

PARAGENESIS OF THE ORES AT THE SAN ANTONIO MINE,
CHIHUAHUA, MEXICO

by

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TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS.....	ii
LIST OF ILLUSTRATIONS.....	v
LIST OF TABLES.....	vi
CHAPTER	
I. INTRODUCTION.....	1
Location.....	1
Historical Notes.....	1
Previous Geologic Work.....	4
General Geology.....	5
Topography and Climate.....	5
Stratigraphy.....	6
Structure.....	9
Geologic History.....	11
Field Work.....	12
Procedure Used in Preparing Polished Sections.....	13
II. GEOTHERMOMETRY.....	15
Relation of Exsolution to this Investigation.....	15
Results of Exsolution Experiments.....	18
X-ray Diffraction and Geochemical Analysis of Sphalerites to Determine FeS Content...	21
III. RESULTS AND INTERPRETATION OF DATA.....	37

The Ore Bodies.....	37
Types.....	37
Localization.....	37
Mineralogy.....	38
Hypogene Minerals.....	38
Supergene Minerals.....	43
Oxidation Minerals.....	43
Gangue Minerals.....	44
Paragenesis.....	47
Zonation.....	52
Origin.....	55
Conclusions.....	58
BIBLIOGRAPHY.....	61

LIST OF ILLUSTRATIONS

Figure	Page
1. Reference map, Santa Eulalia, Chihuahua, Mexico.....	2
2. Physiography surrounding the Santa Eulalia mining district.....	3
3. Surficial geology and structure of the San Antonio Mine area.....	pocket
4. Techniques for preparing and observing Sauereisen mounts.....	20
5a. Stringer texture of chalcopyrite exsolved from sphalerite.....	22
5b. Chalcopyrite shows some signs of rehomogenization after heating at 400°C for 119 hours.....	22
6a. Stringer texture of chalcopyrite exsolved from sphalerite.....	23
6b. Chalcopyrite shows almost total rehomogenization after heating at 400°C for 119 hours.....	23
7a. Rimming exsolution texture of chalcopyrite in sphalerite.....	24
7b. Some signs of rehomogenization after heating at 450°C for 94 hours.....	24
8a. Star-shaped exsolution texture of sphalerite in chalcopyrite.....	25
8b. Considerable resolution has taken place after heating at 550°C for 22 hours.....	25
9. X-ray spacing curve for determining the FeS content of sphalerite.....	28
10. Standard curves for Fe, Mn, and Cu analyses....	30
11. Variation of the FeS content of sphalerite with temperature.....	35
12. Proposed order of deposition.....	49

LIST OF TABLES

Table	Page
1. Unit Cell-edge Parameters and FeS Contents of Selected Sphalerites.....	29
2. Operating Conditions for the Atomic Absorption Spectrophotometer.....	32
3. Summary of X-ray Diffraction and Atomic Absorption Analyses.....	33
4. Temperatures of Formation as Indicated from FeS Content of Sphalerites.....	36
5. Minerals Observed in the San Antonio Mine and their Relative Abundance in Each Zone.....	46

CHAPTER I

INTRODUCTION

Location

The Santa Eulalia Mining District is situated in the central part of the state of Chihuahua, Mexico. The District covers an area of approximately 30 square kilometers and contains two areas of extensive mining operations, East Camp and West Camp. The San Antonio Mine lies in the East Camp area, 7 kilometers northeast of Santa Eulalia, the principal town in the district. Access is gained by 25 kilometers of paved road from Chihuahua City eastward to Santa Eulalia and by 12 kilometers of dirt road from Santa Eulalia to the San Antonio Mine (Figs. 1 and 2).

Historical Notes

The deposits of the Santa Eulalia District were discovered by the Spanish in 1591. Little activity was initiated until the year 1700 when high grade silver ore was recognized in the deposits. When the outcrops and shallow mineralization were exhausted, deeper shafts were sunk. The lead assay rose considerably, but silver content declined, and for this reason activity diminished until about the turn of the twentieth century.

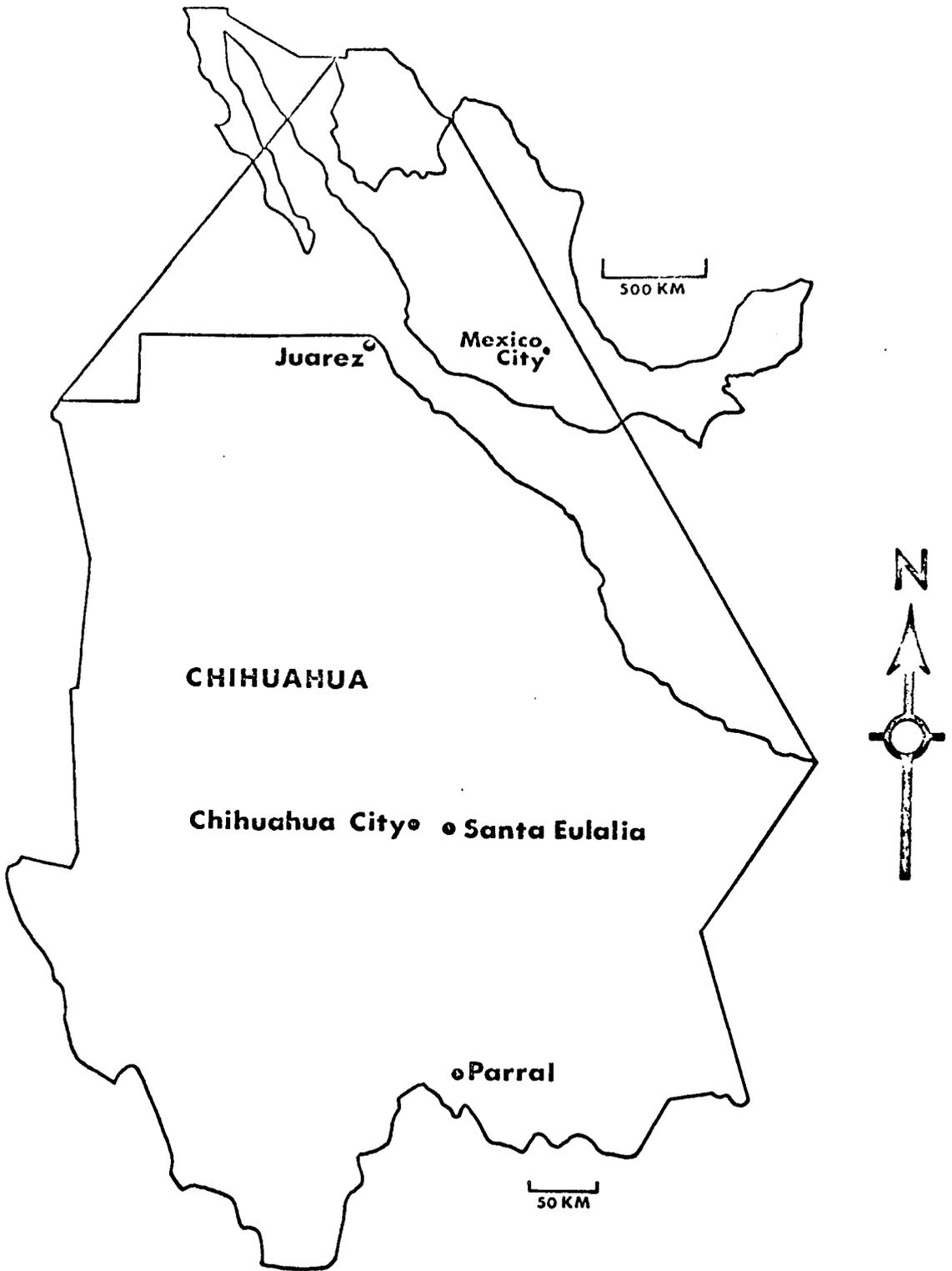


Fig. 1.--Reference map, Santa Eulalia, Chihuahua, Mexico.

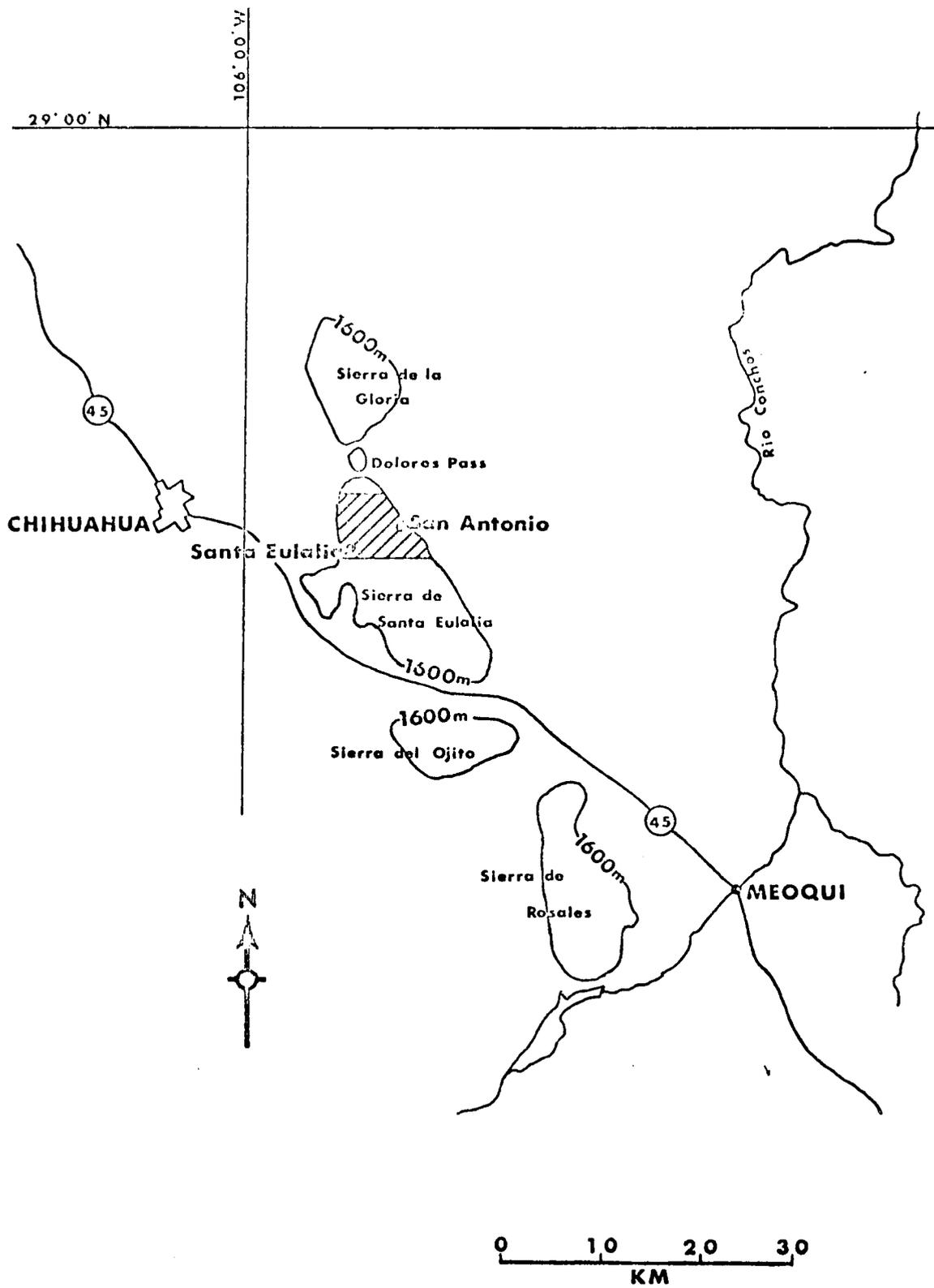


Fig. 2.--Physiography surrounding the Santa Eulalia mining district.

In 1899, the Santa Eulalia Unit was founded by the American Smelting and Refining Company (today Asarco Mexicana, S.A.). Extraction of lead and zinc oxide minerals began in 1912. 1928 brought the construction of an aerial tramway for transportation of the ore between the San Antonio Mine and the Avalos Foundry near Chihuahua City. Subsequently, a mill was built at the foundry for the recovery of tin and vanadium and for selective flotation recovery of primary lead and zinc sulfides discovered in 1942. In mid 1971 the aerial tramway was eliminated following the construction of a new mineral concentration plant at the San Antonio Mine. This mill and concentrator processes approximately 420 metric tpd of ore extracted from both Santa Eulalia camps. Production from the Santa Eulalia District (to 1975) has probably exceeded 45 million tons of lead, zinc, and silver ores.

Previous Geologic Work

No documented geologic work exists concerning the ore deposits of the Santa Eulalia District prior to the acquisition of the property by the American Smelting and Refining Company in 1899. A cultural and historical description of the mines was written by Lew Wallace in 1867.

Soon after Asarco began operations, investigations by several geologists were initiated, including M.A. Knapp, Basil Prescott, J.P. Clendenin, and W.M. Benham. Major published reports on the district include Prescott's (1916) description of the general geology and mineralogy, Hewitt's (1943) discussion of the geology, structure, and mineralogy of the San Antonio Mine, and a description of pyroxenes and amphiboles of the San Antonio Mine by V.T. Allen and J.J. Fahey (1957). Other important unpublished company reports used by the author include those by Benham (1925) and Hewitt (1965). Comprehensive studies of the ore minerals using reflective microscopy, as well as investigations regarding the temperature of formation of the ores, had not been made prior to this report on the paragenetic sequence and exsolution features of the mineralogy.

General Geology

Topography and Climate

The Santa Eulalia Mining District lies in the Santa Eulalia Mountains which are part of a range near the western edge of the Mexican plateau limestone province. The crest of the range rises abruptly 650-700 meters above the adjacent valleys. The mountains are composed mainly of massive limestones overlain by conglomerates

of variable thicknesses and by rhyolites, tuffs, and andesites. The topography is extremely rugged and the area is dissected by many steep-walled canyons and narrow gorges, some approaching 250 meters in depth. Vegetation in the area consists mainly of mesquite, juniper, creosote bush, and tarbush, as well as a wide variety of succulents and grasses.

The climate is classified as arid to semi-arid with an annual average rainfall of 350-400 mm (14-16 inches) and a mean annual temperature of 17.5°C (64°F) (Schmidt, 1973).

Stratigraphy

Limestone: The limestone is thick-bedded (almost massive), dense, dolomitic in part, and is the oldest unit exposed in the district. It has been probed (by drilling) for more than 1100 meters without revealing its base. This unit varies in color from light to dark gray with occasional bluish tints. Fossils are rare, but Hewitt (1965) reports that a suite, collected at a depth of 200 meters, was identified by Dr. H.N. Coryell of Columbia University and is thought to indicate the unit is of Upper Cretaceous age. Species identified by Dr. Coryell included Peregrinella sp., Kingenia sp., and Cyclothyris sp. The limestone has been correlated (Hewitt, 1965) with blue limestones of probable Glen

Rose Age near Los Lamentos (220 kilometers north of Santa Eulalia). On this basis, the limestone would be equivalent to the basal Commanchean Glen Rose Formation of the Trinity Group of Texas.

Weathered exposures of the limestones vary from gray to shades of brown to black near fault zones. This color change is attributed to the oxidation of iron and manganese bearing minerals. Due to its thick-bedded nature, the limestone requires little or no support in the mine drifts and stopes except in the upper extremely oxidized portions of the ore body.

Capping Series: Unconformably overlying the limestone unit is a series of predominantly volcanic rocks with interbedded conglomerates. The series consists of four main members: lower conglomerate, thin-bedded tuffs, upper conglomerate, and upper tuffs and associated volcanics. The capping series is believed to be Tertiary in age according to a suite of fossils collected in 1964 and identified by W.L. Stokes (of the University of Utah) for W.P. Hewitt (1965). Freshwater terrestrial gastropods were identified as Holospira sp. and Viviparua paludinaeformis. The Holospira are similar to H. leidvi (Meek) of Eocene age in Wyoming and H. grangeri (Cockerall) of Oligocene age near Mendez, Tamaulipas. Viviparus

paludinaeformis has also been found in rocks of Paleocene and Eocene ages in Wyoming and Colorado (Hewitt, 1965).

The lower conglomerate has a maximum thickness of about 100 meters and consists of limestone pebbles cemented by a calcareous matrix. This matrix is slightly tuffaceous in places, especially toward the top of the unit.

Conformably overlying the lower conglomerate are the thin-bedded tuffs. They consist of thin-bedded rhyolitic and andesitic tuffs as well as occasional interlayered rhyolite sills. The unit has an approximate thickness of 30 meters.

The upper conglomerate conformably overlies the thin-bedded tuffs. The unit varies in thickness from 2 to 6 meters and serves as a marker bed and indicator of local structure.

The upper tuffs and associated volcanics cover a large part of the surface area. The original maximum thickness is unknown but exceeded 250 meters. The tuffs are dominantly rhyolitic, and are cut by and interlayered with rhyolite dikes and sills.

Intrusives: Rhyolites, andesites, monzonites, and diorites occur as dikes and sills throughout the area. By far the most important intrusives in relation to the ore body are the rhyolites.

The rhyolite occurs mainly in the form of dikes, but a few sills have been recognized. The rhyolite is white to tan and fine grained. There is actually a series of dikes in the immediate vicinity of the San Antonio shaft which is collectively known as the San Antonio Dike. These rhyolite dikes are the youngest of the intrusives.

The andesites are few in number and occur in the upper levels of the limestone and lower conglomerates in the form of sills rarely exceeding 15 meters in thickness. These sills are severely weathered and vary in color from brown to greenish-tan.

Diorites and monzonites occur mainly as sills in the southern portion of the area. One dioritic sill 70 meters thick, known as the Ibera Sill, outcrops near the Ibera shaft. Diorite (sills?) varying in thickness from 1-6 meters were also encountered in deep exploratory core drilling in the San Antonio Mine. This drilling has been completed to a maximum depth of approximately 1145 meters.

Structure

The bulk of the Cerro de Santa Eulalia is composed of thick-bedded Cretaceous limestones which have been warped into a dome of slight structural relief. The

flanks of this dome are truncated on the north by Dolores Pass, an erosional feature which now forms a wind gap, and are covered to the south by the capping volcanics. The western edge of the Cerro de Santa Eulalia is severed by important block faulting which positions it a minimum of 1080 meters above the downfaulted plains to the west. On the east, the limestones dip sharply eastward beneath the adjacent valley (Hewitt, 1943).

The San Antonio ore body is located almost exclusively in a downfaulted block referred to as The Graben. This graben strikes approximately north-south, is roughly 500-1000 meters wide, and has been downfaulted 150-250 meters (Hewitt, 1943). The structure is formed by a single normal fault on the west (West Fault), which dips steeply to the east; however, the eastern wall of the block is more complicated, being composed of two fault zones, the East Fault and the Central Fault. These two faults actually form a type of hinge or scissor fault. The East Fault is normal with westward dip and with more displacement on the northern portion of the downthrown block. The Central Fault is also normal and westward dipping, but has greater displacement on the southern end of the downthrown block. These two faults converge in the central part of the area but

never actually join (Fig. 3).

A few small fissures along which mineralization is found show some signs of minor displacement but these faults are not considered to be structurally significant. The outcrop of the West Fault shows evidence of mineralization and correlates with high lead-zinc values on geochemical maps. Various old prospects from which oxides were extracted can still be seen in the area of West Fault. The Promontorio Tunnel was probably driven to prospect this fault (Benham, 1925). Today the extraction of oxidized ore minerals from the fault zone is not profitable because of the topographical setting of the area, and the fact that the mill is equipped for selective flotation of primary sulfides.

Geologic History

The thick-bedded limestones were deposited in Middle to Late Cretaceous time, making them equivalent to the Trinity Group of Texas (Hewitt, 1965). The Hidalgoan orogeny, which correlates approximately with the Laramide orogeny (Guzman and Cserna, 1963), uplifted the area in Early Eocene and produced large scale block faulting (this does not include The Graben of the San Antonio area). The capping series, comprised of tuffaceous and calcareous conglomerates and rhyolitic tuffs,

was derived from volcanic activity during Oligocene-Miocene time. The remainder of the geologic history is somewhat speculative. There has not been a large intrusion mapped in the area, however, the writer envisions an intrusion of approximately dioritic composition at depth which warped the area into a gentle dome and was the source of the dikes and sills of rhyolite and diorite in the San Antonio area. Normal faulting, producing The Graben and associated fractures, was superimposed on the dome structure. Finally, ore deposition of relatively late Tertiary age was introduced. Pleistocene-Recent erosion and deposition produced the topography which exists today.

Field Work

Sample collection was conducted during a two week trip to the Santa Eulalia District (May 16-30, 1973). Locations of samples were made possible by the use of Asarco mine maps and cross sections. Samples from the oxidized zone were limited, as this mineralogy exists on abandoned levels of the mine which have been extensively backfilled and whose drifts are no longer maintained. Lower levels, composed mainly of sulfides, were sampled at random locations, but samples were

selected so as to obtain a representative portion of the ore minerals.

A limited amount of surface investigation was also undertaken to observe fault exposures and rock units in the vicinity of the San Antonio Mine.

A total of 42 large polished sections, 20 thin sections, plus numerous "Sauereisen" mounts for observation of furnace products were made in order to determine mineralogy, textural relationships, and temperature data dealing with paragenesis of the ore body.

Procedure Used in Preparing Polished Sections

Initial sectioning of the samples was made with a diamond bladed trim saw. Slabs approximately 7 millimeters thick were cut, and an area selected and shaped to fit within 25 millimeter diameter bakelite rings. Saw marks were removed from the samples using coarse carborundum fixed abrasive. The slabs were then mounted in the bakelite rings using appropriate proportions of polyester base resin and catalyst. After sufficient cure time (approximately 24 hours) the edges of the rings were beveled and coarse carborundum fixed abrasive was again used to remove any resin covering the sample face. Fine grinding and rough

polishing were carried out on rotating laps using silicon carbide sliding abrasives and sufficient water to facilitate easier grinding and to keep heat buildup to a minimum. Abrasive sizes used in fine grinding and subsequent rough polishing included 240, 400, 600, 1200, and 3200. Final polishing was done using a 0.3 micron alumina powder on a felt pad.

Polished sections were examined and studied using a binocular Leitz reflecting microscope equipped with oil immersion lenses.

CHAPTER II

GEOTHERMOMETRY

Relation of Exsolution to this Investigation

Exsolution is the unmixing of a solid solution to form two or more distinct phases from a previously homogeneous one. This unmixing, in most cases, is caused by a decline in temperature. As the initial homogeneous phase is cooled, its atomic structure becomes more ordered and rigid until such a point is reached where impurities, if they are present, are forced, or diffused, out of the structure to form a second distinct phase. In many cases, the atomic structure of the host mineral will exert an influence upon the orientation of the exsolved mineral. Brett (1964) summarized that when atoms diffuse through the structure of the host in search of a place to nucleate, they prefer areas of imperfection such as "dislocations, twin lamellae, grain boundaries, and slip planes, because there the lattice is disordered and has a free energy which is higher than the average."

Many factors exert influence on exsolution, but of these temperature is the most important. Temperature controls the total amount of substitution possible in a solid solution at any point in time, i.e., the higher

the temperature the greater the degree of substitution possible due to expanded lattice. The cooling rate of a solid solution is also of utmost importance because this controls the amount of material which can be exsolved from the host phase. At the point at which exsolution begins, the system is saturated with the phase to be exsolved. As the temperature is lowered, the host becomes supersaturated with the exsolved phase and exsolution speeds up. The rate of exsolution increases with supersaturation because the system is attempting to attain equilibrium. However, the diffusion rate of ions is slower at lower temperatures.

It can be seen that exsolution is a highly complicated process which is dependent upon many variables. In addition to temperature, rate of cooling, crystal structure, and rate of diffusion already mentioned, exsolution is also influenced by pressure, concentration, purity, and distribution of stresses within the host.

A major portion of this investigation deals with geothermometry. If an exsolved phase can be rehomogenized with the host, the temperature at which rehomogenization takes place can be regarded as a minimum temperature of formation for that solid solution (Brett, 1964). In regard to the validity of this minimum tem-

perature of formation, Edwards (1954) discusses the point that at low temperatures diffusion in solids is extremely slow. With an increase in temperature the diffusion rate becomes perceptible in the form of rehomogenization. He further states that the temperature gap between which perceptible and nonperceptible diffusion takes place is very small. Thus, the accuracy of this determination can be considered good.

Extensive work has been done regarding exsolution and its textures in sulfide minerals (Schwartz, 1931; Bastin, 1950; Ramdohr, 1950; Edwards, 1954; Oelsner, 1961; Brett, 1964; Galey, 1971). Textural nomenclature used in this investigation will be the same as that used by Galey (1971). It has been stated that a great deal of ambiguity may exist concerning interpretation and identification of exsolution versus replacement textures. Therefore, the previously mentioned rehomogenization method will serve a twofold purpose in this investigation; if rehomogenization is found to occur within reasonable and repeatable temperature ranges, it can be inferred that the texture was indeed the result of exsolution and the temperature at which remixing took place can be regarded as a valid minimum temperature of formation.

Results of Exsolution Experiments

A fairly accurate minimum temperature of formation can be obtained for a mineral assemblage which exhibits exsolution, by heating a sample until the exsolved phase is redissolved into solid solution. In other words, if inclusions in minerals are indeed the result of exsolution, we should be able to rehomogenize the two phases by heating and, thus, make the inclusions disappear. Sphalerites from San Antonio exhibit bleb-like inclusions of chalcopyrite. Massive chalcopyrite also displays star-shaped inclusions of sphalerite. This texture was not as common as chalcopyrite exsolved from sphalerite, but has been known to occur in ores formed at temperatures above 550°C (Edwards, 1954). For this reason, the chalcopyrite-sphalerite solid solution assemblage was used in geothermometry estimates on the ore body.

Samples of chalcopyrite and sphalerite approximately 2 mm in diameter were first chipped out of mine specimens. These samples were then mounted in Sauereisen brand ceramic putty which was molded into a cylinder 3 mm in diameter and approximately 3 mm long. The cylindrical mounts were then mounted on petrographic slides with vinyl plastic and polished using a similar procedure as described earlier except that rotating laps were not used.

Figure 4 shows polishing technique and method for observing the small beveled mounts.

Each polished sample mount was then studied in reflected light for signs of inclusions. If inclusions were present, locations were carefully noted, and oriented photographs were made for later comparison. The samples were then placed in evacuated silica glass tubes and put into furnaces at various temperatures. Controllers for the furnaces are solid state units which operate "on a wheatstone bridge principle in which the resistance of a platinum sensing element is balanced against a variable potentiometer. Temperature control of a nichrome-wound resistance furnace is maintained to $\pm 2^{\circ}\text{C}$ in the range $100\text{-}900^{\circ}\text{C}$ " (Howe, Craig, Harris, Hadidiacos, 1969). After several days the charges were removed from the furnaces and again observed in reflected light for signs of rehomogenization. The samples in which a single phase appeared were photographed at the same position and orientation as the earlier photograph. The temperature at which the sample was heated was also compared to the temperature of formation indicated from Kullerud's FeS content in sphalerite versus temperature of formation relationship.

Furnace studies showed that no exsolved chalcopyrite

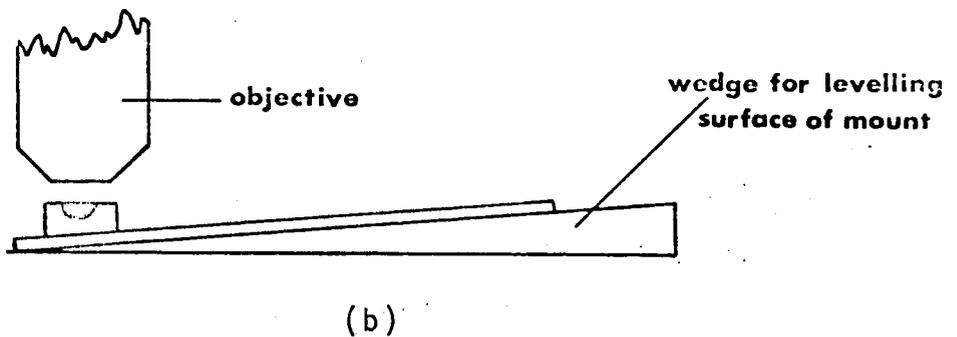
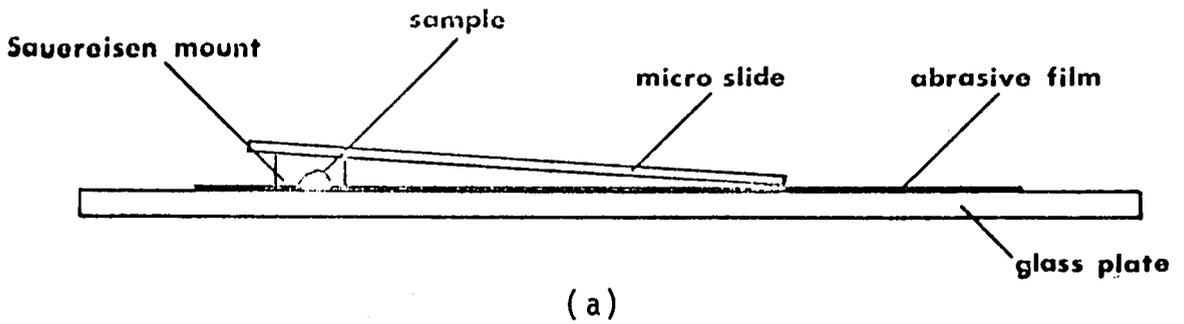


Fig. 4.--(a) Polishing technique used in preparing the Sauereisen mounts. (b) Method for observing Sauereisen mounts using a wedge to level the surface of the beveled mount.

could be rehomogenized with sphalerite at temperatures of 350°C or below. At 400°C some inclusions either partly or totally disappeared (Figs. 5a, 5b, 6a, and 6b) in sample 12-9A. Sample 6-2A showed signs of homogenization at a temperature of 450°C (Figs. 7a and 7b). Therefore, a minimum temperature of 350-450°C can be established for exsolution of chalcopyrite from sphalerite in the San Antonio ores.

The star-shaped inclusions of sphalerite in chalcopyrite showed no signs of rehomogenization at temperatures of 350, 400, 450, or 500°C. Figures 8a and 8b show that considerable resolution of sphalerite in chalcopyrite has taken place at a temperature of 550°C. Figure 8b exhibits a more rough and pitted appearance than 8a. Several of the samples which had been heated at relatively high temperatures showed these signs which are interpreted as being initial stages in recrystallization of the host. The star-shaped inclusions of sphalerite in chalcopyrite indicate an initial temperature of at least 500-550°C.

X-ray Diffraction and Geochemical Analysis of Sphalerites to Determine FeS Content

Initial investigations by Kullerud (1953) and subsequent work by Skinner, Barton, and Kullerud (1959)

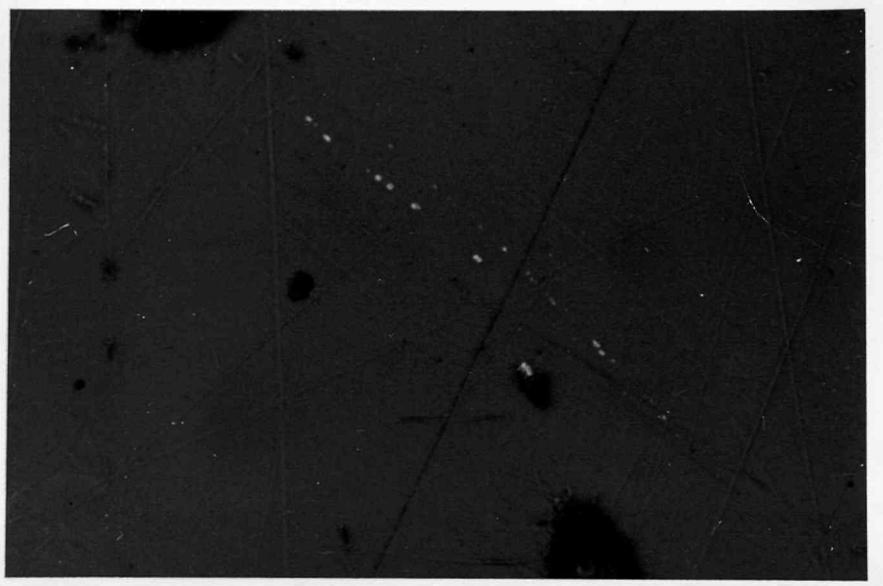


Fig. 5a.--Stringer texture of chalcopyrite (white) exsolved from sphalerite (gray) in sample 12-9A (360x).

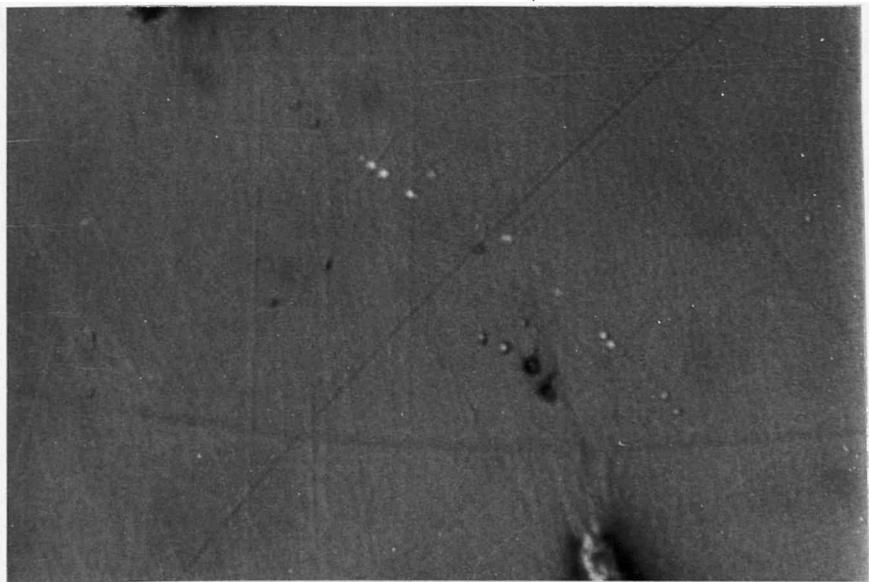


Fig. 5b.--Same position as Figure 5a after heating at 400°C for 119 hours. Chalcopyrite shows some signs of rehomogenization.

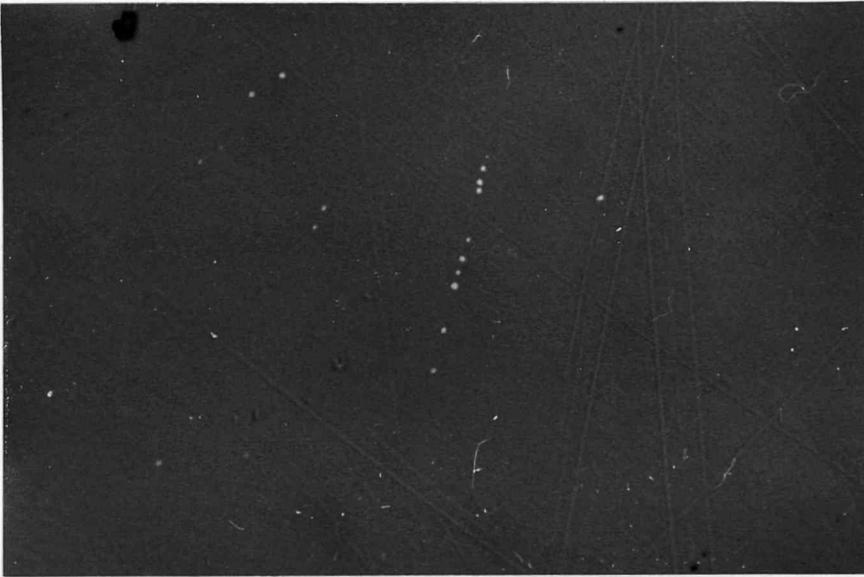


Fig. 6a.--Stringer texture of chalcopyrite (white) exsolved from sphalerite (gray) in sample 12-9A (325x).

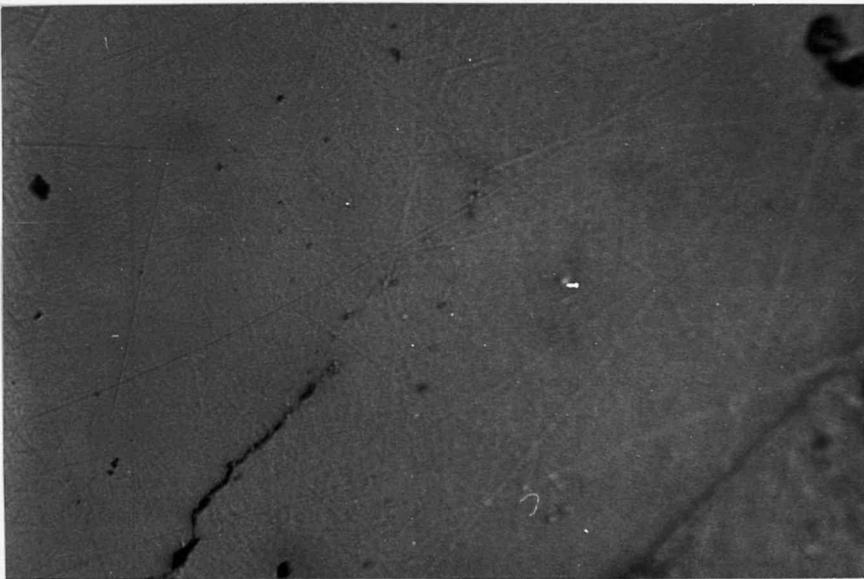


Fig. 6b.--Same position as Figure 6a after heating at 400°C for 119 hours. Chalcopyrite shows almost total rehomogenization with sphalerite.



Fig. 7a.--Rimming exsolution texture of chalcopyrite (white) in sphalerite (gray). Sample 6-2A (420x).

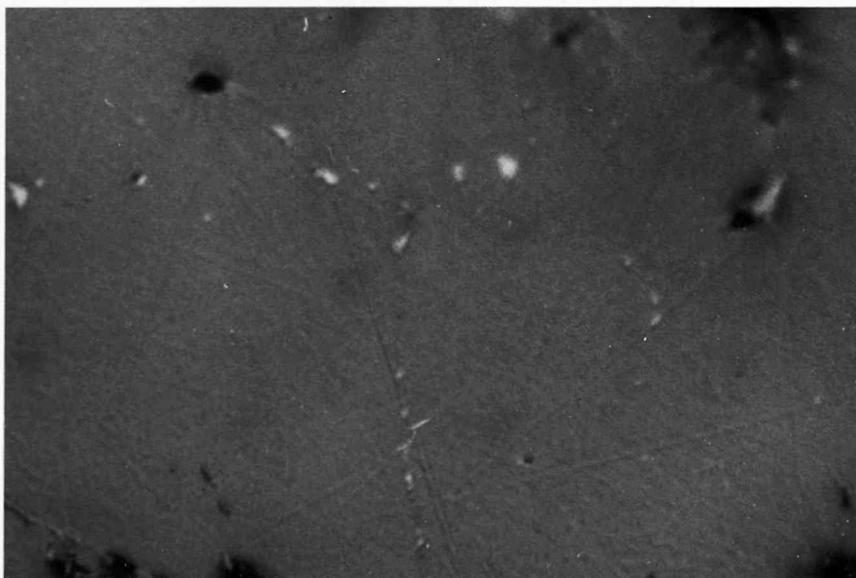


Fig. 7b.--Same position as Figure 7a showing some signs of rehomogenization after heating at 450°C for 94 hours.

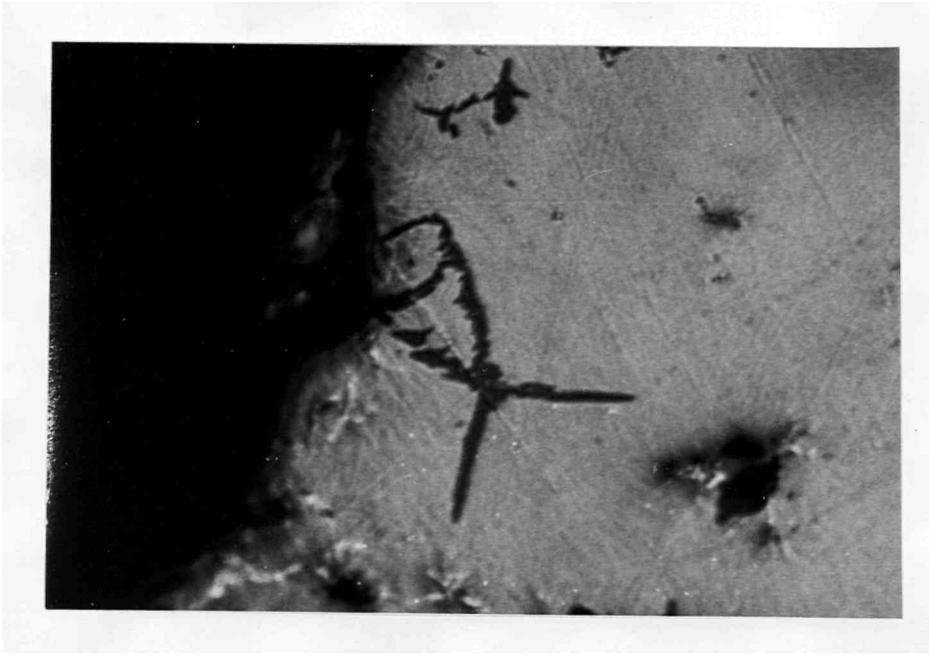


Fig. 8a.--Star-shaped exsolution texture of sphalerite (dark gray) in chalcopyrite (light gray). Sample 3-4A (365x).



Fig. 8b.--Same position as Figure 8a after heating at 550°C for 22 hours. Considerable resolution has taken place. Rough and pitted appearance attributed to initial stages of recrystallization of the chalcopyrite.

and Barton and Toulmin (1966) indicate that there exists a definite relationship between the amount of FeS which can be substituted into the ZnS structure of sphalerite, and the temperature of formation of that sphalerite. Kullerud first devised a method (later revised by Skinner, Barton, and Kullerud in 1959) which relates the FeS content to the unit cell-edge dimension of sphalerite. His method, which was also used by the author, calls for precise x-ray diffraction techniques and depends upon important assumptions. This method assumes that at the time of deposition, there was an excess of iron in the system so that the sphalerite would be as saturated with iron as possible at a given temperature. The pressure is also assumed to be small (field relationships at San Antonio do not indicate any excessive depth for ore deposition). For this method to work ideally, it must be assumed we are working with a Zn-Fe-S system exclusively, without the common interferences by such ions as Mn^{2+} and Cd^{2+} . Attempts were made to correct for manganese and cadmium substitutions in this study according to figures given by Kullerud (1953). The activity coefficients of sulfur and other components were not considered. Barton (1970) points out that the composition of ore minerals may be more dependent

upon the activities of the components than upon pressure and temperature variables.

Sphalerite samples were ground to less than 100 mesh in a mortar and pestle and smear amounts prepared on glass slides using analytical grade NaCl as an internal standard. Each sample was placed on a Norelco X-ray diffractometer and subjected to Ni filtered $\text{CuK}\alpha$ radiation at a scan speed of $\frac{1}{4}^\circ$ per minute so as to resolve α_1 and α_2 reflections. The unit cell-edge of NaCl was taken as 5.64028 \AA (Skinner, Barton, and Kullerud, 1959). The sphalerite (422) and (331) reflections were measured relative to the NaCl (422) and (420) reflections. Measurements on all peaks were made in exactly the same manner to insure that any experimental or instrumental errors were handled the same in each case. Unit cell-edge calculations of the sphalerites were made. These calculations were then used to determine FeS content from the graph in Figure 9. The FeS contents from the unit cell-edge calculations and FeS contents are summarized in Table 1.

Kullerud (1953) and Barton and Toulmin (1966) both state that the ZnS structure of sphalerite is highly receptive to ionic substitution by Mn^{2+} and Cd^{2+} in addition to iron. Substitution by manganese or cadmium

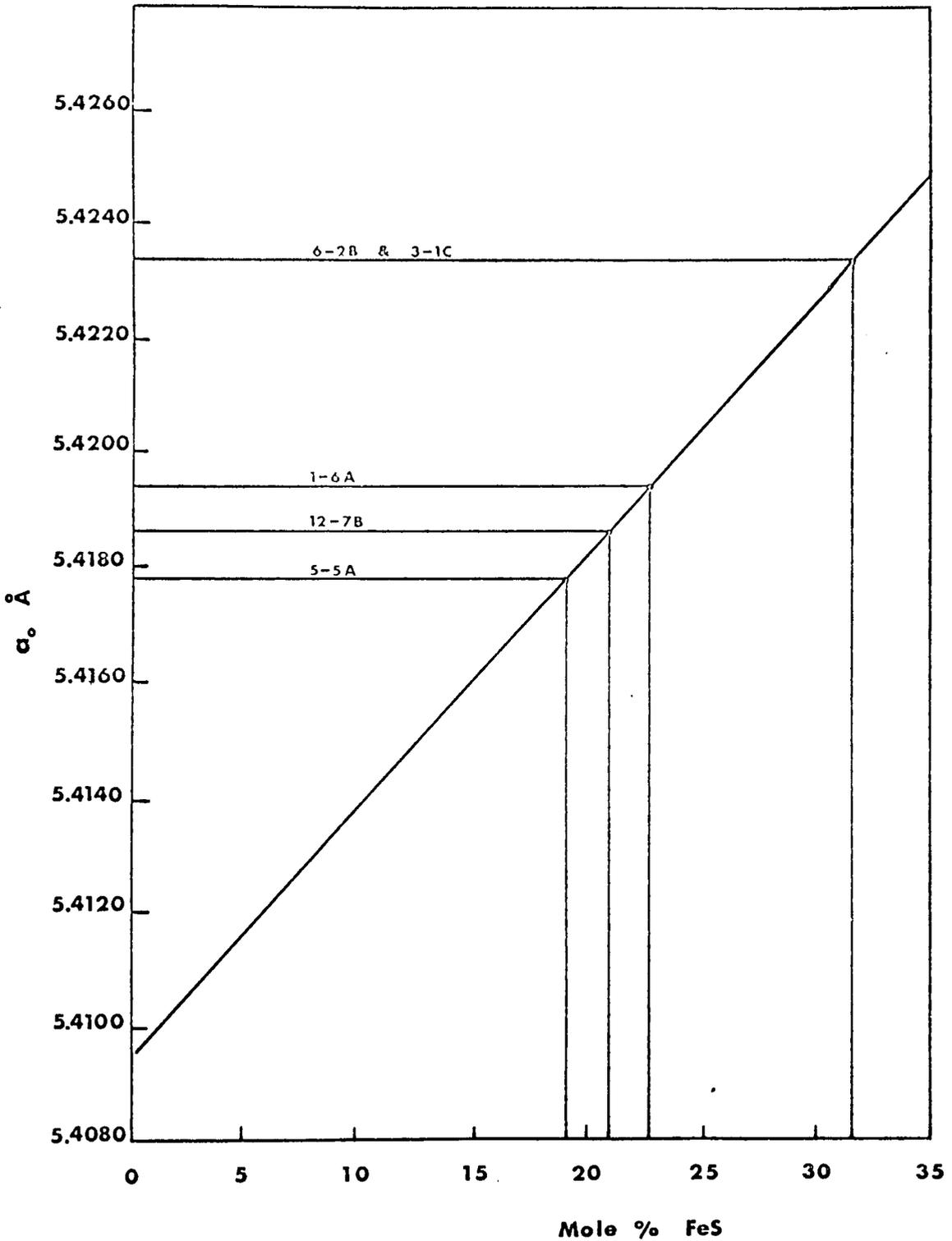


Fig. 9.--X-ray spacing curve for determining the FeS content of sphalerite. (After Skinner, Barton, and Kullerud, 1959).

TABLE 1
UNIT CELL-EDGE PARAMETERS AND FeS CONTENTS
OF SELECTED SPHALERITES

Sample No.	Unit Cell-edge	FeS Mol. %	FeS Wt. %
5-5A	5.4178±.0005 Å	19.2	17.3
1-6A	5.4194±.0005 Å	22.7	20.3
12-7B	5.4186±.0005 Å	20.8	18.8
6-2B	5.4234±.0005 Å	31.6	28.6
3-1C	5.4234±.0005 Å	31.6	28.6

would have large effects on the unit cell-edge dimension of the sphalerite giving erroneously high apparent FeS contents. Kullerud (1953) investigated this effect and found the following results: "the increase (of the unit cell-edge) obtained when 1.0 Mol. % CdS is dissolved in the ZnS lattice is equal to that caused by 3.6 Mol. % MnS or to 11.5 Mol. % FeS." It is therefore possible that FeS contents from x-ray diffraction data alone may be too high. Additional analysis of the sphalerites was made using atomic absorption spectroscopy. The samples were analyzed for Fe, Cd, Mn, and Cu. Standard curves for Fe, Mn, and Cu are shown in Figure 10, whereas Cd analyses were done on a self calibrating instrument.

Samples for atomic absorption analysis were weighed

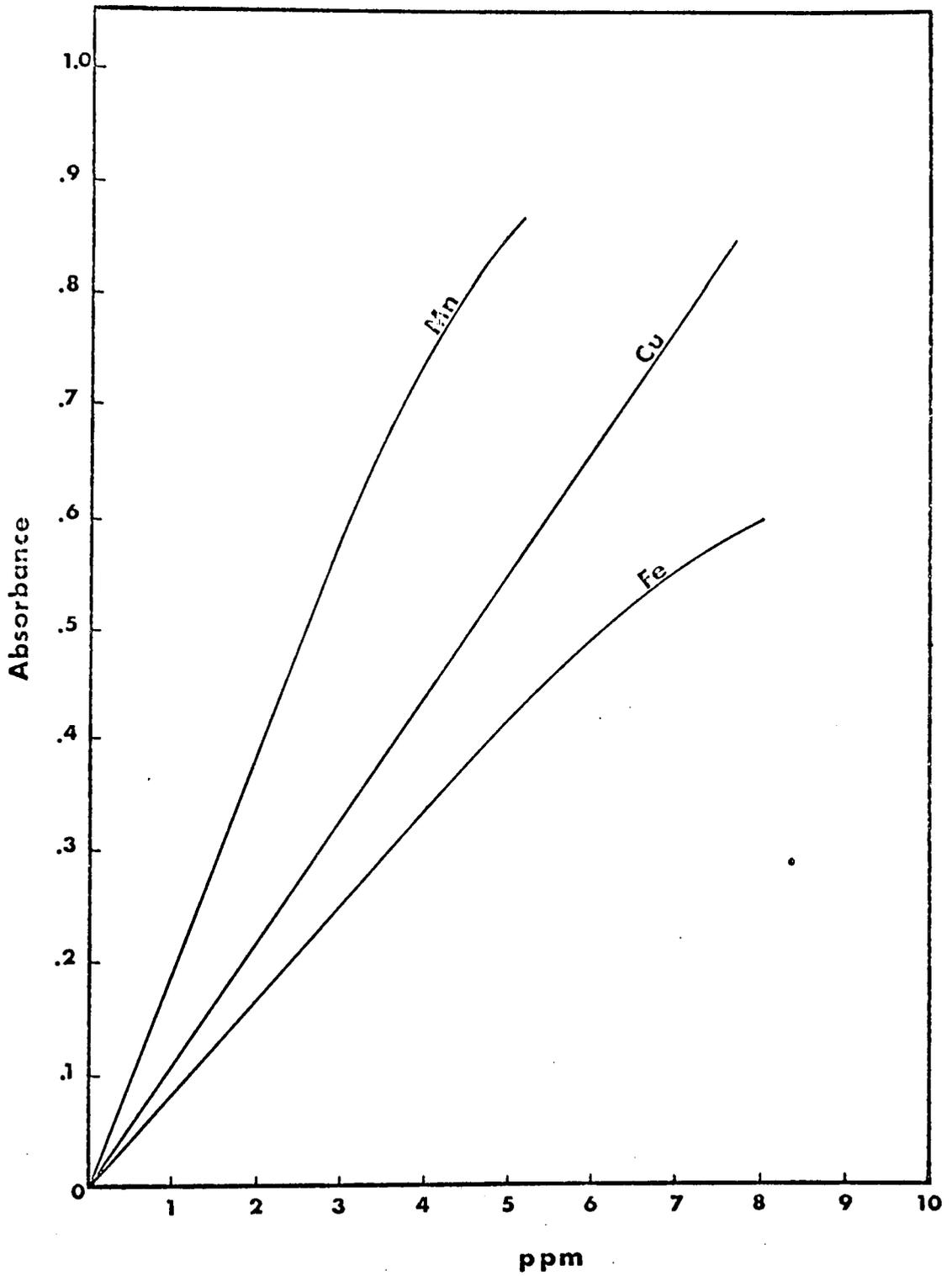


Fig. 10.--Standard curves for Fe, Mn, and Cu analyses.

out and dissolved in a mixture of 5 ml HNO_3 and 5 ml HF. Operating conditions of the spectrophotometer for analysis of each element are summarized in Table 2.

From Kullerud's relationships of the effect of MnS and CdS on the unit cell-edge of sphalerites, one can determine the equivalent amount of FeS each of these contributes to the unit cell dimension calculated from x-ray diffraction analysis. Thus, FeS (from atomic absorption) plus equivalent FeS from CdS and MnS (also from atomic absorption) should equal the FeS content indicated by x-ray diffraction work. These results are given in Table 3.

It can be seen that the actual FeS content of sphalerites determined from atomic absorption spectroscopy is considerably less than that reported by x-ray diffraction. Good correlation exists between FeS contents by x-ray diffraction and total FeS (actual FeS plus equivalent FeS from Cd and Mn analyses) from atomic absorption spectroscopy in three of the five samples. Samples 5-5A and 3-1C show approximately 20% deviation. In each of the analytical methods, duplicate analyses were made on each sample and showed reasonably good agreement in both cases. In both of the samples with high deviations, the atomic absorption data showed higher Cu content than for the remaining three samples. This copper may

TABLE 2
OPERATING CONDITIONS FOR THE ATOMIC ABSORPTION SPECTROPHOTOMETER

Element	Absorption Line	Flame & Type	Lamp	Selection Zone	Remarks on Sample Preparation
Fe	2483 Å	Lean air acetylene	Hollow Cathode	Low	Samples and standards saturated with Ca ²⁺ to prevent interference by SO ₄ ⁼
Cu	3248 Å	Lean air acetylene	Hollow Cathode	Standard	
Mn	2795 Å	Lean air acetylene	Hollow Cathode	Standard	
Cd	2288 Å	Lean air acetylene	Hollow Cathode	Low	

TABLE 3

SUMMARY OF X-RAY DIFFRACTION AND ATOMIC ABSORPTION ANALYSES

Sample No.	Cu		FeS		CdS from A.A.		MnS from A.A.		Total FeS		% from X-ray Diff.
	Wt. % from A.A.	Wt. %	Equiv. FeS Wt. %	Wt. %	Equiv. FeS Wt. %	Wt. %	Wt. %				
5-5A	0.18	12.22	.468	5.38	1.16	3.72	21.32	17.3			
1-6A	0.07	12.59	.482	5.54	0.84	2.67	20.80	20.3			
12-7B	0.04	11.81	.454	5.22	0.64	2.04	19.07	18.8			
6-2B	0.03	18.40	.553	6.36	1.04	3.33	28.09	28.6			
3-1C	0.24	25.04	.530	6.10	1.31	4.19	35.33	28.6			

be present ionically substituted within the ZnS structure and not in the form of chalcopyrite as assumed here. There may also be substitution of ions other than Fe, Mn, Cd, or Cu such as Pb or V within the sphalerite, thus causing apparently incorrect results in the analysis of these two samples.

Figure 11 shows Kullerud's relationship of weight percent FeS in sphalerite to temperature of formation. Increasing temperature of formation corresponds to increasing FeS which can be substituted into the ZnS structure. For this relationship to be valid, the system must be saturated with FeS at the time of deposition, or for practical purposes, the sphalerite must have been crystallized in equilibrium with pyrrhotite or possibly pyrite. In each of the samples from San Antonio, the sphalerite was found to co-exist with either pyrrhotite or pyrite. FeS contents from atomic absorption spectroscopy were used in determination of formation temperature from Figure 11. These results are summarized in Table 4. Due to the discrepancy between FeS contents from atomic absorption spectroscopy and x-ray diffraction, samples 3-1C and 5-5A were not considered reliable. From Table 4 samples 12-7B and 1-6A suggest a temperature of formation of approximately 400-450°C, while sample 6-2B indicates a temperature of approximately 580°C.

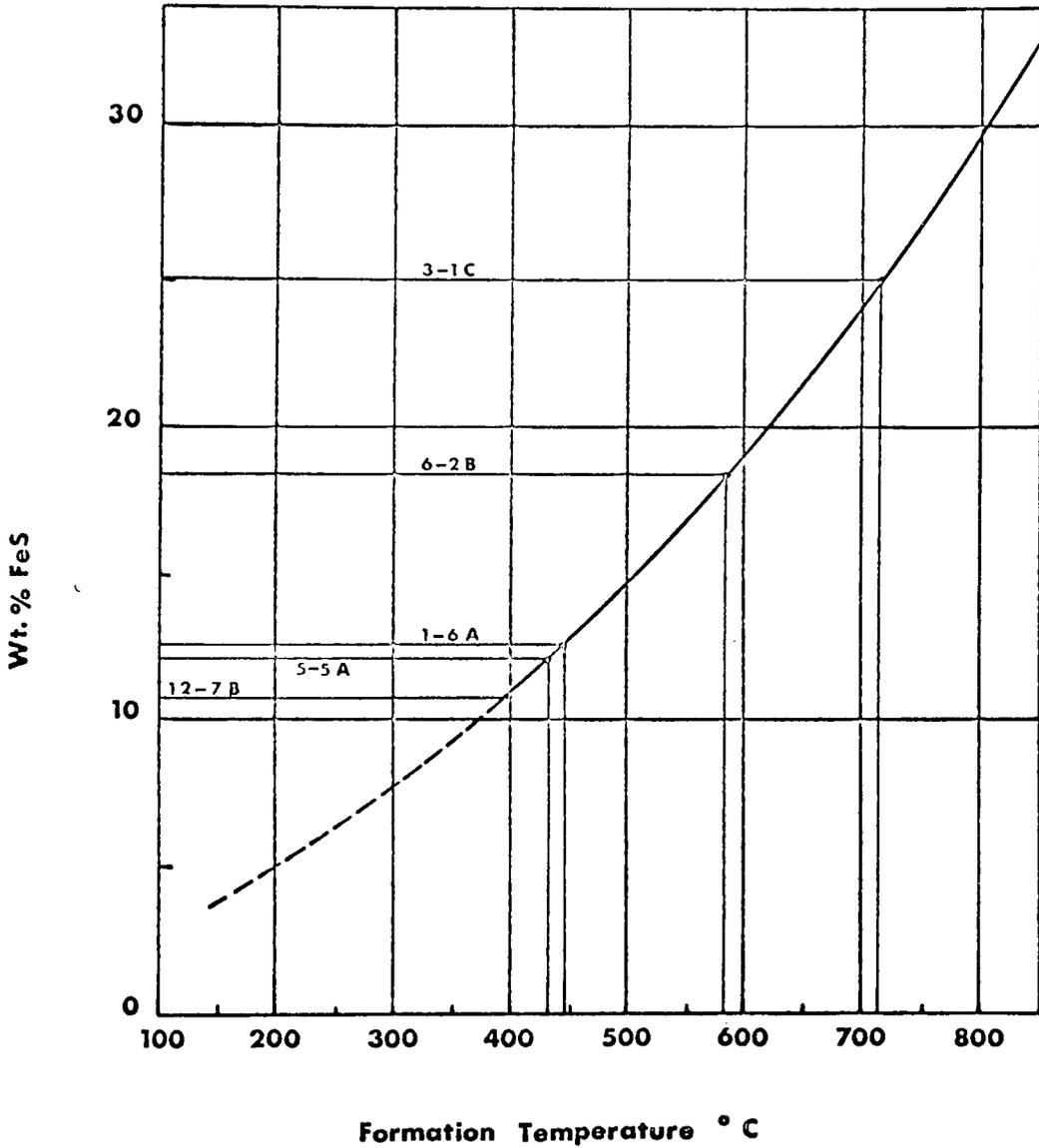


Fig. 11.--Variation of the FeS content of sphalerite with temperature at a pressure of 1 atmosphere. (Figure after Lovering, 1958. Data from Kullerud, 1953).

TABLE 4
TEMPERATURES OF FORMATION AS INDICATED FROM
FeS CONTENT OF SPHALERITES

Sample No.	FeS Wt. % from A.A.	Indicated Temperature of Formation from Figure 5
5-5A	12.22	430°C
1-6A	12.59	445°C
12-7B	11.81	400°C
6-2B	18.40	580°C
3-1C	25.04	725°C

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CHAPTER III

RESULTS AND INTERPRETATION OF DATA

The Ore Bodies

Types

The deposits of the Santa Eulalia District are characteristic of most ore bodies which lie in the Mexican plateau limestone districts. The major portion of the ore occurs in the form of pipe-like replacement bodies known in Mexico as "mantos" (cloak-like) and "chimneys", which are roughly circular in cross section. A manto refers to a more or less horizontal pipe-like body, while a chimney is considered to be vertical or nearly so (Prescott, 1926).

Most of the ore from San Antonio has been mined from chimneys although small mantos are known to exist as offshoots of some chimneys. Small but important tonnages have also been extracted from replacement veins known as fissures (e.g. the Dolores Fissures). In addition to the chimneys, mantos, and replacement veins a good deal of the mineralization is found at contacts of the limestone and rhyolite dikes and sills.

Localization

Except for the fissures, the bulk of the ore is found

at or near the limestone-rhyolite contacts. Sulfides exist as disseminated ore in the contact silicates and limestone as well as massive replacement bodies in the limestone. Despite the spatial relationship of the ore to the rhyolite dikes, the dikes are not believed to be the source for the sulfide mineralization (Hewitt, 1943). The silicate gangue, on the other hand, is believed to have resulted from contact metamorphism of the limestone by the rhyolite intrusions. Petrographic evidence indicates the sulfides are definitely younger than the rhyolite as well as the silicates with the possible exception of some of the quartz. A reasonable explanation seems to be that the intrusion of the dikes and the contact metamorphism prepared the ground for the mineralizers, and the branching habit of the dikes exerted a fair amount of control on the localization of the ore.

Mineralogy

Hypogene Minerals

Sphalerite: Sphalerite is the most important and widespread of the sulfides in the San Antonio area. The color varies from dark brown to black which classifies the sphalerite as the iron rich variety, marmatite.

From petrographic studies in transmitted light, some of the sphalerite (especially when present with contact

silicates) is zoned, with the color varying from dark brown in the center to opaque on the outer rims, without a distinct boundary. The lighter color denotes lower iron content. The possibility exists that the color of the darker sphalerites reflects a greater amount of exsolved chalcopyrite in the structure, which would also suggest that these formed at higher temperatures. However, the darker color may be the result of greater amounts of iron disseminated within the lattice, which could be indicative of either higher temperature or an increase in the amount of iron in the depositing solution.

The sphalerite occurs as massive replacements of limestone along with chalcopyrite, pyrrhotite, and galena. These massive replacement bodies generally occur in the deeper portions of the mine. Sphalerite also exists as disseminations within the silicate gangue minerals such as hedenbergite, garnet, epidote, and quartz. A few vugs were also noted to contain tetrahedron forms of sphalerite crystals but these instances are rare.

Galena: Galena is the second most important major ore mineral from San Antonio. It is found associated with sphalerite, chalcopyrite, and, to a lesser extent, pyrite and pyrrhotite. In general, the galena occurrence

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is spatially slightly above that of the sphalerite but a large degree of overlap exists. A small amount of the galena is also argentiferous. In the upper oxidized portions the mine, galena is found in association with anglesite and cerrusite.

Chalcopyrite: The chalcopyrite occurs both as massive primary ore and as an exsolved mineral from the sphalerite. Its association seems to be closely related to the sphalerite, pyrrhotite, and galena. The darker more iron rich sphalerite shows more extensive exsolution of chalcopyrite than does the translucent brown sphalerite. This suggests that the translucent sphalerite formed at lower temperatures than the opaque sphalerite. However, as pointed out by Galey (1971), "with a low iron content in the hydrothermal solution, excess iron is not available for the formation of chalcopyrite..." and "...the absence of chalcopyrite from the translucent sphalerite neither proves nor disproves that the translucent sphalerite is a result of low iron content in the hydrothermal solutions or that it results from a lowering of the temperature."

Pyrrhotite: Pyrrhotite occurrence is widespread in the San Antonio Mine in the entire hypogene mineralized zone. Its abundance seems to increase with depth where it becomes closely associated with sphalerite, and pyrite.

In one instance arsenopyrite was found with pyrrhotite. The pyrrhotite is moderately magnetic, indicating it is of a monoclinic structure. Barton and Skinner (1967) report that monoclinic pyrrhotite is not stable above 300°C and that it will invert to the nonmagnetic hexagonal form at 325°C. The pyrrhotites of San Antonio exhibit a peculiar intergrown texture with pyrite, with the pyrite replacing pyrrhotite. Barton and Skinner (1967) also state that pyrrhotite upon the addition of sulfur will form pyrite at temperatures in the region of 740°C. The present monoclinicity of the pyrrhotites, then, does not rule out the possibility that they were initially of a hexagonal structure and subsequently inverted to the monoclinic form as the ore body cooled.

Pyrite: Pyrite is especially found in association with sphalerite and pyrrhotite. Pyrite also exists disseminated within the silicate gangue. There is a wide variety of textures observed in pyrite occurrences. The pyrite-pyrrhotite texture has been described earlier, but other occurrences of pyrite are common. Euhedral pyrite cubes are found associated with sphalerite, galena, and chalcopyrite. In addition, massive granular pyrite has been observed with the same associations and with the silicate gangue. Some of this pyrite was found to be

weakly anisotropic. Botryoidal or colliform forms of pyrite also exist but are not as common as the other textures. This texture, according to Ramdohr (1966), is undoubtedly of low temperature origin. Botryoidal pyrite textures also exhibit signs of shrinkage fracturing. The occurrence of pyrite is interpreted to indicate a widespread and fairly uninterrupted sequence of deposition and that the iron content of the depositing solutions was fairly high throughout mineral deposition.

Cassiterite: The writer encountered only one occurrence of acicular cassiterite associated with quartz in a single thin section. However, because San Antonio has in the past produced commercial amounts of tin, a brief description appears necessary. The levels of highest tin concentration lie between elevations of 1230 meters and 1550 meters, which are in the upper abandoned portions of the mine. These areas have been extensively backfilled and sealed off and sample collection was extremely limited on these levels. For this reason the occurrence of tin is described from Hewitt (1943).

Tin occurs intimately associated with other oxide minerals mainly in chimneys and along dike contacts. Cassiterite seems to be the only abundant tin bearing mineral and has been found with contact silicates, magne-

tite, ilmenite, hematite, topaz, columbite, muscovite, tourmaline, and fluorite. From Hewitt's field observations, the cassiterite and other primary oxide minerals appear to be genetically younger than the sulfides found at depth, and the "erratic distribution of tin was caused by volatile mineralizers which followed closely upon the introduction of the sulfides."

Supergene Minerals

Despite the fact that a large portion of the mine lies at and beneath the water table, extremely limited supergene enrichment appears to have taken place. Water is currently being pumped from the lower levels at a rate exceeding 200 gallons per minute. The existence of water has in the past caused many problems and loss of lives (as in the accidental flooding of the mine in 1945), but exploration in the deepest portions of the mine, between elevations of 1013 meters and 963 meters, suggests that the influx of water into the workings is diminishing.

In two polished sections, minor bornite and covellite were found selectively replacing chalcopyrite, but the occurrence of these minerals is thought to be of very minor significance.

Oxidation Minerals

Extensive oxidation has occurred in the San Antonio

ore body above an elevation of 1220 meters. A wide variety of secondary minerals have formed which have been reported by various investigators. Due to extensive backfilling and caving in the upper levels the author's description of the occurrence of oxide mineralization will be incomplete.

The most abundant and important oxidation minerals are cerussite, smithsonite, and anglesite. Cerussite and anglesite are found associated with minor galena found in the oxidized zone, and smithsonite commonly forms botryoidal crusts on limonite matrix. Hemimorphite is also common, occurring in radiating sheaf-like groups of tabular white crystals. Malachite, azurite, chalcantite, pyrolusite, and plattnerite occur as encrustations on limonite and hematite. Vanadenite and manganocalcite are also found in the oxidation zone.

Gangue Minerals

Twenty thin sections were made in order to determine the mineralogy and textural relationships of the gangue, as well as its relationship to the sulfides.

The gangue mineralization consists mainly of numerous contact silicates as well as quartz, fluorite, and calcite. Common minerals found along the dike contacts are hedenbergite, epidote, grossularite garnet, and calcite, as well

as lesser amounts of cummingtonite, actinolite, tremolite, and diopside. The hedenbergite occurs in radiating crystalline masses of various shades from medium to dark green. The occurrence of epidote is in massive form, often with disseminated sulfides. Both hedenbergite and epidote are commonly found in association with grossularite garnet (both isotropic and birefringent) which varies in color from honey yellow to greenish brown.

Quartz and calcite gangue are found in veins cutting the sulfides and contact silicates. They are also abundant in both small and large solution vugs and channels in the limestone. Calcite exhibits a wide variety of interesting crystal forms. Fluorite occurrence does not seem to be restricted to any particular association. It is found both with silicates and sulfides and has been reported (Hewitt, 1943) to coexist with primary oxides such as cassiterite and magnetite.

A complete list of minerals observed by the author to occur in the San Antonio Mine and their relative abundances are given in Table 5.

TABLE 5
 MINERALS OBSERVED IN THE SAN ANTONIO MINE AND
 THEIR RELATIVE ABUNDANCE IN EACH ZONE

Mineral	Formula	Abundance*
Hypogene Minerals		
Sphalerite	ZnS	A
Galena	PbS	A
Chalcopyrite	CuFeS ₂	A
Pyrrhotite	Fe _{1-x} S	A
Pyrite	FeS ₂	A
Arsenopyrite	FeAsS	S
Marcasite	FeS ₂	S
Magnetite	Fe ₃ O ₄	C
Cassiterite	SnO ₂	A
Supergene Minerals		
Bornite	Cu ₅ FeS ₄	S
Covellite	CuS	S
Oxidation Minerals		
Cerrusite	PbCO ₃	A
Limonite	FeO(OH)·nH ₂ O	A
Hematite	Fe ₂ O ₃	A
Hemimorphite	Zn ₄ Si ₂ O ₇ (OH) ₂ ·H ₂ O	C
Anglesite	PbSO ₄	C
Smithsonite	ZnCO ₃	C
Mimetite	Pb ₅ Cl(AsO ₄) ₃	S
Malachite	Cu ₂ CO ₃ (OH) ₂	A
Azurite	Cu ₃ (CO ₃) ₂ (OH) ₂	A
Plattnerite	PbO ₂	C
Chalcanthite	CuSO ₄ ·5H ₂ O	C
Pyrolusite	MnO ₂	C
Vanadenite	Pb ₅ (VO ₄) ₃ Cl	S

* A-abundant, C-common, S-small

TABLE 5 (Continued)

Gangue Minerals		
Quartz	SiO_2	A
Calcite	CaCO_3	A
Hedenbergite	$(\text{Ca}, \text{Fe})\text{SiO}_3$	A
Cumingtonite	$(\text{Mg}, \text{Fe})_7(\text{Si}_8\text{O}_{22})(\text{OH})_2$	S
Epidote	$\text{Ca}_2(\text{Al}, \text{Fe})_3(\text{SiO}_4)_3(\text{OH})$	C
Grossularite	$\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	C
Fluorite	CaF_2	C
Orthoclase	KAlSi_3O_8	S
Topaz	$\text{Al}_2\text{SiO}_4(\text{F}, \text{OH})_2$	S
Diopside	$\text{CaMgSi}_2\text{O}_6$	S
Actinolite	$\text{Ca}_2(\text{Mg}, \text{Fe})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	S
Tremolite	$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	S
Muscovite	$\text{KA l}_2(\text{Si}_3, \text{Al})\text{O}_{10}(\text{OH})_2$	S

Paragenesis

Paragenetic relationships of minerals were observed in reflected light by means of a binocular Leitz reflecting microscope. Several criteria were used in determining relative ages of minerals in polished sections and also in hand specimens. Specific criteria are referenced from Park and MacDiarmid (1970) and Bastin (1951).

Pseudomorphs, relict structures, nonmatching walls of fractures and guided penetration have all been used as textures suggesting replacement. Veins of one mineral intersecting another mineral indicate that the intersecting mineral is younger than the mineral it cuts. Vein walls can either be parallel or nonparallel. Parallel vein walls suggest open space filling while nonmatching

vein borders are indicative of replacement. Irregular borders between two minerals are also suggestive of replacement.

Exsolution textures, as noted by Brett (1964), present somewhat of a problem. Some textures thought to have formed by exsolution may in fact be the result of replacement. This study has attempted to establish that at least some of the inclusions of chalcopyrite in sphalerite and sphalerite in chalcopyrite are due to exsolution. The exsolved phase must definitely be younger than that of the host mineral because exsolution may be thought of technically as a replacement phenomenon whereby the structure of the exsolved phase replaces the structure of the host.

Crystal forms were also used in establishing the order of deposition. Euhedral crystals surrounded by a second mineral were generally considered to be younger than the surrounding mineral. This criterion must, however, be used with caution since euhedral crystals can be formed by replacement. Where samples were removed from vugs or fractures, the crystal forms and enclosing relationships were considered as good indicators of relative ages of the minerals.

Colloform textures are thought to be typically due

ciation of pyrrhotite with chalcopyrite. In most cases chalcopyrite is found replacing pyrrhotite and unsupported grains of pyrrhotite exist "floating" in chalcopyrite.

Pyrite appears to have been deposited throughout most of the sequence showing a variety of textures already described. Euhedral cubic pyrite is found in association with pyrrhotite and sphalerite. Intergrown pyrite and pyrrhotite are common with pyrite replacing the pyrrhotite. A limited amount of colliform pyrite is also found associated with chalcopyrite, galena, and quartz. This texture is believed to be indicative of late stage deposition of pyrite.

Chalcopyrite exists in two forms, as exsolved blebs within sphalerite and in massive form associated with sphalerite, galena, and pyrrhotite. Some of the massive chalcopyrite shows star-shaped inclusions of exsolved sphalerite. Thus there appears to have been overlapping deposition of chalcopyrite and sphalerite. A later generation of chalcopyrite is shown by veins and masses replacing sphalerite. The later chalcopyrite does not contain exsolved sphalerite.

Galena has a definite preferential association with sphalerite and chalcopyrite. Galena, in most instances,

replaces the sphalerite and chalcopyrite, but at different rates. As the galena replaces sphalerite, chalcopyrite is recrystallized at the contact to form larger masses with a convex portion extending into the galena. Similar textures have been described by Galey (1971) and Oelsner (1961). Chalcopyrite bodies do exist engulfed by galena, but these occurrences are rare, and may represent an apparent effect due to random sectioning.

Sphalerite shows close association with pyrrhotite, chalcopyrite and galena. The sphalerite as a rule replaces pyrrhotite but exceptions do exist. Exsolved star-shaped bodies of sphalerite are replacing the chalcopyrite structure, but the later chalcopyrite (devoid of sphalerite inclusions) appears to replace sphalerite preferentially, both massively and as exsolved blebs within the sphalerite. Thus, sphalerite and chalcopyrite show overlapping deposition. Galena is sometimes enclosed by sphalerite and has irregular boundaries. Two polished sections show minor arsenopyrite as euhedral crystals being replaced by sphalerite. The contact silicates often contain disseminations of sphalerite. Petrographic evidence shows that the sphalerite is definitely later than the silicates indicated by numerous sphalerite pseudomorphs.

The occurrence of cassiterite was observed in a single thin section. It, as well as magnetite, is not found with the sulfides and for this reason, deposition of primary oxides is thought to have been a separate period of mineralization. The cassiterite occurrence was as acicular crystals enclosed by euhedral quartz crystals. The quartz exhibits some ferruginous zonation near the crystal terminations. If this iron-rich quartz zone could be correlated with the lead, zinc, copper, and iron sulfide mineral deposition, it would suggest that the cassiterite was of an earlier depositional phase. [This would be in contradiction of Hewitt's (1943) observations.]

Numerous exceptions are found to the proposed paragenetic sequence. In a few specimens chalcopyrite exists only as an exsolution phase. Galena, in some instances appears to be earlier than the sphalerite. Frequently, pyrrhotite and pyrite are absent in polished section and sphalerite seems to be the first mineral deposited. Two samples from vugs show successive euhedral pyrite deposition after sphalerite and galena.

Zonation

The sulfide mineralization of San Antonio is intimately associated with a series of acidic dikes. Mineralization is found either in the form of disseminations within

silicate gangue surrounding the dikes or as massive replacements in limestone. Specimens were collected which reflected a representative sample of the ore at any one point.

The largest scale zonation is shown by the division of the ore body into an upper oxidized zone and a lower hypogene zone. The boundary between these two zones corresponds closely with the elevation of the present water table - approximately 1220 meters.

Sulfide zonation is somewhat erratic. A few trends, however, are visible. Pyrrhotite shows a definite increase in occurrence with depth and toward the southwest. Sphalerite and galena do not appear to show any particular zonation except that in most instances the sphalerite to galena ratio increases with depth. The few significant occurrences of arsenopyrite were in the lower southern portions of the workings. Chalcopyrite shows very erratic distribution with no perceptible trends noticeable.

No apparent spatial relationship exists between the iron content of the sphalerites analyzed and their positions in the ore body. This would lead one to believe that evidence for a general increase in temperature of formation (based on FeS contents of sphalerite) toward the lower levels is not visible in this ore body. There

also appears to be no direct correlation between the amount of chalcopyrite inclusions found in the sphalerites and the iron content of the sphalerites (assuming that all copper from atomic absorption data existed in the form of CuFeS_2). Higher iron contents in sphalerites should correlate with higher temperature of formation. This in turn should correlate with higher amounts of chalcopyrite exsolved from the sphalerite structure. From these statements it can be inferred that not all chalcopyrite in the San Antonio sphalerites is exsolved. This supports petrographic observations as well as furnace data.

There appears to be some telescoping of the ores at San Antonio. In some instances sphalerite is found to increase at intermediate levels and greater chalcopyrite percentages are noted at depth. Cassiterite (as well as other primary oxides and rare earth minerals) is the most drastic example of the telescoping effect. These minerals do not occur at all in the deeper portions of the mine. The highest concentrations of tin occurs in a chimney between 1230 meters and 1550 meters. As already stated, the primary oxides are of a different mineralization episode than the sulfides.

The silicate gangue shows a significant amount of zonation in relation to the rhyolite dike. The silicates

are found mainly at or near rhyolite-limestone contacts. The generalized sequence is rhyolite dike, epidote, garnet, hedenbergite, unreplaced limestone. In places one of the silicates may be absent or an actinolite and cummingtonite zone is noticed between the epidote and garnet.

Origin

The deposits at San Antonio have been and still are considered to be metasomatic replacements of limestone. Hewitt (1943) and Allen and Fahey (1957) place the ore body in the pyrometasomatic grouping of Lindgren's classification. San Antonio shows characteristics of hypothermal, xenothermal, and pyrometasomatic origin. The mineral assemblage suggests high temperature, yet the field evidence does not indicate that the ore body formed at any excessive depth. Lindgren considers minerals such as "pyroxenes and amphiboles, the garnets, ilmenite, magnetite, specularite, pyrrhotite, tourmaline, topaz..." as indicative minerals for hypothermal deposits. He further says that "simple sulfides and arsenides prevail and are in many deposits associated with oxides such as magnetite, specularite, ilmenite, and cassiterite." Lindgren bases the differentiation between hypothermal and pyrometasomatic on the absence or presence of an igneous body. A direct

connection between the ores and a known igneous body at San Antonio has not been confirmed.

A xenothermal classification of the ore body would imply deposition of the ores at high temperatures and low pressures. This would seem to fit San Antonio, as well as the fact that telescoping often occurs in xenothermal deposits. On the other hand, Park and MacDiarmid (1970) state that replacement bodies are seldom of xenothermal origin due to the rapid mineral deposition which must take place in xenothermal deposits. Fissure veins are the most common loci for deposition in xenothermal ore bodies. A rapid temperature and pressure drop suggested in a xenothermal classification would not allow time for large scale replacement to take place.

The mineral assemblage at San Antonio suggests a reasonably high temperature of formation. The presence of birefringent garnet suggests that the early silicate mineralization and contact metamorphism took place at temperatures in excess of 860°C (Allen and Fahey, 1957). Telescoping of the ore body indicates that the temperature, pressure, and chemistry of the hydrothermal solution was constantly changing. The drastic telescoping effect portrayed by the occurrence of the primary oxides does not call for a massive increase in temperature. It has

been established that the cassiterite is definitely a separate phase of mineral introduction. If it is older than the primary sulfides, then one must be inclined to believe that it closely followed the intrusion of the acid dikes. If molten material moved through these conduits for an extended period of time, the temperature of the country rock would have been raised considerably, allowing the fluids containing the primary oxides to be deposited at relatively shallow depth. On the other hand, these primary oxides are possibly post-sulfides (as Hewitt suggests). The same criterion could be used, however, to account for the spatial relationship of the cassiterite to the sulfides. The introduction of the primary sulfide mineralization must have increased the host rock's temperature. Oxide mineralization could, therefore, be prevented from being deposited until it reached cooler, shallower elevations. The general increase in pyrrhotite with depth and to the southwest, as well as the occurrence of arsenopyrite, indicates a heat source, possibly an igneous intrusion, in that direction. A hydrothermal fluid source to the southwest would correlate nicely with the hypothesis that the similar ore bodies of the West Camp are genetically related to those of San Antonio. On the basis of the mineral assemblage, experimental tempera-

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ture of formation data, and the suggestion of an undiscovered intrusive to the southwest, the writer believes it best to classify the ore body as San Antonio as pyrometasomatic.

Faults and fissures seem to have produced only a small percentage of loci for deposition of the ore at San Antonio. The fact that the major sites for mineralization were not produced along major faults is probably due to the limestone's susceptibility to the production of gouge along planes of major movement. Gouge is less permeable than the limestone itself and, thus, inhibits any great amount of mineralization. By far the most important controls over ore deposition in the San Antonio area are the contacts between the limestone and the rhyolitic intrusions. The fracturing and contact metamorphism of these areas provided ideal channels for transporting and sites for deposition of the ore solutions.

Conclusions

The sequence of primary sulfide mineralization at the San Antonio Mine, Chihuahua, Mexico, was established using reflective microscopy. The ores show a preferred depositional sequence of pyrrhotite, pyrite, early chalcopyrite, sphalerite, late chalcopyrite, with galena

deposited last. Quartz seems to have been deposited throughout the sequence. Time of introduction of cassiterite and other primary oxides is still in question, but has been established to be a separate episode.

Localization of the ore bodies was controlled by contacts between rhyolitic dikes and limestone, and to a lesser degree by faults and fissures. Intrusion of the dikes caused significant contact metamorphism of the limestone, producing mainly hedenbergite, garnet and epidote, which acted as a ground preparation phase. Field evidence suggests that the faults comprising The Graben are premineralization but post rhyolite in age.

Geochemical analyses and furnace data indicate that the temperature of formation for the early chalcopyrite was at least 500°C, but possibly as high as 580°C. The sphalerite and later chalcopyrite suggest temperatures in the range of 350-450°C. These temperatures are in the range of 350-600°C determined on sphalerite-chalcopyrite exsolution by Ingerson (1955). Birefringent garnet indicates that the early contact metamorphism took place at temperatures in excess of 860°C.

Zonation of pyrrhotite and arsenopyrite (increasing occurrence with depth and to the southwest) suggest a heat source, possibly an igneous intrusion, in that

direction which supplied the mineralizers. The possibility of an igneous intrusion to the southwest strengthens the hypothesis that the ores of San Antonio are genetically related to those of the West Camp.

On the basis of mineral assemblages, experimental temperature results, and the probability of the existence of an igneous intrusion as a heat source, the ore body is placed in Lindgren's pyrometasomatic classification.

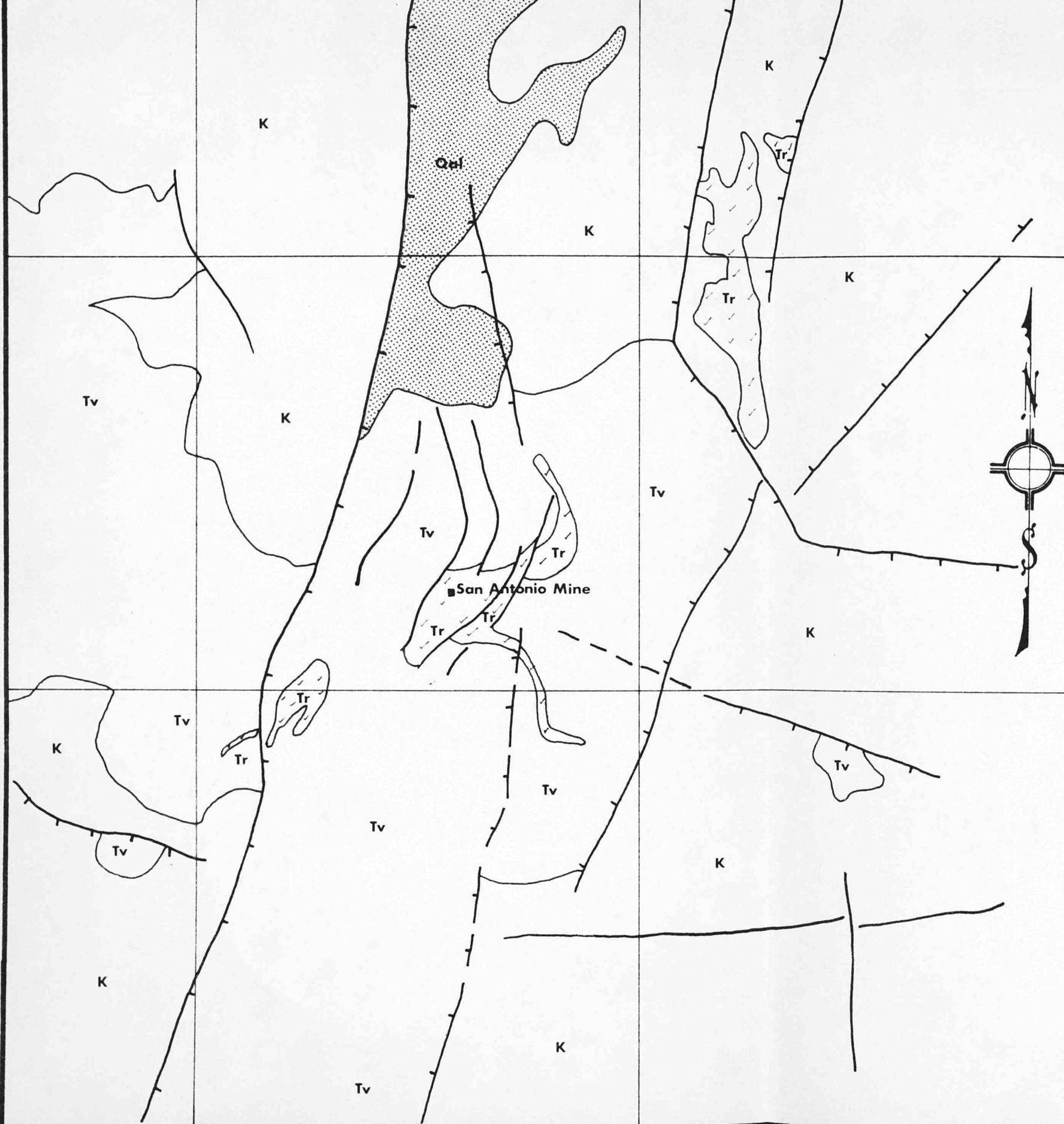
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LEGEND

Quaternary Qal alluvium

Tertiary Tr rhyolite
Tv capping series

Cretaceous K limestone

fault- hatchures indicate downthrown block

fracture or fissure

geologic boundary

SURFICIAL GEOLOGY and STRUCTURE of the
 SAN ANTONIO MINE AREA

scale : 10,000