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METALS DISTRIBUTION AT THE SAN ANTONIO MINE, SANTA EULALIA MINING DISTRICT, CHIHUAHUA, MEXICO

by

Timothy George Walter

A Thesis Submitted to the Faculty of the
DEPARTMENT OF MINING AND GEOLOGICAL ENGINEERING
In Partial Fulfillment of the Requirements
For the Degree of
MASTER OF SCIENCE
WITH A MAJOR IN GEOLOGICAL ENGINEERING
In the Graduate College
THE UNIVERSITY OF ARIZONA

1985
STATEMENT BY AUTHOR

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William C. Peters

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Date
ACKNOWLEDGMENTS

I wish first and foremost to thank my major professor, Dr. William C. Peters, for his diligence in the initial arrangements for support of this research and also for his guidance, advice, and unfailing interest in the project despite his present status as professor emeritus. Sincere appreciation is also extended to Professors Deverle P. Harris and Spencer R. Titley for their suggestions and other help. Special thanks are due as well to Industrial Minera Mexico, S.A. and in particular to Ing. Armando Ibarra A., general superintendent of the Santa Eulalia Unit for allowing me access to IMMSA properties, reports, maps, and other documents. Grateful appreciation is extended to the geological engineers at the Santa Eulalia Unit, especially Ings. Dionisio Maldonado E. and Rodolfo Juarez P. for their abiding assistance and valuable insights into the geology of the San Antonio area. I would also like to thank the Department of Mining and Geological Engineering, The University of Arizona, for providing computer funding. Heartfelt thanks are given to Ing. Cesar Arroyo of the Santa Eulalia Unit for his unselfish aid in lessening language difficulties experienced by me while in Mexico and for his helpful technical discussions as well as his tireless concern for my well-being. Special thanks go to H. R. Hauck for her help in preparation of the manuscript. I also wish to thank my wife, Cindy, for her enduring patience during the evolution of this work.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF ILLUSTRATIONS</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vii</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>viii</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Geography and Physiography</td>
<td>3</td>
</tr>
<tr>
<td>History</td>
<td>4</td>
</tr>
<tr>
<td>Previous Work</td>
<td>6</td>
</tr>
<tr>
<td>Purpose and Scope of Thesis Study</td>
<td>7</td>
</tr>
<tr>
<td>2. GEOLOGY</td>
<td>9</td>
</tr>
<tr>
<td>Lithology and Stratigraphy</td>
<td>9</td>
</tr>
<tr>
<td>Cretaceous Units</td>
<td>11</td>
</tr>
<tr>
<td>Cuchillo Formation</td>
<td>11</td>
</tr>
<tr>
<td>Glen Rose Formation</td>
<td>12</td>
</tr>
<tr>
<td>Lagrima Formation</td>
<td>14</td>
</tr>
<tr>
<td>Tertiary Units</td>
<td>15</td>
</tr>
<tr>
<td>Intrusions</td>
<td>17</td>
</tr>
<tr>
<td>Structure</td>
<td>19</td>
</tr>
<tr>
<td>Mineralization</td>
<td>19</td>
</tr>
<tr>
<td>Occurrence</td>
<td>21</td>
</tr>
<tr>
<td>Mineralogy</td>
<td>28</td>
</tr>
<tr>
<td>Paragenesis</td>
<td>30</td>
</tr>
<tr>
<td>Oxidation</td>
<td></td>
</tr>
<tr>
<td>3. CONTOURS AND METAL RATIOS</td>
<td>32</td>
</tr>
<tr>
<td>General Theory</td>
<td>34</td>
</tr>
<tr>
<td>Procedure</td>
<td>37</td>
</tr>
<tr>
<td>Results</td>
<td>42</td>
</tr>
<tr>
<td>Plan Contours</td>
<td>42</td>
</tr>
<tr>
<td>Metal Value Vertical Section Contours</td>
<td>43</td>
</tr>
<tr>
<td>Metal Ratio Vertical Section Contours</td>
<td>44</td>
</tr>
<tr>
<td>4. DISCUSSION</td>
<td>46</td>
</tr>
<tr>
<td>Structural Integration</td>
<td>46</td>
</tr>
<tr>
<td>Considerations for Exploration</td>
<td>52</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS—Continued

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. CONCLUSIONS</td>
<td>54</td>
</tr>
<tr>
<td>APPENDIX A: ASSAY DATA FOR SAN ANTONIO MINE</td>
<td>56</td>
</tr>
<tr>
<td>APPENDIX B: CONTOUR MAPS FOR METAL VALUES AND RATIOS, SAN ANTONIO MINE</td>
<td>63</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>97</td>
</tr>
</tbody>
</table>
### LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Location map of the Santa Eulalia mining district, Chihuahua, Mexico</td>
</tr>
<tr>
<td></td>
<td>Page 2</td>
</tr>
<tr>
<td>2.</td>
<td>Stratigraphic column of the San Antonio mine area</td>
</tr>
<tr>
<td></td>
<td>Page 10</td>
</tr>
<tr>
<td>3.</td>
<td>Cross section of the San Antonio graben</td>
</tr>
<tr>
<td></td>
<td>Page 18</td>
</tr>
<tr>
<td>4.</td>
<td>Surface geology of the San Antonio graben area, Santa Eulalia mining district, Chihuahua, Mexico</td>
</tr>
<tr>
<td></td>
<td>Page 18, in pocket</td>
</tr>
<tr>
<td>5.</td>
<td>Polished section from mine level 13 of the San Antonio mine</td>
</tr>
<tr>
<td></td>
<td>Page 27</td>
</tr>
<tr>
<td>6.</td>
<td>Photomicrograph of a portion of polished section in Figure 5</td>
</tr>
<tr>
<td></td>
<td>Page 27</td>
</tr>
<tr>
<td>7.</td>
<td>Paragenesis of minerals at the San Antonio mine</td>
</tr>
<tr>
<td></td>
<td>Page 29</td>
</tr>
<tr>
<td>8.</td>
<td>Vertical section contours of zinc/lead within the West fault for the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico</td>
</tr>
<tr>
<td></td>
<td>Page 48</td>
</tr>
<tr>
<td>9.</td>
<td>Plan projection of West fault structure contours for the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico</td>
</tr>
<tr>
<td></td>
<td>Page 49</td>
</tr>
<tr>
<td>10.</td>
<td>Vertical section structure contours for the West fault of the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico</td>
</tr>
<tr>
<td></td>
<td>Page 50</td>
</tr>
</tbody>
</table>
### LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Observed minerals in the San Antonio mine</td>
<td>24</td>
</tr>
</tbody>
</table>
ABSTRACT

The San Antonio mine, located in the Santa Eulalia mining district in the State of Chihuahua, Mexico, is a classic example of skarn and Zn-Pb-Ag sulfide replacement mineralization within Cretaceous carbonate rocks. Localized within a north-south-trending graben structure and intimately associated with felsic dikes, the nature of the orebodies is such that depositional controls are difficult to determine. Drill core and mine workings at the San Antonio mine were used to examine metal distribution by using plan and section contoured plots. Simple metal assays and ratios yielded comparable results, which demonstrate the metal zoning relative to both the dikes and the West fault. Vertical sections indicate ore-fluid movement laterally from the north and from depth. Correlation of contours with West fault structural inflections shows that the ore fluids may have been trapped and forced upward by a zone of steeper dip along the West fault.
CHAPTER 1

INTRODUCTION

The San Antonio mine, located in the State of Chihuahua, Mexico, 25 km east of the City of Chihuahua (Fig. 1), is considered the type example for chimney-manto-type silicate-sulfide replacement bodies within limestone beds. As part of the Santa Eulalia mining district, this deposit is perhaps the most familiar of all Mexican ore deposits known to economic geologists in North America.

The Santa Eulalia district appears as two distinct mineralized areas, locally termed "Camps," separated by 5 km of heretofore nonproductive ground. The central area is known as the Middle Camp. Collectively, the district occupies more than 25 km$^2$ of area. The West Camp, located in the vicinity of the towns of Francisco Portillo (formerly Santo Domingo) and Aquiles Serdan (formerly Santa Eulalia) contains the El Potosi and Buena Tierra mines, which have produced greater than 90 percent of the historic total district output (Hewitt, 1968).

The San Antonio mine, currently the only producer in the East Camp, is now the principal mine in the district. The mine together with the Buena Tierra mine is currently owned and operated as the Santa Eulalia Unit of Industrial Minera Mexico, S.A. (IMMSA).
Figure 1. Location map of the Santa Eulalia mining district, Chihuahua, Mexico. — Modified from Hewitt (1943b).
Geography and Physiography

The Santa Eulalia district lies in the northern part of the Sierra de Santa Eulalia and is one of a series of north-northwest-striking ranges found in north-central Mexico. These ranges are areally and directionally concordant with the southern extension of the Basin and Range province of southwestern United States. This subprovince is known as the northern Central Mexican Plateau (Ordoñez, 1926) and is bordered to the east and west by the Sierra Madre Oriental and Sierra Madre Occidental mountain ranges, respectively.

In contrast to the block-faulted ranges of the Basin and Range region, the ranges and valleys of the northern Central Mexican Plateau are more typically associated with asymmetrical folds and thrust faults. As with the Basin and Range province, Tertiary volcanic rocks are also present but not to the degree seen in the regions farther to the north (West Texas Geological Society, Road Log Committee, 1964). This difference is possibly related to the lesser degree of crustal fracturing in the region, i.e., horst-and-graben faulting. There is a suggestion here that Laramide postcompressional relaxation was less pronounced in the southern portion of the larger region.

The Sierra de Santa Eulalia itself is approximately 20 km in length and 11 km at its maximum width and rises more than 600 m above the surrounding valleys (de la Fuente L., 1969). The range has a mean altitude of 2,000 m above sea level. The northern portion of the range where the mines are encountered can be described as a broad, rolling upland extensively dissected by Pleistocene erosion processes to form dramatic ridges and canyons, typically with a sparse vegetative
cover, which includes ocotillo, mesquite, and various cactus varieties usual for the region.

The climate is semiarid, with rains in the summer (yearly average 17-18 inches) and occasional light snowfalls in the winter. Although the extremes range from $35^\circ C$ to $-15^\circ C$ ($95^\circ F$ to $5^\circ F$), a median annual temperature of $18.5^\circ C$ ($65^\circ F$) provides year-round comfort for the area's inhabitants.

### History

Probably first discovered circa 1591, the district as a whole has subsequently experienced large variations in mining activity. With the ores carrying no gold values and only an unattractive silver-lead content, significant exploitation of the district did not occur until the early 1700s when the first denouncements took place (Signer and Hewitt, 1952).

Most of the district history is summarized by de la Fuente L. (1969). The early boom years (1707-1790) were characterized by Spanish Colonial operators, who mined the outcropping silver-rich oxide orebodies. This was followed by an interim period of reduced output from 1791 to 1880, as the mines reached greater depths and accordingly less easily exploited ores. Political unrest associated with the war for independence in Mexico prevented the influx of technology and financing necessary for the development of these deeper ores.

The year 1880 marked the first entry of significant North American capital with the establishment of the Santa Eulalia Mining Company as an offshoot of Kidder, Peabody & Company. For numerous reasons
pertinent to the era, the mines at Santa Eulalia underwent several changes of ownership, with concurrent activity for part of that time by as many as 20 companies, mostly North American. This activity resulted in exploitation of oxide ores at greater depth. Gradually two of these companies, ASARCO Mexicana (now Industrial Minera Mexico, S.A.) and the Potosi Mining Company (now Minerales Nacionales de Mexico, S.A.) gained control of the entire district. The epoch of modern development began in 1925 when the first selective flotation plant was built, permitting beneficiation of primary sulfide ores.

Historic production data from the San Antonio mine alone are not available. According to Maldonado E. and Megaw (1983), district-wide production, from available records, has been 37 million tonnes (t) of ore, yielding 395 million ounces silver, 2.716 million tonnes lead, and 1.797 million tonnes zinc. This district has also produced 5,000 tonnes copper and 32,000 ounces gold. The San Antonio mine has also produced 4,000 tonnes tin and 700 tonnes vanadium in the period from 1927 to around 1940. Probably an additional 10 million tonnes of ore was produced but not recorded in the early years (Maldonado E. and Megaw, 1983).

Current production methods at the San Antonio mine make use of two counterbalanced ore skips and an adjacent double man and supply cage, with workings down to 15 levels and to a depth of 640 meters. With known reserves of at least 10 million tonnes laterally and at depth, the mine has an assured life well into the next century. A new mill is under construction, and conversion of the mining method to inclined ramp haulage is scheduled for completion in 1985. Average
grade of the reserves is 3.2 oz/ton (110 g/t) Ag, 2.5% Pb, 7.5% Zn, and 0.25% Cu. A historical average for the entire district is somewhat higher at 9.7 oz/ton (333 g/t) Ag, 8.4% Pb, 7.2% Zn, and copper approximately the same (Maldonado E. and Megaw, 1983).

**Previous Work**

Available geologic studies at Santa Eulalia are fewer in number than those for most other deposits of its size and importance. Early published works concerning the district have tended to be short articles that focused on the mining aspects and human interest news of the newly developing Mexican province (Adams, 1909; Argall, 1904; Burrows, 1911; Fletcher, 1929; Hill, 1903; Lakes, 1903; Merrill, 1909; Spurr, 1926; Weed, 1902).

One of the earliest, wholly geologic works on the district was that of Kimball (1870), which focused on mineralization in the West Camp. A paper by Knapp (1906) concerned, even at that early date, the curious association of structure and mineralization in the East Camp. An exhaustive paper by Prescott (1916) became the first major geologic treatise embracing the West Camp. This study, which served for many years as the main reference on Santa Eulalia geology, outlined many of the enigmatic problems that still invite study today.

In 1943, Hewitt published his doctoral study of the San Antonio mine. Twenty-five years later, in 1968, after having the benefit of many years' experience as chief geologist for ASARCO Mexicana, he published a study on the West Camp to supersede that of Prescott.
These two papers stand today as the most modern and informative geologic studies of the district.

Another contribution of Prescott (1926), however, was important in that it recognized similarities between the Santa Eulalia deposit and other carbonate replacements deposits in northern Mexico and summed up the problems that exist concerning geologic evaluation of the region. Significant advances toward finding solutions to these problems were subsequently made by Hewitt and his co-workers, but the problems themselves still remain. The current status of geologic research within the district and elaboration of these problems are the subject of the most recent publication on district geology, a 1983 paper by Maldonado E. and Megaw. This need for continued study is reemphasized. These studies have provided recognition of the direction in which geologic examination should proceed, as well as a sound, insightful basis for investigating replacement deposits at Santa Eulalia. The purpose of this contribution was to shed light on these problems.

Purpose and Scope of Thesis Study

Santa Eulalia-type deposits are more difficult to explore for and to locate than are most other types of economic sulfide deposits. A major reason for this difficulty is the lack of knowledge concerning ore depositional controls. The research here focused on further study of these controls by looking at metal zoning in the sulfides.

Metal distribution studies and statistical examinations of such are best accomplished by using large data bases, which provide a higher degree of confidence in the results. The East Camp at Santa
Eulalia, where a long mining history has provided many kilometers of mine workings and diamond core drilling, is amenable to this endeavor. Thus a fairly adequate three-dimensional picture of the mine area can be fabricated, as well as a large tabulation of assay data, from which information on the interrelationships between rock characteristics, structure, and mineralization can be extracted. In turn, this can yield clues about those geologic agents most applicable in regard to ore depositional control.

Besides ore control, geologic work at the San Antonio mine suffers from lack of knowledge concerning the source direction of the ore-forming fluids. It has been shown that a perception of the source direction can often be helpful in determining the most favorable areas for continued exploration (Gross, 1956). A past method employed to accomplish this end has been the use of metal ratios (Goodell and Peterson, 1974). Analysis of the distribution of these ratios as employed by Goodell and Peterson was accomplished by contouring the plotted ratios in planar or in volumetric space and yielded a set of roughly concentric lines or curved surfaces with the mineralizing source in the direction of the concave side. Based on the belief that changes in metal ratios are large and systematic, this is considered a viable hypothesis for single-phase systems in physicochemical equilibrium without discontinuities.

Similar techniques were employed in this study and will be elaborated upon later in this thesis.
The deposits at Santa Eulalia are characterized as massive sulfide replacement bodies occurring within the extensive carbonate strata that forms the bedrock of much of northern Chihuahua, Coahuila, and southwestern Texas. These rocks are also host to many other replacement deposits in northern Mexico, among them those at Naica, Aurora, and Los Lamentos, in the State of Chihuahua and at Mapimi in Durango. (Gutierrez and Gutierrez, 1969; Gableman and Krusiewski, 1968). Among deposits of this type in the western United States, those of East Tintic, Utah, Groundhog, New Mexico, and Gilman, Colorado are the best known. A comparison of these northern counterparts with those of the Mexican province shows that they are dissimilar in time and space relationships even though they are much the same in genetic form and type of host rock.

**Lithology and Stratigraphy**

**Cretaceous Units**

The stratigraphic column in the San Antonio mine area is shown in Figure 2, which is a composite derived from drill-hole information, mine workings, and surface mapping by the geological staff of IMMSA. The Sierra de Santa Eulalia is largely composed of thick-bedded Lower Cretaceous limestones, probably part of the Aurora Series, which is
Figure 2. Stratigraphic column of the San Antonio mine area.
well-documented to the east and north (Hewitt, 1968). The section at Santa Eulalia is represented by three formations with a combined thickness of well over 1,300 meters.

**Cuchillo Formation.** The oldest Cretaceous rocks in the district are the basal evaporitic sequence but are known in the East Camp only from drill-hole information. From lithologic similarity and stratigraphic position, these sediments have been correlated with the Cuchillo Formation known to exist in areas north of the district and are late Aptian age. At the mine the Cuchillo Formation is expressed as beds of white anhydrite alternating with narrow layers of calcareous shale. The shales are black and highly carbonaceous and locally contain abundant coral fragments and framboidal pyrite. Thicknesses for the anhydrite vary, ranging from 0.6 to 16 m, and the total thickness of the formation is at least 200 m. Minor fossiliferous limestone beds are also present.

**Glen Rose Formation.** The remainder of the Cretaceous strata in the district is slightly younger and Albian in age. Immediately overlying the Cuchillo Formation is found what is considered by many to be a Glen Rose equivalent (Hewitt, 1943b). The lowest member, resting on the Cuchillo Formation, is called the Black Limestone, which Maldonado E. and Megaw (1983) mentioned as appearing to have a gradational contact with the Cuchillo, and in fact is practically indistinguishable in composition from the black sediments of that formation.

The Black Limestone member is described as a black bituminous limestone with a compact, fine-grained texture, erratically interspersed
with minute pyrite cubes and veinlets. These characteristics indicate formation in a quiet, reducing environment. Stratification planes are not easily recognized, but numerous fossiliferous layers and thin gray limestone beds are present. The total thickness of this unit is approximately 100 m.

The upper member of the Glen Rose Formation is known as the Blue Limestone. This is the thickest and most massive member of the Cretaceous rocks found in the district and is also the most important in that it hosts most of the sulfide orebodies in the East Camp. Individual strata range in thickness from 1 to 4 m (de la Fuente L., 1969), and the total thickness of the unit ranges from 500 to 570 m.

Color of the Blue Limestone at the San Antonio mine varies from dark gray to blue, and the texture is microgranular, exhibiting very few fossils except in some of the uppermost strata. Much of the limestone shows strong recrystallization, particularly near the replacement bodies, but stratification planes remain strong. A few of the beds have a magnesium content of around 6 percent and are therefore dolomitic. The origin of these is not clear.

Lagrima Formation. Overlying the Glen Rose Formation is the Lagrima Formation, which has been arbitrarily divided into three units solely on the basis of physical characteristics (de la Fuente L., 1969; Maldonado E., 1979; Maldonado E. and Megaw, 1983). These units are called the Lower Fossiliferous Limestone, the Intermediate Limestone, and the Upper Fossiliferous Limestone. A host to only chimney ores in
the East Camp, the Lagrima Formation has also been important in the West Camp as a host to mantos.

The Lower Fossiliferous Limestone is expressed as a single massive limestone bed, light gray to white, containing no bedding planes or chert (Hewitt, 1968). Fossils are abundant, but most are difficult to identify because of the member's coarse-grained texture caused by strong recrystallization. A reducing environment of deposition is inferred for the Lower Fossiliferous beds because of a characteristic sulfide odor emitted from fresh limestone surfaces. The unit is approximately 70 m in thickness in the East Camp.

The Intermediate Fossiliferous Limestone member is a shaly, fine-grained, dolomitic, recrystallized limestone with white and black nodular chert horizons. These strata are medium bedded. The unit greatly resembles the upper portions of the Blue Limestone member in that it contains a fair amount of fossils, but it is gray to brown. Thickness range from 150 to 170 m and crops out on the surface, although only at the bottom of the deepest canyons in the northern part of the sierra.

The Upper Fossiliferous Limestone member also contains horizons extremely rich in fossils of unidentified species. These medium-to massive-bedded strata are light gray and finely recrystallized and contain discernible white chert horizons. This member constitutes practically all of the limestone outcrop found on the surface. Total thickness is on the order of 200 m in the San Antonio mine area.
Tertiary Units

A mixed group of sediments and volcanics, collectively termed the "Capping Series," overlie the Cretaceous sediments throughout the district. This package of rocks is divided by some authors (de la Fuente L., 1969; Maldonado E. and Megaw, 1983) into two subordinate series, but can be considered simply as a cyclic interlayering of conglomerates, volcanic pyroclastics, and rhyolitic flows. At least four cycles are observed, each unit with its own identifying characteristics. The oldest and only economically important unit is termed the "Basal Conglomerate." This unit is not everywhere present and apparently occurs as sedimentary wedges deposited in the deep canyons of a rugged early Tertiary paleosurface. It consists dominantly of rounded to subhedral limestone cobbles and minor amounts of andesitic volcanic fragments and chert cemented by clay (ash?) and calcium carbonate. The conglomerate is particularly important in the San Antonio mine area because it contains ore-grade chimney mineralization.

The overlying volcanics and other sediments do not host any economic mineralization and will not be discussed in detail. The percentage content of andesitic fragments in the conglomerates tend to increase upward within the individual units and within the group as a whole. The volcaniclastics, which are mostly porphyritic tuffs, also show an upward change from rhyolitic to andesitic. Thicknesses of individual units are highly variable, partly because this capping sequence appears to have been deposited upon a highly eroded, nonlevel surface and filled in the deep arroyos first, thus lessening the relief (Prescott, 1916). The younger units consequently show much smaller
variations in thickness. The representative unit thicknesses shown in Figure 2 were obtained mainly from drill-hole information.

Intrusions

It is perhaps the relationships between mineralization and intrusive phases that most strikingly differentiate the East Camp from the West Camp. A number of major igneous phases are known in the East Camp, all having some association with mineralization.

The phase most directly associated with ore occurs as a group of rhyolitic bodies (Hewitt, 1943b; de la Fuente L., 1969). These bodies occur as a series of white, compact dikes and sills, seldom exceeding 20 m in thickness, and are macroscopically porphyritic with quartz phenocrysts and an aphanitic matrix. Thin-section examination also reveals feldspar phenocrysts. Although cross-cutting relationships show that these felsic intrusive phases are not all the same age, they are the youngest intrusive phases at the mine and are genetically the most important. They frequently contain veinlets of sulfides and disseminated pyrite, and the massive sulfide and silicate bodies are spatially zoned on either side of these dikes. In the West Camp, the rhyolitic intrusions, more sill-like in occurrence, have been dated at 26.8 ± 0.6 m.y. B.P. (Shafiquallah, Damon, and Clark, 1983). It is speculated that the felsic intrusions in both camps are cogenetic.

A series of diabase sills are also present throughout the district; drill-hole information shows that these sills take the form of a complex series of flat-lying, parallel and intertwining sheets ranging in thickness from 1 to 15 m. Mineralization is present below, above, and
between many of these sills. Cross cut by the felsic dikes, both of these intrusive phases apparently created or followed the channels associated with the ore fluids that subsequently passed along their margins.

A few drill holes in the West Camp of the district have penetrated a large crystalline igneous body at depth (Hewitt, 1968) and modally appear to be a quartz diorite porphyry. Zoned plagioclase phenocrysts, quartz, hornblende, and some potassium feldspar constitute the rock, which also shows some substantial amounts of the alteration phases, sericite, chlorite, calcite, and disseminated and veinlet pyrite. Potassic alteration is indicated by the presence of abundant secondary potassium feldspar. There is also almost certainly potassium depletion in zones of higher fracture density associated with pyrite mineralization. Although minor sphalerite, galena, and chalcopyrite have been observed within the cores (Hewitt, 1968), any direct association with the ore mineralization remains speculative.

Existence of the intrusion beneath the East Camp is also speculative. It has not been penetrated by drilling in the San Antonio mine, but indirect evidence allows the possibility of its presence. Hewitt (1968) noted that the igneous body intrudes the West Camp from the southeast toward the San Antonio mine. More compelling support was presented by Aiken and others (1981), whose regional aeromagnetic studies of the State of Chihuahua showed a strong positive anomaly centered on the mining district. This finding suggests that an intrusive body of some type may underlie the district (Maldonado E. and Megaw, 1093).
Structure

The rocks constituting the Sierra de Santa Eulalia are broadly folded in a gentle north-south-trending anticline (Prescott, 1916). The beds have very shallow dips, with the mining areas on opposite flanks of the structure. The western edge of the sierra is a truncating fault-line scarp with at least 1,000 m of offset (Hewitt, 1968). The adjacent plains of Chihuahua City are found immediately west of this prominent feature. On the eastern side, east of the San Antonio mine, the beds of the sierra dip sharply beneath the Conchos River valley sediments.

The mineralization of the East Camp is confined within a north-south set of normal faults known as the San Antonio graben (Fig. 3 and Fig. 4, in pocket). Hewitt (1943b) estimated that the vertical displacement of this graben is between 150 and 250 m. The western wall of the graben, known locally as the West fault, is a single normal fault with a steep eastward 60-degree dip, which varies slightly. The eastern wall of the graben is formed by two west-dipping faults, not everywhere traceable, which are more complex in their interrelationship and exhibit a scissored rotational displacement centered in the mining area (Hewitt, 1943b). The two faults, called the Central fault and the East fault, overlap parallel to the graben axis, with the northern end of the Central fault veering westward toward the central area of the graben prior to disappearing altogether.

Prescott (1916, 1926) and Hewitt (1968) have theorized that this north-south structural trend is related to the north-south folding. Figures 3 and 4 show that numerous lesser faults, many with the same
Figure 3. Cross section of the San Antonio graben.
Legends

**Lithologic Units**

- **Quaternary**
  - Qal: Alluvium and talus, Recent gravels

- **Tertiary**
  - Tva: Andesitic volcanic tuffs and flows undifferentiated
  - Tfr: Rhyolite flows
  - Tcp: Basal Conglomerate calcareous
  - Tf: Felsite dikes, some porphyritic
tiles
  - Td: Gneissite and diabase sills

- **Cretaceous**
  - Kis: Limestone undifferentiated units

**Symbols**

- Mine shaft, numbered levels
- Sulfide bodies and stopes
- Oxide stopes
- Lithologic contact dashed where approximated
- Fault or fracture arrows indicate relative movement

Scale 1:5000

**Location**

Looking North of the San Antonio graben. -- Modified from Maldonado E. (1979)
north-south trend, are recognizable throughout the graben area. These lesser faults are accordingly thought to be part of a series of fractures formed in response to the tensional forces created by the folding event. Alternatively, Maldonado E. (1979) suggested that the north-south trend in the area of the East Camp is related to intrusive emplacement occurring at moderate depth, and that the fractures formed in response to pressures created by such an event. It thus remains possible that both hypotheses are likely, as has often proved to be the case with tectonic and igneous activity.

An east-west fracture trend, represented by a major rhyolitic porphyry dike, known as the Middle Camp dike, immediately adjacent west of the graben (Fig. 4, in pocket), may be the result of similar tension in a north-south direction. The doubly plunging nature of the anticline (Maldonado E. and Megaw, 1983) may also be the result of emplacement of an intrusive body at depth. Very little exploration work has been performed along the Middle Camp dike, but what few drill holes have crossed the structure did not intercept any mineralization or promising alteration.

Mineralization

Occurrence

Orebodies at Santa Eulalia occur as chimney- and manto-shaped bodies within the host carbonate rocks. Curiously, the literature has held a continuing argument on the definition of these terms, and the most controversial point concerns the relationship of the orebodies to the attitude of the host strata. The following quotation represents
Prescott's (1926, p. 248) definition of those deposits as seen in the West Camp:

The orebodies occur in pipes and chimneys, and in mantos or flats and runs; and, as the limestone lies nearly horizontal, the chimneys are those that cross the beds, the mantos those that follow more or less along the bedding, though frequently jumping from one bed to the next higher one. The chimneys vary considerably in size and are extremely irregular in shape.

Hewitt (1943b, 1968) elaborated further, noting that as a rule mantos and chimneys are roughly circular in cross section and generally have a much greater length than width. Ambiguity exists only where the orebodies are inclined, and Hewitt has dealt with this by defining mantos as those that are approximately horizontal, regardless of the dip of the host strata and chimney as those orebodies that are approximately vertical.

In the San Antonio mine, most of the ore has been mined from chimneys and steep vein-form replacement bodies. Small mantos are present, mostly in the upper levels of the mine. These generally have been found to originate from the larger mantos (Hewitt, 1943a, 1943b) and tend to be lead rich and subordinate in economic importance (Maldonado E. and Megaw, 1983).

As mentioned previously, deep drilling has shown that a number of nearly horizontal orebodies exist in association with the diabase sills. These are tabular calc-silicate and sulfide mantos that parallel the sill contact, very much like those of the West Camp. Many have entirely replaced the thickness of limestone between parallel sills, whereas other interlayered limestone beds were apparently unfavorable for any replacement. All of these sill-associated orebodies seem to be continuous
but of variable thickness along their length. They sometimes split to follow the upper and lower sill contacts and occasionally recoalesce to full thickness or pinch out altogether.

The chimneys at the San Antonio mine are intimately associated with the rhyolitic dikes and take the form of tabular massive sulfide and calc-silicate bodies with a distinct zonation outward from the dike. In general, calcic skarns are found immediately adjacent to the dikes. These skarns often yield to massive sulfide mineralization, commonly zinc rich, which abuts against clean limestone. Maldonado E. and Megaw (1983, p. 373) indicated that these contacts often possess "a 1 cm thick bleached and recrystallized selvage that gives way to recrystallized, but otherwise megascopically unaltered, limestone." No other alteration effects within the limestone are seen.

Mineralogy

Mineral assemblages at the San Antonio mine are typical, both genetically and regionally, of those established in the literature for deposits of this type. The anhydrous silicate phase and sulfide phase assemblages found here fit well the classification established by Einaudi, Meinert, and Newberry (1981). This fit would categorize orebodies at the San Antonio mine as a zinc-lead skarn formed in proximity to an igneous dike. The realization that the dike associated with ore at the San Antonio mine is too narrow to have produced such quantities of skarn is important. It is more likely that the dike provided the channelways for mineralizing fluids originating at moderate distance and depth. If a magmatic source for these fluids is assumed, they were
possibly cogenetic with such an igneous body. Most notable, however, are those characteristics of the San Antonio deposit that deviate from those established for chimney deposits by the aforementioned investigators.

The most significant difference is the extraordinary size of this deposit. Total ore tonnage is in excess of 10 million tonnes, readily eclipsing the chimney deposit size typical for orebodies of this type, which commonly falls in the range of 0.20 to 2.70 million tonnes. No significant difference in grade is observed for the deposit as a whole, although zinc grades have increased with depth and silver has correspondingly decreased. For current reserves, zinc-to-lead ratios are markedly higher, but, again, for the overall deposit they may be close to a normal 1:1.

Primary silicate minerals observed at the San Antonio deposit are manganese rich and magnesium poor. Iron is an important constituent. In abundance typically are manganoan hedenbergite, ferroactinolite, chlorite, grossular and andraditic garnet, and rhodonite.

Massive silicate bodies commonly show a crude horizontal zoning relative to the dike. In many places a zone of massive, fine-grained epidote, usually with chlorite and fluorite, can be found immediately adjacent to the dike (Hewitt, 1943b; Maldonado E. and Megaw, 1983). This zone grades outward into a varying mixture of hedenbergite, actinolite, and grossular garnet, with hedenbergite and garnet increasing away from the dike. However, small amounts of fluorite and chlorite can still be found at considerable distances from the dike, and quartz and calcite are ubiquitous throughout.
The dike contact is often obscured by the silicate zoning, and the dike may show intense kaolinitization (Hewitt, 1943b). The felsite may exhibit a green epidote color or be nearly white, has an aphanitic texture, and is commonly impregnated along fractures with sulfides and fluorite. Some areas of the dike contact show a much coarser texture and a greater variety of mineral assemblage, notably a "ruby jack" sphalerite and large blebs of chalcopyrite, both of which are atypical.

Sulfide minerals include iron-rich sphalerite as the main zinc ore, galena, pyrrhotite, pyrite, chalcopyrite, and some arsenopyrite. A list of observed minerals is given in Table 1. These minerals generally occur as massive replacement bodies with each constituent present in varying percentages. Textures appear to coarsen away from the periphery of any one sulfide mass, an observation that indicates that recrystallization of the sulfides occurred as part of the replacement process.

Zoning of the sulfides is not visually apparent, but mineralogical associations are discernible. Sphalerite tends to occur with pyrrhotite, chalcopyrite, and galena and becomes more massive with depth, almost to the exclusion of other sulfides. Much of the galena is apparently argentiferous and is associated with sphalerite and chalcopyrite. Some of the galena is accompanied by sulfosalts of silver. Chalcopyrite is less abundant than either sphalerite or galena and is most readily seen as an exsolution mineral within sphalerite. Massive blebs are common where sulfides are in contact with the dike. Fluorite is a common gangue mineral.
Table 1. Observed minerals in the San Antonio mine. -- Modified from Clanton (1975) and Prescott (1916)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
<th>Mineral</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphalerite</td>
<td>ZnS</td>
<td>Arsenopyrite</td>
<td>FeAsS</td>
</tr>
<tr>
<td>Galena</td>
<td>Pb</td>
<td>Marcasite</td>
<td>FeS₂</td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td>CuFeS₂</td>
<td>Magnetite</td>
<td>Fe₃O₄</td>
</tr>
<tr>
<td>Pyrrhotite</td>
<td>Fe₁₋ₓS</td>
<td>Cassiterite</td>
<td>SnO₂</td>
</tr>
<tr>
<td>Pyrite</td>
<td>FeS₂</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Hypogene Minerals**

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cerrusite</td>
<td>PbCO₃</td>
</tr>
<tr>
<td>Limonite</td>
<td>FeO(OH)•nH₂O</td>
</tr>
<tr>
<td>Anglesite</td>
<td>PbSO₄</td>
</tr>
<tr>
<td>Mimetite</td>
<td>Pb₅Cl(AsO₄)₃</td>
</tr>
<tr>
<td>Azurite</td>
<td>Cu₃(CO₃)₂(OH)₂</td>
</tr>
<tr>
<td>Plattnerite</td>
<td>PbO₂</td>
</tr>
<tr>
<td>Pyrolusite</td>
<td>MnO₂</td>
</tr>
<tr>
<td>Vanadinite</td>
<td>PbH₅(VO₄)₃Cl</td>
</tr>
<tr>
<td>Siderite</td>
<td>(Fe₂Mn)CO₃</td>
</tr>
<tr>
<td>Rhodochrosite</td>
<td>MnCO₃</td>
</tr>
<tr>
<td>Goslarite</td>
<td>κ(Zn,Fe)SO₄•7H₂O</td>
</tr>
<tr>
<td>Gypsum</td>
<td>CaSO₄•2H₂O</td>
</tr>
</tbody>
</table>

**Oxidation Minerals**

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemimorphite</td>
<td>Zn₄Si₂O₇(OH)₂•H₂O</td>
</tr>
<tr>
<td>Hematite</td>
<td>Fe₂O₃</td>
</tr>
<tr>
<td>Smithsonite</td>
<td>ZnCO₃</td>
</tr>
<tr>
<td>Malachite</td>
<td>Cu₂CO₃(OH)</td>
</tr>
<tr>
<td>Brochantite</td>
<td>CuSO₄•3Cu(OH)₂</td>
</tr>
<tr>
<td>Chalcantite</td>
<td>CuSO₄•5H₂O</td>
</tr>
<tr>
<td>Psilomelane</td>
<td>Mn oxides</td>
</tr>
<tr>
<td>Melanterite</td>
<td>FeSO₄•7H₂O</td>
</tr>
<tr>
<td>Manganite</td>
<td>MnO(OH)</td>
</tr>
<tr>
<td>Hydrozincite</td>
<td>Zn₅(CO₃)₂(OH)₆</td>
</tr>
<tr>
<td>Cerargyrite</td>
<td>AgCl</td>
</tr>
<tr>
<td>Calcite</td>
<td>CaCO₃</td>
</tr>
<tr>
<td>Mineral</td>
<td>Formula</td>
</tr>
<tr>
<td>---------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td><strong>Hypogene Silicate and Gangue Minerals</strong></td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td>SiO$_4$</td>
</tr>
<tr>
<td>Hedenbergite</td>
<td>(Ca,Fe)SiO$_3$</td>
</tr>
<tr>
<td>Orthoclase</td>
<td>KAlSi$_3$O$_8$</td>
</tr>
<tr>
<td>Grossularite</td>
<td>Ca$_3$Al$_2$Si$<em>3$O$</em>{12}$</td>
</tr>
<tr>
<td>Cummingtonite</td>
<td>(Mg,Fe)$_2$(Si$<em>8$O$</em>{22}$)(OH)$_2$</td>
</tr>
<tr>
<td>Epidote</td>
<td>Ca$_2$(Al,Fe)$_3$(SiO$_4$)$_3$(OH)</td>
</tr>
<tr>
<td>Actinolite</td>
<td>Ca$_2$(Mg,Fe)$_5$Si$<em>8$O$</em>{22}$(OH)$_2$</td>
</tr>
</tbody>
</table>
Pyrrhotite is widespread in occurrence and appears to increase in abundance with depth, although it remains secondary to sphalerite. Pyrrhotite is commonly found with pyrite.

Contact relationships between silicates and sulfides and the host rock are variable. Skarns commonly contain disseminated sulfides, usually sphalerite with some galena, which are contained within grain interstices and minute fractures (Muñoz C., 1978). The sulfides within the skarn commonly grade into massive sulfide mineralization, frequently on the outer fringe of the replacement bodies. A fair amount of silver is tied up within the silicate masses, which are mined as ore.

In some places sulfide mineralization can be found cross cutting silicate bodies (Figs. 5 and 6). Contacts between silicates or sulfides and the limestone host are always razor sharp. Sulfide bodies, even though zinc rich, very commonly show a pyrrhotite selvage at this contact.

Quartz, calcite, and magnetite, as well as fluorite, are main accessory minerals of the San Antonio deposit and are of secondary importance in hand specimen. Most quartz appears to be younger than the sulfides and skarn but in some places exhibits contemporaneous relationships (Hewitt, 1943b; Clanton, 1975). Muñoz C. (1978) and Torres A. (1982) both interpreted that quartz occurs exclusively as a postore event simultaneously with the introduction of silver sulfosalts. Clanton (1975), however, from his thin-section study, indicated that formation of quartz was continuous from the earliest periods of skarn formation.
Figure 5. Polished section from mine level 13 of the San Antonio mine. -- Cross-cutting relationship between the skarn and sulfides can be observed. Mexican coin is 20 mm in diameter.

Figure 6. Photomicrograph of a portion of polished section in Figure 5. -- Chalcopyrite is feathering into and replacing silicates. Galena is replacing sphalerite as seen in lower right quadrant.
White calcite is ubiquitous as small veinlets and blebs, but age relationships are not conclusive. Calcite was apparently introduced as a postskarn event, yet earlier or at the same time as quartz. The relationship of the calcite to sulfide deposition is also unclear. Some earlier calcite veinlets may very well be secondary.

Magnetite is in minor abundance. According to Hewitt (1943a, 1943b), magnetite is associated with calcite veinlets and, at least on some of the deeper mine levels, also occurs separately as acicular blades in veinlets and small masses. Magnetite has not been found within the sulfide bodies but does accompany fluorite where sulfides are found in contact with the dike.

Paragenesis

Studies of the paragenesis at the San Antonio mine include those of Clanton (1975), Muñoz C. (1978), and Torres A. (1982). The observed sequence is shown in Figure 7. Calcic silicates, undifferentiated, formed as an early stage and are barely overlapped by the earliest phases of the sulfide stage—arsenopyrite and pyrrhotite. The main period of sulfide deposition was dominated by sphalerite and galena, with earlier appearances of pyrite and chalcopyrite. Quartz, fluorite, and calcite were deposited as post-sulfide phases, probably along with sulfosalts of silver. Torres A. (1982) indicated that the sulfosalts were contemporaneous with late quartz, followed later by fluorite and calcite.
<table>
<thead>
<tr>
<th>Mineral</th>
<th>Period of Skarn Formation</th>
<th>Period of Sulfide Deposition</th>
<th>Late Hydrothermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicates</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arsenopyrite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrrhotite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marcasite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sphalerite</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Galena</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfosalts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calcite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluorite</td>
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</tbody>
</table>

Figure 7. Paragenesis of minerals at the San Antonio mine. -- Modified from Torres A. (1983) and Muñoz C. (1978).
Oxidation

Oxidation of the orebodies has occurred through the upper eight mine levels to a depth of approximately 350 m. A multitude of minerals has resulted from this process, and most are predictable, given the hypogene assemblage. Table 1 shows a partial list of these oxidation minerals. Polymorphic calcite and iron oxides are ubiquitous in these upper mine levels, and manganese oxides are also quite common. At the base of the oxides, a narrow supergene zone of covellite and bornite is observed.

The San Antonio mine is famous for its producible quantities of tin and vanadium from orebodies in the upper mine levels. These discoveries were the first economically important tin-bearing orebodies mined in North America (Hewitt, 1943b). Tin occurred as a fine-grained cassiterite \((\text{SnO}_2)\), a hypogene ore mineral, and assayed an average 1.5\% Sn in the main stopes. The genesis of this primary tin mineralization has been a major subject of hypotheses for many decades.

Commercial vanadium mineralization, according to Hewitt (1943b), was a direct result of secondary concentration of the element during oxidation. Vanadium-bearing silicates and sulfides are proposed as the source, but no primary vanadium-bearing mineral has been identified. Vanadinite \((\text{Pb}_5(\text{VO}_4)_3\text{Cl})\) is the identified ore mineral.

The thesis study was not vitally concerned with the oxidized portions of the orebody, except in the above-mentioned areas. Prescott (1916) believed that significant redistribution and depletion of metal constituents occurred during oxidation. Metal distribution analyses such as for this thesis, considered for diagnosis of source direction,
would not likely yield dependable results in the oxidized portions of the orebodies.
CHAPTER 3

CONTOURS AND METAL RATIOS

Metal ratios have been applied at the San Antonio mine as a tool for determining zoning within the mine. In general, this method involves only simple ratioing of the weight percent assays of the major elements as sampled within the mine. Unlike the ratioing procedure often applied to deposits, such as Mississippi Valley-type deposits with only a very few major sulfide phases, the procedure employed in this study does not use ratios of single element percentages of total sulfides. Complex mineralogy precludes such practice. However, percentages relative to other individual element percentages were used and still provide useful zoning information.

Assaying and ratioing for the elements lead, zinc, copper, iron, and silver are common practice. Although assays for precious metals such as silver are given in mass per unit mass rather than weight percent, they may still be ratioed directly with other phases because only the relative differences are important for interpretation.

For any pair of metal values within an assay, the ratios are plotted spatially and the values contoured. These contours are lines of isomorphic variation related directly to the environment of deposition. In fact, it is mostly the chemical controls of this environment that influence the relative phase percentages. Often these contour lines are concentric in some degree, and this concentricity has been interpreted
to be representative of the fluid path or paths, with the convexity of the contours occurring in the direction away from the source.

An adequate understanding of the orebody, as obtained from other sources of geologic information, is vital to the interpretation of metal ratios. The paragenesis is necessary for comparing mineralogic changes to ratio changes and for determining relative quantities of sulfide phases. Some knowledge of those structural and chemical processes that were at work during ore genesis is necessary for accurate interpretation of the results. This need is well illustrated by Goodell and Petersen (1974) in their study at Julcani, Peru, where the maxima and minima that can be seen in the ratios reflect zones of optimum or deficient conditions for deposition, respectively. It is not clear what is the cause of this nonmonotonic directional change. The change could be the result of subtle chemical changes or of more dynamic processes such as multiple and telescoped periods of deposition. Postore structural complexity may also play a part, and only at times can all these interactions be resolved.

It is apparent then that the deposit type itself also plays an important role in ratio interpretation. Goodell and Petersen (1974), in applying metal ratios to vein systems at Julcani, Peru, found that the lead-copper ratio served as a useful zoning index for the district. Both elements are in large abundance at Julcani. However, because the San Antonio deposit is a low-copper system, this ratio has not proved extremely useful. Vein systems, it appears, generally rely on a different set of physical and chemical processes for depositional control where the important operative controls are open-space filling and limited
gangue mineralogy. In contrast, replacement deposits are characterized by solid-solution chemical processes involving a diverse silicate gangue accompanied by sulfides. Both types thus may yield erratic metal distributions, but for different reasons, and so these reasons must be considered in interpretation.

**General Theory**

Considering the potential usefulness of metal ratios as a tool for exploration, relatively little has been published about the method. Although many researchers have studied typical ratios for respective deposits and districts, extensive zoning studies for type deposits remain lacking. Brown (1935) was the first to provide an application involving metal ratios. Examining zoning in carbonate replacement deposits at the Austinville mine, Virginia, he showed systematic change with depth by simply graphing averaged assay ratios along mine drifts and crosscuts. Importantly, Brown noted that, although the graphs indicated that the ratios were erratically distributed, a general trend was nevertheless distinguishable.

Similar results were obtained by Goodell and Petersen (1974), who used a sophistication of this technique. They employed contouring as a means of extracting further information from the ratios. This method allowed the researcher to observe changes more easily and in two dimensions rather than one. The contouring also had the effect of smoothing out the erratic nature of the ores without camouflaging the important changes.
Irrespective of the graphical technique employed, metal ratios have been credited with an advantage over the use of simple metal assays in that they may help in determining directions of change within an orebody. Past studies have shown that changes in metal values are often related more to preore structural inhomogeneities than to chemical changes. As explained by Goodell and Petersen (1974, p. 347) "high metal values reflect areas where veins are unusually wide or the ground more strongly fractured, and consequently where a large amount of sulfide was deposited." More specifically, metal assays alone are much more strongly influenced by individual sample size than are relative percentages of the same assays.

Metal ratios of major elements are by comparison believed to be largely independent of structural features and accordingly are representative only of the physicochemical conditions present. Considering a hydrothermal fluid moving through a gradient of these conditions, metal ratio changes can be assumed to result from mineralogic changes and variations in the relative amounts of phases occurring within the fluid. The physical conditions are influenced largely by the external medium, whereas changes in the chemical conditions are due mainly to local variations in host-rock lithology.

More can be said specifically about replacement deposits in carbonates. Chemical fluctuations within the gradient of change in conditions account for much of the erratic nature of the assay values. These fluctuations are most probably due to precursor skarns and to undefined "favorable beds" within the carbonate sequence. Numerous researchers of skarn deposits (Umpleby, 1916; Rose and Burt, 1979;
Einaudi and others, 1981) have noted that sulfide orebodies are commonly found restricted to a zone within or along the contacts between skarn bodies and their host carbonates. There is much evidence for this same skarn-sulfide-limestone relationship at the San Antonio mine. The skarns appear to have served as a barrier that insulated the late acidic, sulfide-rich hydrothermal fluids that passed through them from the host carbonates. In those places where the fluids encountered the limestones, they were presumably neutralized and thereupon dumped their sulfides.

Rose and Burt (1979) cited a number of contributing factors in support of this spatial relationship. One observation was that the later ore-bearing solutions generally must use the same channelways, i.e., plumbing system, as did the skarn fluids. The skarns thus may have further prepared the ground for the later ore solutions through such items as volume decrease, coarsening, and increased vugginess. Consequently, the silicates may exert textural and chemical controls on later ore deposition through buffering processes.

A common tendency for manganiferous hedenbergite and sphalerite to occur in close proximity has long been noted by such authors as Allen and Fahey (1957), Burt and Petersen (1974), and Yun and Einaudi (1982). This tendency was also observed in experimental studies by Zharikov (1970) and Burt (1972). Burt suggested that the retrogressive breakdown of hedenbergite, which contains ferrous iron, might tend to reduce the ore-bearing fluids that pass through them and thus lower the solubility of sphalerite and induce precipitation. Yun and Einaudi (1982), however, noted that more recent experimental
studies (Burton, Taylor, and Chou, 1982; Gamble, 1982) would suggest that these reactions are much more complex and that deposition may in part be aided by an inherent low oxidation-sulfidation state of the hydrothermal solutions. Quantitative evaluation must await additional geochemical research.

The nature of replacement is suggested as being subtly controlled by structural discontinuities and dramatically controlled by changes in pressure, temperature, and chemistry. Sharp structural features and periodic lithologic and pressure-temperature fluctuations account for variability among the assay values. Contouring helps smooth these erratic points and thus delineates trends, which are accordingly useful in determining fluid paths. However, replacement is a relatively slow, solid-state process, which does not always maintain a two-dimensional form permitting easier analysis.

**Procedure**

The distinct north-south trend of the mineralization at the San Antonio mine may be assumed to have the graben structure as a districtwide control. The degree of influence allotted this structure is the subject of four or five hypotheses. Ore fluids entered the ore zones from the north, the south, from directly below, or perhaps from some combination of these directions. The purpose of this study was to determine which hypothesis gains most support from metal zoning and to determine the subsequent implications for exploration at the mine.

For studies of this type, it is generally desirable to have a large number of metal assays covering the volumetric space of the
orebody. Previous ratio studies have variously satisfied this need through the use of rotary drill samples (Brown, 1935), ore inventory block averages (Goodell and Petersen, 1974), or ore shipment records (Sims and Barton, 1962) or by using the reported annual mine production statistics (Shimazaki, 1975). At the San Antonio mine, diamond drill core assays, supplemented by chip-channel sampling, were employed by me for this purpose.

Goodell and Petersen (1974), again in their study at Julcani, Peru, utilized ore inventory records as their source of data. They took advantage of the standard mine practices in which weight averages of 5 to 50 individual grab samples were taken as representative of ore blocks, typically 20 by 15 m in vertical projection. At the San Antonio mine, these types of records were not easily available, nor did those that were available appear adequate for these purposes. However, the mine has been subjected to an extraordinary amount of drill sampling with routine assaying for silver, lead, and zinc and often for copper and iron. Typically, these holes were drilled in fan-shaped arrays, each core assayed in intervals the length of the sulfide ore intercepts. Separate assays were usually run for the skarn ores. In this study, weighted averages were calculated for those holes in reasonable proximity. Over half of the assay data was obtained in this manner, and a total of 342 sample points from levels were accumulated.

The inadequate coverage of some mine areas by drilling prompted a program of systematic chip-channel sampling on mine levels 8 through 14, excluding level 9. Those samples collected were assayed
by the company laboratory for weight percent of lead, zinc, copper, and iron and for g/t of silver. A total of 160 were collected.

In addition, 27 limestone samples adjacent to ore zones were obtained. This random sampling did not yield any statistically reliable data for metal ratios. This result lends support to the existence of threshold limits for detection of ore zones and illustrates the knife-edge character of the orebodies. Only the sulfide and silicate samples were adequate for use in this study.

Even though sample density at the San Antonio mine was determined by block size, it was ultimately controlled by accessibility and economic considerations. An irregular drilling density and regular chip sampling combined to establish arbitrarily set, uniform ore blocks of size 25 by 50 m in vertical projection. The data set of 308 averaged points is given in Appendix A. The two types of data were sampled irrespective of their lithologic or structural association. Therefore, it is assumed that no significant differences are present in the arithmetic means and variances to an extent that might warrant treating the samples separately.

Nevertheless, blocks with an abundance of drill information may be considered to have a fairly small confidence interval, whereas those that have just a few drill-hole or chip-channel samples have a greater confidence interval. Predictably, the less densely sampled blocks usually occur on the fringes of the mine area. No attempt was made to equalize the confidence intervals across the entire set of samples.

Goodell and Petersen (1974) noted two considerations associated with the use of averaged data. The first concerns whether a bias
exists due to the cutoff grade's excluding part of the mineralized area. The second bears upon data averaging and whether it masks important variations in zoning that might otherwise be observed.

Regarding the first, Goodell and Petersen (1974) found no significant differences in ratios between ore and poorer grade material within the vein. Mathematically, this observation can be interpreted to say that, although the sampling distribution employed is truncated, it is of no consequence in zoning interpretation because the total distribution patterns are unimportant. Only the relationships between the accessible individual sample points are relevant. This analysis also holds true for the separate sampling populations of sulfide and silicate ores at the San Antonio mine. No differences are apparent statistically between the metal ratios of the two types. This conclusion might be arrived at intuitively, if the sharp contacts of the orebodies are considered, and offers evidence of a contemporaneous origin for the massive sulfide bodies and the sulfides found distributed within the silicates.

In answer to the second consideration, the most important factor bearing on the effect of averaging appears to be block size. Goodell and Petersen (1974) concluded that the ore-block size used in the Julcani study, i.e., the assigned area of influence of the averaged assay, was sufficiently small to preserve the character of the ore zoning within the district. It is prudent to point out here that this area of influence also depends on the purposes of the study and that the scale thus considered is important to determine significance. In this study of the San Antonio mine the scale is deposit wide, and only the major variations are necessary for the study purposes.
Both simple metal values and ratios of metal values gathered at the San Antonio mine have been plotted and contoured as the major instruments of analysis. Those plots have been constructed horizontally, superimposed on plan maps of mine levels 8 through 14, and vertically, with data points projected to the vertical plane. Projected points nearer than 3 m to each other have been averaged for simplicity.

An attempt has been made to locate the plane of projection concordantly with the main felsic dike bodies and the West fault. Therefore, vertical plots are not strictly vertical. This plotting method is important interpretively, because the fluids apparently used the dikes and fault as their main plumbing system and individual dikes may exhibit their own zoning pattern. The method has, however, introduced a mildly subjective process into the construction of the plots, with the attempt made to segregate assays to individual conduits. Also, mantos originating off of the ore chimney maintain a separate zoning pattern that may confuse the vertical contours if not filtered out. Only those assays in close proximity, within 25 m of the projection plane, have been utilized. Because the vertical plots have been projected and sometimes translated, they do not always directly agree with the corresponding mine level plot.

Criteria for determining the location of contour lines are relatively simple. Plots of the point assays reveal clusters of similar assays with only occasional spurious points. I have not endeavored unnecessarily to link separate but similar assay zones, because this linkage may or may not be geologically warranted. Some mine areas were not mineralized adequately enough to permit comprehensive
coverage of the entire mine level, and contours are dashed to show interpretive connections. Contours thus reveal a general depositwide zoning but do not imply that the entire area of contouring is ore material. Also, the assumption may not be made that this zoning pattern is exhibited everywhere within the orebody.

Results

Data have been plotted for each metal and for 10 simple ratios: silver/lead, silver/zinc, silver/copper, silver/iron, lead/copper, zinc/lead, zinc/copper, iron/lead, iron/zinc, and iron/copper. Although all plots have yielded some information, only the most satisfactory representatives are presented. Those contours involving iron have been excluded from this presentation because the number of assays for this metal are only marginally acceptable statistically. I believe that the small number of assays has introduced an unacceptable level of subjectivity into the contoured results for iron. The number of copper assays is also questionable, and only the lead-copper ratio is presented. These plots are shown in Figures B-1 to B-33 (Appendix B).

Plan Contours

Plan contours for mine levels 8 through 14 are presented in Figures B-1 through B-6 (Appendix B) for silver, Figures B-8 to B-13 (Appendix B) for lead, Figures B-15 to B-20 (Appendix B) for zinc, and Figures B-24 to 29 (Appendix B) for lead-zinc ratios. Distinct zoning relative to the felsic dikes is evident in all metals and ratios. In general, contour values near the felsic dikes are lower but are higher in the areas between and with distance from the dikes. Silver
exhibits an ambiguous relationship but tends to have higher values nearer the dikes.

Continuity between mine levels is erratic. Plots of silver, lead, and zinc assay values depict a very rapidly changing fluid orebody with numerous arms and only subtle control. The erratic nature may be expected for these orebodies. Zinc contours in particular, however, may be reservedly correlated between mine levels. Although generally still characterized by shapelessness, zinc contours develop a sinuous form, which varyingly widens and then constricts from mine level to mine level. This characteristic is representative of the ore chimney as could be defined by contours of the high metal values.

Correlation between mine levels is much more distinct in the plots of the metal ratios. Illustrated by that of Zn/Pb (Figs. B-24 to B-29, Appendix B), low ratio values are again associated with the felsic dikes, but more importantly, high values accompany the West fault. A relationship between the fault and mineralization is thus evident. These ratio contours also again illustrate the amorphous, chimney-form orebody shape with delicate depositional control.

Metal Value Vertical Section Contours

Zone patterns are remarkably exposed, perhaps unusually so, in the vertical plots of individual metals (Figs. B-7, B-14, B-21 to B-23, and B-30 to B-33, Appendix B). The contours show a narrowing of the orebody at depth. All contours for the five metals reveal the presence of a transmuted zone, an area of change in the nature of the contours located approximately between mine coordinates 2100N and
2200N in the upper portions of the mine and widening upward and to the north. Outside this area, to the north and south, contours appear to be nominally similar.

This transmuted contour zone is well exemplified by the lead contours shown in Figure B-14 (Appendix B). Lead zoning is roughly concentric in vertical section, with the lowest values centered at depth between mine coordinates 2125N and 2225N, with the highest values on the fringes of this transmuted zone. Downward to the north the contour values again progressively diminish.

Most of the metal value contours exhibit a general orientation that is linear and rising to the north. This observation may be interpreted in two ways. With regard to fluid direction of the mineralizers, contours for silver, lead, and iron (Figs. B-7, B-14, and B-23, Appendix B) appear to be convex upward and to the north. This characteristic implies fluid movement in that direction. All metal contours also show a concavity downward to the north. This finding indicates universal support for the hypothesis of fluid movement upward and to the south. However, contours for zinc and copper (Figs. B-21 and B-22, Appendix B) are more subtle in their concavity in this direction. Bar- ring knowledge of multiple events, actual metal value contours presented support the hypothesis that ore-fluid introduction occurred from depth directly beneath the study area and from the north.

Metal Ratio Vertical Section Contours

Metal ratio vertical sections (Figs. B-30 to B-33, Appendix B) provide similar results. Even though definite zoning patterns are
exhibited, interpretation concerning fluid movement is speculative because of the ambiguous differences between various plots. Contours for silver/lead (Fig. B-31, Appendix B) and for silver/zinc (Fig. B-32, Appendix B) show clear indications of fluid invasion from beneath the ore zone, but the contour for lead/copper (Fig. B-33, Appendix B) suggests introduction from the north at depth. Zinc/lead contours (Fig. B-30, Appendix B) possess concentric, convex traits that would probably support an interpretation of fluid introduction laterally from the north. Zinc and lead are the two most abundant metals at the San Antonio mine, and for that reason the zinc-lead ratio is considered probably the most reliable of the ratios contoured.
CHAPTER 4

DISCUSSION

**Structural Integration**

Spatial comparisons between the contours of the different metals and ratios of metals has raised the question concerning the effects of structural features upon the zoning. To better define this relationship a detailed examination has been undertaken of the West fault in the vicinity of the mine. For various reasons, the West fault is considered most appropriate for this endeavor because it is the major and most important structural feature. Sympathetic and adjacent faults and fractures have not been examined nor have the felsic dikes. Even though the dikes maintain the most intimate spatial and possibly genetic relationship to the mineralization, they are not continuous or everywhere identifiable for structural correlation. The West fault has thus far been considered to have had only indirect influence on the ore fluids.

Field relationships at the surface as well as underground support the hypothesized relative ages of ore, faulting, and igneous intrusion. The fault is a preore, prediking event without significant postore movement as determinable from offsets, slickensides, or other features. This fault relationship has permitted a simpler interpretation. The metal ratio vertical section contours were constructed as projections to an imaginary plane along the strike of the felsic diking, subparallel to the fault. The amount of influence that the fault may have exerted
upon zoning is masked by the dike influence. In an attempt to recover this last influence and to filter out the effects of the dike zoning, the vertical section of the zinc-lead ratio has been recontoured by using those data points in close proximity to the fault. The results shown in Figure 8 correlate well with the directional information indicated in the other contours. The directional sense is even much clearer than in the previous results. This contour section also provides evidence of limited influence by the West fault as an ore-fluid conduit. The nature of this influence was explored further.

Examination of successive mine-level contours reveals that the West fault progressively traverses the ore zone and that most sets of contours show some degree of influence upon the ore by this structure. To further distinguish the fault in the mine area, inflections have been delineated by a structural method similar to that outlined by Conolly (1936). Figure 9 shows a plan projection of the West fault, and Figure 10 a vertical projection.

The structural contours have been constructed by first establishing an arbitrary reference plane subparallel to the structure. Respective vertical and horizontal distances from the plane to the fault were measured and plotted systematically. The plots were then contoured, with interpolation between points. Negative values indicate only that the reference plane has crossed the structure.

Interpreting the structural contour was facilitated by its simplicity. Each contour line represents the sum of all points in the structure that are the same distance from the plane of reference. For vertical sections, dips in the contour represent a steepening of the
Figure 8. Vertical section contours of zinc/lead within the West fault of district, Chihuahua, Mexico
within the West fault of the San Antonio mine, Santa Eulalia mining
Figure 9. Plan projection of West fault structure contours of the San Antonio r
Contours of the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico
Figure 10. Vertical Section structure contours of the West fault of the San Chihuahua, Mexico
of the West fault of the San Antonio mine, Santa Eulalia mining district,
structure, whereas rises in the contour signify a shallowing of the dip. In plan view, distances between contour lines are important as well because these distances indicate the dip gradient.

Figures 9 and 10 show a uniform dip in the northern portion, which abruptly changes to a much steeper dip between mine coordinates 2100N and 2200N, coincident with the transmuted zone seen in vertical contours. Farther to the south the fault resumes its moderate dip even more sharply, although it maintains a slightly steeper dip on the intermediate mine levels. Although the ore chimney and dikes intercept the fault at approximately mine level 10 for most of the mine area, the intercept is at much greater depth in the zone of flexure. This relationship between ore and structure could not be coincidental but in fact clues to the progression of ore-forming fluids moving through the system.

The correlation of flexure within the West fault with zoning patterns of the metals and metal ratios indicates greater influence by this structure upon ore fluids than previously supposed. A preliminary examination of fault-dike interactions would suggest that the flexure of the fault and subsequent opening provided a structure wedge extending to a greater depth there than to either the north or the south. This opening was probably created by the normal faulting and augmented by rotation of the graben block toward the south.

Downward extension of the fault opening in this area provided uninhibited access for felsic intrusion followed by invasion of mineralizing fluids along the contacts of the felsites. Contour patterns indicate entry of these fluids laterally and from depth in the northern
part of the mine area. These may have been trapped and forced upward at the flexure by the impermeable nature of the contacts at the flexure. Fault gouge or pinching of the felsites, likely related to the restraining bend of the fault, could have caused this impermeability.

Above mine level 10 the inflection in the fault is much less distinct, eventually straightening out entirely. Ore zoning reflects the change in structural influence by appearing much more elongate, stretching to the north and south again along the contacts of the dikes. Mineralization occurs upward from this level along the West fault as well as with the dikes. The dikes traverse into the hanging wall interior to the graben. The fault mineralization exhibits separate but similar zoning patterns like the mantos, as evidenced in the plan contours. In the oxidized levels the fault mineralization constitutes a major portion of the orebody.

**Considerations for Exploration**

Mineralization at the San Antonio mine appears to have very definite controls associated with structural inflections of the West fault. The major fluid conduits are the dike contacts below mine level 10 and the contacts and fault above this level. Again, contours indicate fluid entry from the north laterally and from depth. An exploration model for this deposit take into account these features and their effects.

Fluids moving to the south at depth were apparently trapped by the fault flexure and forced upward, and for this reason prospects of mineralization diminish farther to the south. Movement of fluids to the
south probably occurred only at shallower depths as the flexure straightened.

The nearly flat-lying limestone beds and accompanying sills permit more tenable hypotheses of additional mineralization north of the mine area. Fluids rising along the dike contacts from their source could have moved north as well as south after encountering upward resistance from the sills. Other inflections along the fault may have caused formation of more orebodies, provided these inflections extend to sufficient depth to cut the fluid path.

Drill information is not yet sufficient in the graben area north of the mine to determine exploration targets. Blind drilling along the strike of the felsic dikes would best be oriented to also intercept the fault. Careful analysis of intercepts may reveal any steepening tendencies of the fault that could merit further investigation. Because these structures may not be more than 100 m in width, drill spacing should not exceed this, even though in the upper mine levels the fault inflections may be wider and less distinct.
CHAPTER 5

CONCLUSIONS

The use of metal ratios and metal assay contouring at the San Antonio mine has been justified by the planar nature of the orebody, which permits examination of the distribution of the metals in two dimensions. Knowledge of the orebody must be carefully employed to avoid confusing the results by including inappropriate data. For example, assay information from the mantos introduces separate and horizontal zoning patterns and should be used only with extreme caution in the construction of vertical sections.

The theory of metal ratios and their advantages over the use of actual metal values was employed in this study in the manner established by Goodell and Petersen (1974). The assumption of the theory's validity, especially in its being independent of variations in structure is taken to be true, and conclusions drawn from it are tentative to the degree that the theory bears out on application.

Relative merits of metal ratios over simple assays are minor in this deposit type, but based on the above assumption still show more confident directional indicators because they are less influenced by structure. Assay contours, on the other hand, outline well this change in structure and are perhaps useful as a diagnostic tool. However, sample size and density need to be sufficiently large to provide
adequate contours and therefore would not make an effective exploration tool.

The results of this study are in agreement with the current theory concerning the genesis of this deposit. Evidence presented here does not prove or disprove the presence of an igneous source. If such an igneous body exists and is genetically related to the mineralization, the likelihood is greatest that it is located at depth to the north and within the footwall of the West fault. Evidence also shows that a complex interaction between the dikes and the fault are responsible for location of the orebody. However, changes in the orientation of the dikes were not examined as part of this study. Such research might prove beneficial for further delimitation of the structure-orebody relationships. As the mine is developed to greater depth, additional examination of the contours on a smaller scale could permit more exact definition of the fluid paths to provide even greater reliability for determining exploration targets.
## APPENDIX A

### ASSAY DATA FOR SAN ANTONIO MINE

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APPENDIX B

CONTOUR MAPS FOR METAL VALUES AND RATIOS,
SAN ANTONIO MINE

Vertical sections were constructed roughly parallel to the strike
of the felsic dikes in a vertical plane.
Figure B-1. Plan section contours of silver values for the San Antonio mine, S.
for the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 8
Figure B-2. Plan section contours of silver values for the San Antonio mine, San
For the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 10
Figure B-3. Plan section contours of silver values for the San Antonio mine, Sar.
the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 11
Figure B-4. Plan section contours of silver values for the San Antonio mine, San
For the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 12
Figure B-5. Plan section contours of silver values for the San Antonio mine, St
For the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 13
Figure B-6. Plan section contours of silver values for the San Antonio mine, San...
the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 14
Figure B-7. Vertical section contours of silver values for the San Antonio mine, S
For the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico
Figure B-8. Plan section contours of lead values for the San Antonio mine, Sant.
the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 8
Figure B-9. Plan section contours of lead values for the San Antonio mine, Sant
the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 10
Figure B-10. Plan section contours of lead values for the San Antonio mine, Sant
The San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 11
Figure B-11. Plan section contours of lead values for the San Antonio mine, Sant.
the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 12
Figure B-12. Plan section contours of lead values for the San Antonio mine, Sar
for the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 13
Figure B-13. Plan section contours of lead values for the San Antonio mine, San Antonio, Texas.
the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 14
Figure B-14. Vertical section contours of lead values for the San Antonio mine,
for the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico
Figure B-15. Plan section contours of zinc values for the San Antonio mine, San
the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 8
Figure B-16. Plan section contours of zinc values for the San Antonio mine, San
the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 10
Figure B-17. Plan section contours of zinc values for the San Antonio mine, Sant
the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 11
Figure B-18. Plan section contours of zinc values for the San Antonio mine, Sant
the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 12
Figure B-19. Plan section contours of zinc values for the San Antonio mine, San
the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 13
Figure B-20. Plan section contours of zinc values for the San Antonio mine, San
The San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 14
Figure B-21. Vertical section contours of zinc values for the San Antonio mine, S
for the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico
Figure B-22. Vertical section contours of copper values for the San Antonio mine.
Lines for the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico
Figure B-23. Vertical section contours of iron values for the San Antonio mine,
for the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico
Figure B-24. Plan section contours of zinc/lead values for the San Antonio mine,
Meters for the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 8
Figure B-25. Plan section contours of zinc/lead values for the San Antonio mine,
Felsic Dikes
Meters

[Diagram of felsic dikes for the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 10]
Figure B-26. Plan section contours of zinc/lead values for the San Antonio mine.
for the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 11
Figure B-27. Plan section contours of zinc/lead values for the San Antonio mine.
Figure B-28. Plan section contours of zinc/lead values for the San Antonio mine, 5
for the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 13
Figure B-29. Plan section contours of zinc/lead values for the San Antonio mine,
for the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico, level 14
Figure B-30. Vertical section contours of zinc/lead values for the San Antonio mine,
for the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico
Figure B-31. Vertical section contours of silver/lead values for the San Antonio mine.
as for the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico
Figure B-32. Vertical section contours of silver/zinc values for the San Antonio mine.
COORDINATES (N20'E, LOOKING SOUTHEAST)

Profiles for the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico
Figure B-33. Vertical section contours of lead/copper values for the San Antonio mir
Values for the San Antonio mine, Santa Eulalia mining district, Chihuahua, Mexico
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LEGEND

SEDIMENTARY AND VOLCANIC UNITS

CENOZOIC

Quaternary

\[ \text{Qal} \]
Alluvium and talus; including Recent gravels.

Tertiary

\[ \text{Tva} \]
Andesitic volcanic tuffs and flows; undifferentiated.

\[ \text{Tfr} \]
Rhyolite flows

\[ \text{Tcb} \]
Basal Conglomerate; calcareous.

MESOZOIC

Cretaceous

\[ \text{Kls} \]
Limestone; undifferentiated units.

INTRUSIVE UNITS

Tertiary

\[ \text{Tf} \]
Rhyolite intrusive; hypabyssal.

\[ \text{Td} \]
Felsite dikes and sills; some porphyritic.

\[ \text{Td} \]
Diorite and diabase dikes and sills
FIGURE 4

SURFACE GEOLOGY OF THE SAN ANTONIO GRABEN AREA

SANTA EULALIA MINING DISTRICT
CHIHUAHUA, MEXICO

(Adapted from work by IMMSA Geological Staff, 1977, Santa Eulalia Unit)

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