock, the presence of altered but easily recognizable biotite, and the presence of pyrite and chalcopyrite in moderate quantities.

The hanging wall zone is simply a lean version of the ore zone with lesser amounts of all the primary minerals. This zone is gradational with the ore zone and the amount of mineralization is dependent on the distance from the ore zone. Alteration here is classed as "marginal biotite"[6] type and is recognized by the dark gray appearance of the rock, fresh-looking biotite, and weak pyrite-chalcopyrite mineralization.

The footwall zone is radically different from the ore zone except for the area where it grades into ore. Pyrite is the chief mineral here and occurs in much greater quantities than in the ore zone. The strongest pyrite is found south of the ore zone where it composes about 10% to 20% of the rock by weight. North of the ore zone the pyrite content is somewhat less and gradually diminishes to a very small amount about 1,500 feet north of the ore zone. Chalcopyrite is rarely seen in the footwall zone, and then usually as a tarnish on pyrite. Quartz veinlets are very rare and molybdenite does not occur in visible quantities. The footwall zone is altered by "hydromica-pyrite"[6] type alteration which is characterized by the light gray appearance of the rock, absence of recognizable biotite, and the abundance of pyrite.

A distinctive chlorite[7] alteration occupies an irregular zone within the South orebody, having its long dimension in a northeast-southwest direction, parallel to the long dimension of the South orebody.

The chlorite is found chiefly as a coating on fracture surfaces which is locally very strong, and, in a few places, permeates the rock.

It was originally thought that a close relationship existed between chlorite alteration and the better grade of copper mineralization. A comparison of this zone of chlorite alteration with the better than average grade ore shows many broad similarities, though not always in detail. Due to the fact that chlorite also alters post-mineral rhyolite, it is believed that any similarities that exist are due to a mutual structural control rather than a mutual source of mineralization.

Ore occurs similarly in quartz monzonite, monzonite porphyry, and diabase, in a zone which is roughly coincident with the contact of the large sheet-like mass of monzonite porphyry with the intruded quartz monzonite. This relationship does not hold true at the eastern end of the orebody but here the ore is diminishing in cross-section. It is difficult to relate the ore directly with the intrusion of porphyry since it shows no preference for either rock and does not occur similarly where the large mass of porphyry to the south intrudes quartz monzonite. It may be theorized that the similarity in shape of the sheet-like mass of porphyry and the ore zone, as well as the later chlorite alteration, may be due to a mutual, though unknown, structural control.

OXIDATION AND SECONDARY ENRICHMENT

The upper portions of the orebody, with the exception of the western end, and much of the central lean hanging wall zone have been oxidized or partially oxidized.

The chief minerals resulting from oxidation and enrichment are chrysocolla, chalcocite, and various iron oxides. Cuprite, native copper, and black copper oxides are frequently seen where the oxidized zone grades into the chalcocite zone. Copper carbonates are very rare, only one small specimen of malachite having been recognized in all the drifting that has been done.

In order to better understand the overall oxidation pattern of the area, as mine openings and diamond drilling make more data available considerable thought has been directed toward separating and classifying stages and types of oxidation.

It is possible to separate oxidized rock into two general types depending upon the color that the iron oxides impart to the rock.

The first type, identified by a deep red or reddish-brown color, is seen at the surface, in the upper parts of shafts No. 1 and No. 4, and in diamond drill holes extending above the top of the sulfide ore at the east end of the South orebody.

This type of oxidation which comprises much of the oxidized ore zone, with the chief ore mineral being chrysocolla, is characterized by complete or nearly complete oxidation of the copper minerals and a relatively sharp line of demarcation between the oxide ore and the underlying sulfide. The absence of leaching and migration of copper from the oxidized zone to form an appreciable enriched chalcocite zone is quite marked in the San Manuel orebody. Thus, the chalcocite zone with variable amounts of oxidation and local enrichment is not important tonnage-wise so that, metallurgically speaking, the ore can be mined as clean sulfide with a minimum of mixed sulfide-oxide ore.

Oxidation of this type occurred in at least three stages: first, during the erosional cycle preceding deposition of the Cloudburst formation; second, during the erosional cycle preceding deposition of the Gila(?) conglomerate; and, third, during the present erosional cycle. Much of the oxidized ore explored by churn drilling in the central and eastern portions of the mine is probably "red" type oxidation.

The second type of oxidation is characterized by the yellow to tan color of the rock which is probably due to a lack of hematite and the presence of limonite and goethite[8] and is typical of all the oxidized ground encountered in the deeper mine openings. Oxidation of the sulfides is not always complete and many rather large areas of primary sulfide rock or partially oxidized rock are surrounded or nearly surrounded by "yellow" type oxidation. The outer margins of this oxidation generally contain chalcocite as well as primary sulfides and much iron oxide stain, but very few oxide copper minerals. Enrichment is very slight, if any. The copper content is usually not increased to any marked degree and occasionally is less than that of the primary ore. Chalcocite, and sometimes native copper and cuprite, occur along the top and sides of deep tongues of this "yellow" oxidation in about the same quantities in which they are found beneath them so that there is often an inversion of the normal sequence of oxidation with primary ore lying above secondary ore which in turn overlies oxidized ore.

Deep tongues of "yellow" oxidation are known to follow rhyo-like dikes, the San Manuel fault, and other northwesterly-trending post-mineral faults. In some cases no structural control is evident but it may be surmised that the path of oxidation was controlled by local differences in permeability of the rock.

This type of oxidation invades the sulfide ore locally along certain faults and in some fringe areas, but has not been found to be of particular economic importance. The intensity of oxidation of ore minerals and the volume of such material relative to the volume of sulfide ore is so limited that it does not affect stope layout or draw. The distinctive coloration and mineralogical characteristics do, in fact, provide a marker and guide for the stope engineers in evaluating their draw data in some instances.

"Yellow" oxidation extended much deeper between the two limbs of ore than in the ore itself and extended deeper than previous oxidations so that, in cross-section, the oxidized zone has the shape of a trough with its sides impinging on the two limbs of ore.

ACKNOWLEDGMENT

Acknowledgment is due the officers of San Manuel Copper Corp. for permission to use the information presented.

J. D. Pelletier
November, 1956

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SAN MANUEL

PAY DIRT

A PUBLICATION DEVOTED TO THE INTERESTS OF ALL THE ARIZONA MINE OPERATORS

Number 391 | P. O. Drawer 48, Bisbee, Arizona 85603 | January 24, 1972