THE LAS TORRES MINE, GUANAJUATO, MEXICO

ORE CONTROLS OF A FOSSIL GEOTHERMAL SYSTEM

By

L. J. Buchanan
A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Geology).

Signed: Larry J. Buchanan

Golden, Colorado
Date: 12-5, 1979

Approved: Dr. S.B. Romberger
Thesis Advisor

Dr. J.J. Finney
Head of Department

Golden, Colorado
Date: 2-5, 1979
"There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact."

Mark Twain, *Life on the Mississippi*
ABSTRACT

The Guanajuato, Mexico, mining district has a 432 year history of production in excess of 133 metric tons of gold and 30,600 metric tons of silver. Production is from three northwest-trending quartz-adularia-calcite vein systems cutting Mesozoic black shales, Tertiary red bed conglomerate, and Tertiary rhyolitic and andesitic tuffs, breccias, and small intrusions. Ore shoots within the veins are isolated on strike and vertically by barren vein segments. Ore shoots lie at three distinct elevations above sea level: Upper ore from 2100 to about 2350 meters; Lower ore from 1700 to 2200 meters; and Deep ore from below 1700 meters. This vertical stacking often forms two or three disconnected ore shoots, one above the other, within the same vein.

Mineralogy of both the Upper and Lower ore horizons consists of an acanthite-adularia-pyrite-electrum-calcite-quartz assemblage; that of the Deep ore is a chalcopyrite-galena-sphalerite-adularia-quartz-acanthite assemblage, suggesting the ores may have originated from fluids of two different compositions.

Alteration studies indicate that a pre-ore stage propylitic alteration was widespread, and consists of chlorite-pyrite-montmorillonite and rare epidote as a flooding of the rock groundmass. Pre-ore potassic
alteration is restricted to an inner, more veinward zone, and is primarily adularia-sericite-illite-quartz as a flooding of the rock groundmass. The potassic alteration is irregularly distributed, located only in areas of intense fracturing of vein walls. It is postulated that the fractures high in the vein systems were filled with nearly barren quartz during the pre-ore stage. Seventeen-element analyses of fluid inclusions from this pre-ore stage indicate that the solutions were high in Ca, Cl, Se, total sulfur, Pb, and Cu, but were very low in Ag and K. Nondestructive fluid inclusion studies of the pre-ore stage indicate that the solutions were boiling above the level of the Deep ore, but were not boiling at and below that level.

Argillic alteration, associated with the ore stage fluids, consists of kaolinite and halloysite within and adjacent to the veins; montmorillonite farther from the veins. Argillization is restricted to a halo around the ore shoots, and passes upwards into a phyllic cap above the ore shoots. Analyses of fluid inclusions of the ore stage indicate they were high in Ca, K, Cl, and Ag, but contained only one tenth of the base metals and one fiftieth of the sulfur as the pre-ore stage. Fluid inclusion evidence indicates that the ore stage solutions
were boiling at 230°C at and above the base of the Lower ore horizon, but were not boiling below that level.

A model of ore deposition is proposed where the pre-ore solutions are believed to have propylitized and potassically altered the wall rocks, deposited base-metal sulfides at depth, and filled the fractures with nearly barren quartz, calcite, and adularia. Solutions above the level of sulfide deposition boiled, those at and below did not. After base-metal deposition, renewed fracturing occurred. Ore stage solutions entered the fractures, rose toward the paleosurface, and boiled at a depth of 340 meters. Mineral deposition sealed the fractures, shutting off fluid flow to the paleosurface. Renewed fracturing rapidly returned the system to hydrostatic, allowing flashing of the solution to a depth of 340 meters below the base of the sealing cap. The accompanying loss of dissolved gases, particularly CO₂ and H₂S, caused a pH rise in the remaining liquid. Complex dissociation and mineral deposition resulted. After flashing, the vapor and entrained liquid would rise toward the paleosurface, and again boil under hydrostatic conditions at a depth of 340 meters. This boiling would again lead to mineral deposition and self-seal the system. Repeated fracturing of such a cap would allow repeated flashing episodes at depth, each
one leading to deposition of a thin band of ore and gangue minerals. The associated argillic and phyllic alteration patterns resulted from low-pH condensates of the vapor phase released during each boiling episode.

The base-metal deposits of the Deep horizon were formed from solutions that were paragenetically earlier and chemically different than the solutions that formed the Ag-Au deposits of the Lower and Upper horizons. The Lower horizon formed during numerous flashing episodes and the Upper horizon formed during numerous episodes of boiling under hydrostatic conditions.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT.</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xi</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xii</td>
</tr>
<tr>
<td>LIST OF APPENDICES</td>
<td>xiv</td>
</tr>
<tr>
<td>LIST OF PLATES</td>
<td>xv</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>General.</td>
<td>1</td>
</tr>
<tr>
<td>Location</td>
<td>5</td>
</tr>
<tr>
<td>Purpose.</td>
<td>5</td>
</tr>
<tr>
<td>Scope and Methodology.</td>
<td>8</td>
</tr>
<tr>
<td>Previous Investigations.</td>
<td>11</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>11</td>
</tr>
<tr>
<td>DISTRICT GEOLOGY</td>
<td>14</td>
</tr>
<tr>
<td>General.</td>
<td>14</td>
</tr>
<tr>
<td>Stratigraphy</td>
<td>15</td>
</tr>
<tr>
<td>Intrusive Rocks.</td>
<td>24</td>
</tr>
<tr>
<td>Structure.</td>
<td>27</td>
</tr>
<tr>
<td>ORE DEPOSITS.</td>
<td>31</td>
</tr>
<tr>
<td>General.</td>
<td>31</td>
</tr>
<tr>
<td>Ore Shoot Geometry and Zoning.</td>
<td>32</td>
</tr>
<tr>
<td>Vein Mineralogy.</td>
<td>34</td>
</tr>
<tr>
<td>THE LAS TORRES MINE</td>
<td>38</td>
</tr>
<tr>
<td>General.</td>
<td>38</td>
</tr>
</tbody>
</table>

viii
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Previous Work</td>
<td>38</td>
</tr>
<tr>
<td>Stratigraphy</td>
<td>38</td>
</tr>
<tr>
<td>Intrusions</td>
<td>39</td>
</tr>
<tr>
<td>Structure</td>
<td>39</td>
</tr>
<tr>
<td>Orebodies</td>
<td>43</td>
</tr>
<tr>
<td>Orebody Mineralogy</td>
<td>46</td>
</tr>
<tr>
<td>WALL ROCK ALTERATION</td>
<td>52</td>
</tr>
<tr>
<td>General</td>
<td>52</td>
</tr>
<tr>
<td>Previous Work</td>
<td>53</td>
</tr>
<tr>
<td>Definitions</td>
<td>53</td>
</tr>
<tr>
<td>Propylitic Alteration</td>
<td>54</td>
</tr>
<tr>
<td>Potassic Alteration</td>
<td>58</td>
</tr>
<tr>
<td>Argillic Alteration</td>
<td>62</td>
</tr>
<tr>
<td>Phyllic Alteration</td>
<td>66</td>
</tr>
<tr>
<td>Other Alteration Types</td>
<td>71</td>
</tr>
<tr>
<td>FLUID INCLUSION STUDY</td>
<td>77</td>
</tr>
<tr>
<td>General</td>
<td>77</td>
</tr>
<tr>
<td>Methods</td>
<td>78</td>
</tr>
<tr>
<td>Pre-Ore Inclusions</td>
<td>79</td>
</tr>
<tr>
<td>Ore Stage Inclusions</td>
<td>81</td>
</tr>
<tr>
<td>Fluid Inclusions of the Deep Horizon</td>
<td>96</td>
</tr>
<tr>
<td>Extraction of Fluid Inclusions</td>
<td>98</td>
</tr>
<tr>
<td>Summary</td>
<td>102</td>
</tr>
</tbody>
</table>
GEOCHEMISTRY OF ORE DEPOSITION

General
Ionic Strength
pH
f(CO₂)
f(O₂)
SiO₂ in Solution
Total Sulfur in Solution
Summary

MODEL OF ORE DEPOSITION

General
Pre-Ore Events
Ore Stage (Silver and Post-Silver Episodes)
Events
Later Events
Implications of Suggested Process

REFERENCES CITED

APPENDIX A: CALIBRATION OF HEATING/FREEZING STAGE
APPENDIX B: FLOW CHART OF FLUID INCLUSION
EXTRACTION TECHNIQUE
APPENDIX C: CHEMICAL REACTIONS USED TO CONSTRUCT
LOG f(O₂) - pH DIAGRAM
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Location Map</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>Regional Geology of the Sierra de Guanajuato</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>Generalized Stratigraphic Column</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>Geology of the Guanajuato District</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>Photomicrograph of a Portion of an Ore-Stage Veinlet</td>
<td>48</td>
</tr>
<tr>
<td>6</td>
<td>Paragenetic Diagram of Mineralization at the Las Torres Mine</td>
<td>51</td>
</tr>
<tr>
<td>7</td>
<td>Photomicrographs Illustrating Effects of Propylitic Alteration</td>
<td>60</td>
</tr>
<tr>
<td>8</td>
<td>Photomicrographs Illustrating Effects of Potassic Alteration</td>
<td>63</td>
</tr>
<tr>
<td>9</td>
<td>Photomicrographs Illustrating Effects of Argillic Alteration</td>
<td>67</td>
</tr>
<tr>
<td>10</td>
<td>Scanning Electron Photomicrographs</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>Illustrating Clay Mineral Morphology</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>11A: View of Veins in Block 3-North.</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>11B: Close up of Ore Stage Veinlets.</td>
<td>69</td>
</tr>
<tr>
<td>12</td>
<td>Photomicrographs Illustrating Effects of Phyllic Alteration</td>
<td>72</td>
</tr>
<tr>
<td>13</td>
<td>13A: Wall Rock Alteration at Las Torres, 310 and 390 Levels</td>
<td>74</td>
</tr>
</tbody>
</table>
13B: Wall Rock Alteration at Las Torres, 490 and 590 Levels ............. 75
14 Wall Rock Alteration Along Section A-A'....... 76
15 Histograms of Fluid Inclusion Data ............. 87
16 Photomicrograph of Sample 0804 ............... 88
17 Close up of Radiating Band of Primary Fluid Inclusions in Sample 0804 ......... 89
18 Close up of Primary Fluid Inclusions .......... 90
19 Variation in Number of Fluid Inclusions Across Ore Stage Veinlet ............. 92
20 Log f(O₂) - pH Diagram Ore Stage .............. 111
21 21A: Longitudinal Section of the Veta Madre Showing a Schematic Representation of Fractures Prior to Pre-Ore Stage Events.. 123
21B: Longitudinal Section of the Veta Madre Showing a Schematic Representation of Pre-Ore Events ............. 124
21C: Longitudinal Section of the Veta Madre Showing a Schematic Representation of Ore Stage Events ............. 125

xii
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Results of Nondestructive Analysis of Fluid Inclusions from the Las Torres Mine</td>
<td>82</td>
</tr>
<tr>
<td>2</td>
<td>Fluid Inclusion Study of the Rayas Mine, Guanajuato, Mexico</td>
<td>97</td>
</tr>
<tr>
<td>3</td>
<td>Some Species in Guanajuato Hydrothermal Fluids</td>
<td>100</td>
</tr>
</tbody>
</table>
# LIST OF APPENDICES

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Calibration of Heating/Freezing Stage.</td>
<td>A-1</td>
</tr>
<tr>
<td>B</td>
<td>Flow Chart of Fluid Inclusion Extraction Technique.</td>
<td>B-1</td>
</tr>
<tr>
<td>C</td>
<td>Chemical Reactions Used to Construct Log $f(O_2)$ - pH Diagram</td>
<td>C-1</td>
</tr>
</tbody>
</table>
## LIST OF PLATES

<table>
<thead>
<tr>
<th>Plate</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Surface Geology and Alteration, Las Torres Area</td>
</tr>
<tr>
<td>2</td>
<td>Structure Contour Map of the Veta Madre at the Las Torres Mine, Also Showing Sample Locations</td>
</tr>
</tbody>
</table>
INTRODUCTION

General

The relationship between hydrothermal ore deposits and hot spring systems has received intensive study in recent years, particularly as a consequence of interest in the energy potential of geothermal systems. Base and precious metal deposition in surface pools and at shallow depths in modern geothermal systems has been recorded in numerous publications (Weissberg, 1969; White and others, 1971; Ewers and Keays, 1977; Ellis and Mahon, 1977). Theoretical studies of hydrothermal fluid flow at depth, connected to surficial hot springs systems, have been presented by White and others (1971), Cathles (1977), Henley and McNabb (1978). As a result of these and additional studies, numerous hydrothermal ore deposits are thought to have originated as genetic parts of larger geothermal systems.

In particular, it appears that metal precipitation is greatly enhanced in zones of boiling where volatiles and steam are escaping (Weissberg, 1969). High grade, near surface concentrations of base and precious metals, deposited as a result of partial vaporization of rising fluids, are such a common aspect of modern hot spring systems that ore deposition models are becoming based on what may be called a geothermal model. In its most general
terms, this model requires an anomalously high thermal gradient which acts as the driving force behind a convecting hydrothermal system. The water may be entirely meteoric or may be in part at least of other origins. The water migrates towards the higher temperature area, becomes heated, and picks up alkalies and metals by dissolving minerals along the fluid path. As water exits to the surface above the heat source, a mass balance requires the incoming hot water to rise to replace the lost water. As the water rises past the elevation where the hydrostatic pressure is insufficient to prevent boiling, then boiling will occur. Depending on the salinity and the temperature of the water, boiling can occur anywhere from great depths to near-surface. Boiling results in a loss of volatiles, a pH rise in the fluid phase, a cooling of the fluid, a concentration of salts in the remaining liquid, and precipitation of minerals.

Mineral precipitation often leads to a nearly complete sealing of the fluid channels (Facca and Tonani, 1967; Batzle and Simmons, 1976; Keith and others, 1978), effectively shutting off the flow until tectonic activity or hydrofracturing allows renewed fluid movement. Under these conditions (fracturing of the sealing cap), sudden flashing of the fluid column occurs below the base of the sealing
cap to a depth dependent on the temperature and composition of the solution. This flashing also leads to mineral deposition.

Thus, boiling can occur from two different mechanisms: Hydrostatic boiling and flashing. Flashing would generally occur deeper in the system than boiling under hydrostatic conditions, and if these two levels are not connected, two levels of mineral precipitation may develop.

Of particular interest to this study are precious metal deposits formed in a boiling geothermal system. These deposits are classified under many names: "Epithermal", "Bonanza Ores", "Silver-gold veins of volcanic association", and others, but none of the names are fully descriptive of the processes of formation and many (e.g., epithermal) may actually be incorrect. Recent studies indicate that many of these deposits have boiling as a common factor leading to metal deposition. Therefore, a common genetic process exists despite the local variations of structure or lithology of the area. Deposits as megascopically different as the Mother Lode of California is to Naica, Mexico, in terms of physical setting, mineral assemblages, age, alteration patterns, host rock lithology, original ore solution chemistry, temperature and pressure of formation, are thus relatable one to the other by the common genetic process of
boiling.

It would seem that a more effective classification of these deposits may center on boiling as the basis and the differences between deposits become understandable by examination of local physical-chemical parameters.

The geothermal model, briefly described above, includes boiling. This paper will use the term "geothermal" interchangeably with "hydrothermal". Implicit in this terminology is the realization that hydrothermal silver-gold ore deposits are merely fossil analogs of modern geothermal systems.

In order to fully describe the geothermal model (which results in ore grade mineral deposits) the physical and chemical ore controls of the Las Torres Mine, Guanajuato, Mexico, will be described. During the study of the mine and district, modifications of the general model were made necessary by the accumulating temperature, pressure, and chemical data, however, the overall assumption remained valid that the term "hydrothermal" is nearly synonymous with "geothermal".

The following sections present observable data and a few calculations based upon these data. The final section, titled "Model of Ore Deposition", presents a complete temporal, physical, and chemical scenario of events which
led to the ore deposits, and presents a discussion of the implications of the interpretations.

Location

The Guanajuato Mining District, located near the city of Guanajuato in the center of the state of Guanajuato, is 475 road kilometers northwest of Mexico, D.F. (Figure 1). The mining district covers an area of approximately 500 square kilometers, and includes the subdistricts of La Luz to the west, Santa Rosa to the north, and Peregrina-El Cubo to the east. The Las Torres Mine is 5 kilometers east of the city, on the southeast extension of the Veta Madre (Figure 2).

Purpose

Numerous published and private reports have been written on various aspects of the district, but these have been directed toward satisfying immediate economic needs of mining companies, with little attention paid to detailed studies of geology and ore controls. As a result, by 1950 reserves were approaching depletion. Studies by Gross (1975) on some of the primary ore controls led to major ore discoveries in 1968, revitalizing the district. According to his ideas, the vertical depth to blind orebodies could be predicted with fair accuracy, however, the orebody position along strike in the structure was still unknown,
FIGURE 2
REGIONAL GEOLOGY OF THE
SIERRA DE GUANAJUATO

LEGEND
QUaternary sediments and volcanics
Tertiary volcanics
Tertiary redbeds
Mesozoic metamorphics
Vein/fault (Bail on footwall)

CITY OF GUANAJUATO

Data from CETENAL (1975)
resulting in many fruitless exploration efforts.

This study is aimed at determining what, if any, additional ore controls are present which play major roles in localizing ore shoots at Guanajuato. To accomplish this, study was required of structure, wall rock alteration, and thermodynamic relationships.

Scope and Methodology

The central portion of the district, the Veta Madre section, was studied in a detail which depended on the accessibility of underground workings. However, as the Las Torres Mine is one of the most recently opened mines, offering good three dimensional geological control by use of numerous diamond drill holes and four levels of workings, the most intense study centered on the ore shoots of this mine.

Five months during 1976-1977 were spent by the author in underground and surface mapping. Ing. C. Ortiz, geologist with Cia. Minera Las Torres, had previously mapped the underground geology of the Las Torres Mine at a scale of 1:500. His maps were found to be excellent base maps for subsequent alteration mapping by the author. Surface geology maps of the Las Torres area, at 1:2500, had been prepared by the company prior to 1976, and these were found to be good base maps for plotting geology and alteration
data. The publication by Echegoyen (1970) included three geologic and topographic maps at 1:10,000 of the Veta Madre vein system. These were used to plot alteration patterns along the Veta Madre and subsidiary veins. Where larger scale maps were available, as at San Elias, Cebada, and between Sirena and La Union, the larger scale maps were used. Prior to and during field mapping, black and white aerial photographs (1:17,000 and 1:40,000) were studied, but were found to be of little use.

Core from 20 surface diamond drill holes was made available, and over 5300 meters were logged for alteration. Regrettably, many of the ore intercepts had been used for metallurgical testing and were unavailable. An additional 730 meters of core from 12 underground holes at Las Torres were logged.

Thin sections of fresh and altered rock and polished surfaces of ores were prepared. Many of the altered rocks were too friable to prepare adequate thin sections, therefore, they were studied by x-ray diffraction. Sixty-three samples were crushed to -40 mesh, ground, and the -2 micron fraction separated. This fraction was sedimented on glass slides and x-rayed. If necessary, after x-raying the dry slide, many of these were either glycolated or heated and x-rayed again. Another 23 x-ray patterns were obtained
using the whole rock powders.

Fluid inclusion homogenization temperatures were derived from heating of either thick sections or chips of vein materials. A Leitz 350 heating-freezing stage was used. Eighty-four calibration runs at 22 temperatures were made using organic standards and using sealed capillary tubes containing solutions of known NaCl content. These calibration data are shown in Table A-1 of Appendix A. Fluid inclusion last melting temperatures were derived using the same stage by pumping through the stage dry nitrogen gas which had passed through a coil submerged in liquid nitrogen.

Extraction of fluid inclusion liquids and subsequent analyses followed the flow diagram shown in Figure B-1, Appendix B. This method is a combination of methods reported by Roedder (1958), Roedder and others (1963), Pinckney (1972), and Clark (in preparation), modified by the author. Each sample extracted had two control blanks to check for contamination, and a major blank was run through the entire system as an additional check. No contamination was noted from the extraction procedure.

Na, Ca, and K were analysed by flame emission. Zn and Mg were analysed using a Perkin-Elmer 360 atomic absorption spectrophotometer. All anions except chloride and selenide
were analysed using a Dionex ion chromatograph, generously loaned by Wyoming Minerals Corp., of Boulder, Colorado. All other ions were analysed using the HGA 2100 (graphite furnace) attachment to the Perkin-Elmer 360 A.A.

Previous Investigations

Over 400 years of intensive study by knowledgeable geologists and engineers has resulted in a voluminous bibliography on Guanajuato. Prior to the early part of this century, most published reports were devoted to short description of mineralogy, mining and milling techniques, and presented only minor geologic information (Mallett, 1878; Garcia, 1895; Farrington, 1898; Botsford, 1909; Stewart, 1939; and Toothaker, 1941). The first comprehensive account of the district geology was presented by Monroy (1888). Beginning with the early twentieth century, published reports of the geology and ore controls became more numerous (Hill, 1904; Church, 1907; Wandke, 1930; Guiza, 1949; Wilson and others, 1950; Taylor, 1971; Petruk and Owens, 1974; and Gross, 1975). The more significant papers on detailed geology were published by Wandke and Martinez (1928), Guiza (1949), Antunez (1964), and Echegoyen (1970).

Acknowledgements

This study would have been impossible without the
financial support of Cia. Minera Las Torres. The staff of this company was of immeasurable aid in all phases of the work. The author is especially indebted to Ing. E. Duarte, chief mine geologist at Las Torres and Cebada; to Ing. J. Randall, exploration and research geologist; to Ing. C. Ortiz, Las Torres and Bolanitos mine geologist; to Ing. S. Camacho, mine geologist at the Peregrina Mine; to Ing. R. Almaguer, geologist at the Cebada Mine; and to Ing. Garcia Gutierrez, chief geologist for the Cooperativa Minera de Santa Fe. Support, discussions and critical comments from Dr. G.K. Lowther of Cia. Minera Fresnillo, from Dr. W.H. Gross of Lancana Mining Corp., from H.L. Sobel of Contractista Tormex, and from Ing. Chico of Las Torres greatly enhanced the detail and quality of this study.

Special thanks also go to Dr. W. Barret of Wyoming Minerals Corp., Boulder, Colorado, for allowing use of their laboratory facilities. Stimulating discussions with Dr. F.J. Sawkins, Dr. S.B. Romberger, and Mr. C.G. Clifton enhanced the interpretation of the data. Thanks also are extended to Dr. C. Cunningham of the U.S.G.S. and to Mr. D. Langston for assistance in calibrating the Leitz heating-freezing stage.

Special thanks must also be extended to Dr. S.B. Romberger, thesis advisor; and to Dr. F.E. Moore, Dr. R.H.
Carpenter, Dr. B. Willard, and Dr. A. Petrick, thesis committee members. The analyses of the fluid inclusion liquids would have been impossible without the patient assistance of fellow graduate student, R. Clark.
DISTRICT GEOLOGY

General

The Guanajuato District is near the southern edge of the Mexican Central Plateau, where the northwest structures of the Plateau have been abruptly cut by the easterly trend of the Transverse Volcanic Belt. A few kilometers south of Guanajuato only Pliocene and younger sediments and volcanics crop out; to the north, northwest, and northeast, the most common rocks exposed are Cretaceous calcareous sediments folded into open and tight northwest trending folds.

The district lies on the northeast flank of a poorly defined northwest-trending anticline (Wandke and Martinez, 1928). Figure 2 shows that Mesozoic sediments and volcanics are exposed in the center of the anticline with Eocene and Oligocene clastics and volcanics on the flanks. Normal faults parallel to the anticlinal axial trace have dropped the central portions of the anticline downward, and a younger, second set of normal faults formed a series of horsts and grabens trending nearly perpendicular to the axial trace.

The faults parallel to the anticlinal axial trace cut rocks as young as Late Oligocene and are mineralized with adularia giving a K-Ar date as young as 27.4 m.y. (Gross, 1975). Therefore, a Late Oligocene age is assigned to the
faulting. This age corresponds well to the taphrogenic stage of the post-Hidalgoan orogeny described by De Cserna (1960).

The oldest rocks of the Guanajuato District are marine organic and calcareous black shales deposited in the Triassic through Cretaceous Jaliscoan sea (De Cserna, 1960). These are unconformably overlain by post-orogenic continental red beds (Edwards, 1955) and Eocene and Oligocene andesitic and rhyolitic air fall tuffs. Other than alluvium, colluvium, and landslide deposits, rocks of post-Oligocene age do not crop out near the Las Torres Mine. The nearest outcrops of post-Oligocene rocks, a basaltic cap at Cerro Cubilete is about 13 kilometers southwest of Guanajuato.

**Stratigraphy**

The stratigraphy of the district has been studied by Wandke and Martinez (1928), Edwards (1955), Echegoyen (1970), and Taylor (1971). As mapping of alteration progressed, the author noted details of most formations that were not included in the earlier studies, therefore, the following descriptions are a summary of the earlier published works with minor additions by the author. A generalized stratigraphic column is presented in Figure 3, and Figure 4 shows the local distribution of formations.

**Esperanza Formation**: The oldest nonigneous rocks
FIGURE 3

DESCRIPTION

CHICHINDARO
WHITE AND PINK CRYSTAL VITRIC WELDED TUFF
BLACK PORPHYRITIC HYPERSTHENE ANDESITIC FLOWS AND TUFTS
GREEN ANDESITIC LAPILLI TUFF WITH BASAL VOLCANIClastic MEMBER
WHITE, YELLOW, AND PINK RHYOLITIC LAPILLI ACFALL ASH
GREEN, ANDESITIC VOLCANIClastic SANDSTONE

GUANAJUATO
RED, POOR-TO WELL-BEDDED, POOR-TO WELL-SORTED CONGLOMERATE, SANDSTONE, AND SHALE

ESPERANZA
BLACK, CARBONACEOUS SHALE CAPPED BY GREY CALCILUTITE, INTRUDED BY MAFIC TO FELSIC DIKES, SILLS, AND STOCKS
known in the district are interbedded black and grey carbonaceous, fissile shale, grey calcareous shale, grey calcilutite, and thin sandstone, with interbedded basaltic and andesitic flows (Edwards, 1955; Taylor, 1971). Rocks assigned to this formation are regionally weakly metamorphosed to phyllitic shale, slate, and marble, with local zones of contact metamorphic tactite and marble. As the base of this formation is unexposed in the district, no thickness can be assigned, however, at least 500 meters have been intersected in some of the deeper workings of the Valenciana Mine (Echogoyen, 1970).

No fossils have been found in the Esperanza Formation, but silicified corals from limestone cobbles found in overlying conglomerates were identified by Edwards (1955) as Late Jurassic through Early Cretaceous. The lower age limit of the formation has been placed in part in the Triassic by Wandke and Martinez (1928) because of lithologic similarities to shales at Zacatecas, dated as Late Triassic. As shown on Figure 4, the Esperanza Formation is exposed on the footwall along much of the Veta Madre to the northwest, north and west of Guanajuato. The formation is not exposed at the surface or underground at the Las Torres Mine.

Guanajuato Formation: An angular unconformity separates the Esperanza Formation from the overlying formations.
Directly above the unconformity is the Guanajuato Formation, a red bed sequence of thin to thick bedded, poor to well sorted, shale, sandstone, and pebble to boulder conglomerate. Near the base, the clastics are interbedded with thin volcaniclastic sandstone and andesite flows. This lower part of the formation consists of fine-grained shale, sandstone, and pebble conglomerate, separated by a disconformity from an upper boulder conglomerate which grades upwards to a pebble conglomerate (Edwards, 1955).

The distribution of the formation is restricted to the hanging wall of the Veta Madre at Guanajuato and is covered on the east by younger volcanics, in fault contact to the west with the Esperanza Formation, and covered by younger basin gravels to the south (Figure 4). Several smaller outcrops occur east and north of the city, where the formation is exposed on tilted fault blocks. One of these forms the footwall of the Veta Madre at the Las Torres Mine.

Edwards (1955) estimates that the thickness of the Guanajuato Formation is at least 1500 meters with a maximum of 2000 meters. Based on vertebrate fossils from the lower part of the formation, Edwards concludes that the age is at least Early Tertiary, and probably Late Eocene to Early Oligocene.

Losero Formation: This formation conformably overlies
the Guanajuato Formation, and consists of a very well sorted, thin to medium bedded, slabby, purple, red, and green calcareous volcanioclastic sandstone. Most grains are quartz, plagioclase, and volcanic lithic fragments, with up to 20% by volume calcite as cement. Grains are angular to subrounded. About 15% of the lithic grains are chloritized, imparting a pale green color to most of the formation. Fluvial features are common to the Losero Formation, including cross-bedding, ripple marks, scour and fill features, rain drop imprints, and graded bedding.

The Losero Formation has a 10 to 25 meter thickness throughout most of its exposures in the central part of the district, although to the east of the city near the Las Torres Mine, it becomes less slabby, coarser grained, and thickens to over 52 meters (Edwards, 1955). The formation also coarsens and thickens to the north and northeast, and thins and becomes very fine-grained to the south and southwest.

No age has been determined for the Losero and no fossils have been reported, but an age of Early Oligocene may be postulated from its position between the underlying Eocene through Early Oligocene Guanajuato Formation and the overlying Oligocene Bufa Formation.

Bufa Formation: Conformably overlying the Losero
Formation is the Bufa Formation. It is a poorly bedded yellow, white and rose-red, vitric, crystal, lithic lapilli air fall rhyolite ash. It contains poorly formed columnar jointing near the center of the formation with very weak welding of vitric fragments. Crystals of sanidine, quartz and minor plagioclase make up 15 to 25% by volume. Rhyolite and andesite lithic lapilli are rarely noted, along with a few accidental fragments of shale. The ash matrix varies from 50 to 80% of the total volume.

Gross (1975) reports a K-Ar age of 37.0± 3.0 m.y. for the formation, placing it in the Early Oligocene. The Bufa Formation lies on the hanging wall of the Veta Madre at the Las Torres Mine, and on the hanging wall and footwall of the Veta Madre to the southeast of the mine (Figure 4). Much of the higher elevation of the Sierra de Guanajuato is developed on this formation. Total thickness varies due to original depositional thickness variations and to post-Bufa erosion, but the formation has an average thickness of 360 meters at the Las Torres Mine. The Bufa Formation is separated from the overlying Calderones Formation by a disconformity.

Calderones Formation: This formation is a green, crystal, lithic lapilli andesite tuff. Broken crystals in the formation consist of plagioclase (An24) (Taylor, 1971), augite, hypersthene and minor quartz. Most lithic fragments
are chloritized. Angular aphanitic porphyritic andesite lithic fragments are common, making up to 75% of the rock. The formation is typically medium to thick bedded, except at the base where laminated andesitic volcaniclastic shale and sandstone rest atop the Bufa. These basal fluvial volcaniclastics are not everywhere present, but appear to follow shallow channels eroded into the underlying Bufa rhyolite. Mudcracks, rain drop imprints, and ripples may be observed locally, and graded bedding in sandstone and shale at this interval is often encountered in diamond drill cores at the Las Torres Mine.

The thickness of the Calderones Formation is from 200 to 250 meters (Taylor, 1971). This formation has the most extensive outcrop exposure of the Tertiary volcanics in the district and occurs in wide areas northeast, east, and south of the city (Figure 4).

No age has been determined for the Calderones Formation. An age of Oligocene has been assigned as Late Oligocene veins (Gross, 1975) cut the formation, and it rests atop the Early Oligocene Bufa Formation.

A transition zone up to 5 meters thick exists near the top of the formation, where it grades imperceptibly into the overlying Cedro Formation. This transition zone is a thinly bedded to laminated, grey to black, crystal air fall
andesite tuff.

Cedro Formation: The formation consists of grey to black, porphyritic hypersthene andesite flows interbedded with green and grey lapilli andesite tuff. These rocks have from 10 to 20% by volume plagioclase (An\textsubscript{29}) phenocrysts, 2 to 3% augite phenocrysts, 7 to 8% hypersthene phenocrysts, and 50% aphanitic groundmass (Taylor, 1971).

The formation is well exposed in the hangingwall of the Veta Madre at the Las Torres Mine. The thickness is estimated to be 250 meters by Gross (1975), over 100 meters by Taylor (1971), and up to 640 meters, north of the district, by Echegoyen (1970). The age has not been determined but has been assigned by the author to the Middle Oligocene. Upper contacts of the Cedro Formation are obscured along the Veta Madre by talus and landslide deposits, however, it has been reported (Taylor, 1971) to be unconformable.

Chichindaro Formation: This formation is a white and pink, poorly sorted, massive bedded, crystal, vitric, welded ash, containing irregular lenses of flow breccia. The type location is at the hill of Cerro Chichindaro, 2 kilometers north of the Las Torres Mine. The formation at Cerro Chichindaro is approximately 100 meters thick, but as no younger rocks are exposed in the district, the pre-erosion thickness is unknown.
This formation, exposed only on a few isolated hills in the district, is the least understood of any formation in the district. Numerous authors have placed this formation as being post-mineralization (Guiza, 1949; Taylor, 1971), pre-mineralization but post-faulting (Wisser, 1928), and pre-faulting (Wandke and Martinez, 1928; Gross, 1975). Gross (1975) reported a K-Ar age of 32.0±1.0 m.y. for the formation, whereas the veins give K-Ar ages of 27.4±0.4 m.y. to 28.4±4.0 m.y., and field studies by the author indicate the formation is displaced by the Veta Madre fault and is extremely altered adjacent to the vein. This author believes the Chichindaro Formation is pre-mineralization.

Intrusive Rocks

General: Large intrusive bodies associated with the Hidalgoan Cretaceous through Eocene orogeny (De Cserna, 1960) are present in the district, as are smaller intrusions probably related to the Oligocene volcanic pile. The older intrusions are restricted to the western and northern parts of the district where they intrude the Esperanza Formation as large stocks, dikes, sills and plugs (Figure 4). The intrusions have never been mapped in detail. The past practice in the district has been to map all intrusive bodies which cut the Esperanza Formation as parts of one formation, the La Luz Formation (Echegoyen, 1970). Danger
in this lies in that Oligocene dikes, presumably feeders to the pyroclastics, also cut the Esperanza Formation. To make matters worse, many pillow basalts and andesite flows are placed within the La Luz Formation (Echegoyen, 1970). In order to avoid some of the pitfalls, this writer prefers to use the term La Luz Complex, following the American Geological Institute (1974) definition.

La Luz Complex: This complex consists of a large granite stock (Gonzalez, 1959) bordering the western edge of the district, with possibly related thin (up to 3 meters wide) rhyolite dikes. Other dikes with an unknown age relationship to the granite and rhyolite are quartz-monzonite, monzonite, and diorite. These intermediate and silicic dikes intrude an older diorite and gabbro pluton near La Luz (Echegoyen, 1970). This older diorite and gabbro pluton has assimilated large masses of shale of the Esperanza Formation, converting them to xenoliths of black laminated tectites. The La Luz Complex is restricted to the western and northern portions of the district, in fault contact with the younger Guanajuato Formation (Figure 4).

The age of the complex has not been determined. Fragments of granite and diorite are found in the Guanajuato Formation, and granite and diorite are not observed to cut Tertiary rocks, therefore, the writer agrees with Edwards
(1955) that the age is latest Cretaceous to earliest Tertiary, related to the intrusive stage of the Hidalgoan orogeny.

Calderones Dikes: These are dark green, fine-grained, porphyritic andesite dikes with phenocrysts (up to 10 millimeters in diameter) of plagioclase. These dikes are common throughout the district as thick (up to 20 meters wide), long (up to 1 kilometer), fairly planar bodies cutting all formations up to the Cedro Formation. This crosscutting relationship and the similarity in lithology have led to the assumption that these dikes were feeders to the Calderones Formation.

Cedro Dikes: These are brown and grey, very fine-grained, friable, microporphyritic andesite dikes. They are usually thin (less than 1 meter) and short (under 500 meters) and are found only in the eastern parts of the district, cutting all formations up to the Chichindaro Formation. As with the Calderones dikes, the crosscutting relationship and the similarity in lithology to the Cedro Formation have led to the assumption that these dikes were feeders to the Cedro Formation.

Chichindaro Dikes: These are white, fine-grained, porphyritic aphanitic rhyolite dikes with phenocrysts of sanidine and quartz. They are found near Cerro Chichindaro
cutting the Cedro Formation as thin (under 10 meters) and short (under 250 meters) dikes.

Structure

The Guanajuato district lies primarily on the northeast flank of a northwest-trending regional anticline (Figure 2). Dips of the sediments and flows on the northeast flank average 10 to 20° N and NE. Minor fold hinges in the Esperanza Formation have been recognized with bearings other than northwesterly. These folds are probably structures of the Hidalgoan orogeny. Tertiary sediments and volcanics show little deviation from the regional north to northeast dip except in areas possibly subjected to drag folding adjacent to faults.

Faults in the area belong to three sets, listed below in order of decreasing age:

1. Oldest: NE to E set, pre-ore.
2. Intermediate: NW set, pre-ore and ore stage, containing three systems within the set:
   a. The Sierra System
   b. The Veta Madre System
   c. The La Luz System

The oldest set, with NE to E strikes and steep dips to the north and south, have unknown but probably minor
displacements. Near the Las Torres Mine, these faults apparently preceded or were contemporaneous with Calderones Formation deposition because many of the faults are occupied by andesitic dikes, believed to have been hypabyssal feeders to the Calderones and Cedro Formations. These faults are often weakly mineralized close to their junction with mineralized faults, and the enclosed dikes are strongly propylitically altered.

The northwest set strikes northwesterly although short deviations in attitude form nearly north-trending or east-trending segments. There are three main fault systems within this northwest set:

1) The Sierra System,
2) The Veta Madre System, and
3) The La Luz System.

The Sierra Fault System: This is the most northeasterly of the three and contains many subparallel faults with dips primarily 40 to 80° SE. A few faults in this system dip northeasterly. The Peregrina and El Cubo mines are producing from veins of this system (Figure 4).

The Veta Madre Fault System: This system is located about four kilometers to the southwest of the Sierra System, and is the longest of the three fault systems of the northwest set. The Veta Madre dips consistently 35 to 55° SW
and has been traced on surface for over 20 kilometers. The actual length has never been mapped, but air photograph interpretations and ground investigations by the author suggest that the Veta Madre system may reach up to 100 kilometers in length. The fault strikes generally northwesterly throughout its northwest half but the southeast half has wide arcuate variations in strike from WNW to N. All rocks exposed in the district are cut by this fault, with displacements as much as 1200 meters on the southeast end near the Las Torres Mine to as much as 1700 meters near the central part at the Valenciana Mine (Wandke and Martinez, 1928). Parallel faults are common, especially in the hanging wall, but these are shorter than the Veta Madre. Hanging wall and footwall faults, which are splits and cymoidal loops joining the Veta Madre at low angles, are common in the areas of rapid changes in strike of the Veta Madre. The width of Veta Madre fault gouge, silicified fragments, and quartz and calcite filling is highly variable from an unfilled hairline crack (at higher elevations) to as wide as 30 meters (at lower elevations).

The La Luz Fault System: This is the most variable in attitude of the three systems of the NW set. Many of the faults of the La Luz system dip 40 to 80° NE, whereas others dip 40 to 80° SW. Strikes in general are northwesterly on
the northwest end of the system, but curve more to the east-southeast at the southeast end where considerable horse-tailing and bifurcation occurs. The amounts and directions of the net slip have never been calculated for lack of detailed maps.

The youngest set of faults strike northeast. These younger faults are rare, and fortunately the net slip is usually less than 20 meters. No faults of this set are known to be mineralized and all are assumed to be post ore.
ORE DEPOSITS

General

Prior to the Guanajuato discoveries, some of Mexico's famous mining camps, Zacatecas, Pachuca, and Santa Barbara had already produced ore, and Spanish pack trails criss-crossed most of central Mexico. In 1548, a group of packers en route to Zacatecas camped near the present town of La Luz in the western part of the district, and discovered outcrops of silver-bearing quartz. By 1550, the larger Veta Madre had been discovered, and in 1554 the city of Guanajuato was founded (Antunez, 1964). Numerous mines were opened along the veins near La Luz and Guanajuato, including many which are in production today: Rayas (1558), Cata (1558), Mellado (1550), Sirena (1600), and Valenciana (1771) (Antunez, 1964). Production from the district has been irregular, and was seriously declining by the middle of the twentieth century. Exploration in the late 1960's led to the discovery of three orebodies on the Veta Madre, which were put into production in 1976.

Total production to 1967 is given by Taylor (1971) as 133 metric tons of gold and 30,596 metric tons of silver. Taylor (1971) estimated total district daily production for 1970 as 890 metric tons of ore per day, but with the opening of the Las Torres mill in February, 1976, district
production rose to about 2400 metric tons of ore per day.

**Ore Shoot Geometry and Zoning**

Individual ore shoots in the Veta Madre and in parallel vein systems (Sierra and La Luz) have ranged from a few centimeters up to 40 meters wide and from a few meters to over 450 meters along strike and down dip. The largest orebodies have yielded several millions of tons of ore, the largest being the Valenciana ore shoot.

All formations exposed in the district, with the exception of the Chichindaro rhyolite, are known to host ore shoots. Many ore shoots pass from one formation to another with no apparent change in size or grade. It is generally assumed that host stratigraphy appears to play a minor, if any, role in orebody localization.

Ore shoots may be subdivided into either veins or stockworks. The vein ore deposits are those within fractured areas on the Veta Madre or subsidiary veins, having well-defined structural walls. These are the vein-wallrock contact and serve as a grade cutoff as well as a structural cutoff. On the other hand, stockwork orebodies generally contain larger tonnages of ore than the veins, and occur as irregular zones with gradual assay cutoffs. Stockworks can occur on either the hanging wall or the footwall along the Veta Madre (Randall, 1977, verbal communication) and are
characteristically a network of intersecting mineralized veins and veinlets. The veinlets diminish in frequency away from the Veta Madre. Often, the Veta Madre adjacent to the stockworks is barren and is left on the floor or back of the stopes. Most of the more famous mines contained stockwork orebodies: Valenciana, Rayas, Sirena, and Las Torres.

Gross (1975) studied the vertical productive range of ore shoots, and found that most could be placed between three horizons: The Upper ore horizon, surface to 2100 meters above sea level (a.s.l.); the Lower ore horizon, between 2200 and 1700 meters a.s.l.; and the Deep ore horizon, below 1700 meters a.s.l. Gross' (1975) study showed that not all three horizons of ore need be present at any one section of the vein, but if more than one horizon did exist (as at Las Torres, among many others), they were usually separated by a barren zone. Often, the Lower ore horizon was not discovered by the earlier miners. Many of the orebodies of the Upper horizon cropped out, such as the Cedro, Siglo XX, Sirena, and Guanajuatito; as did some from the Lower horizon, such as Rayas and Mellado. Refer to Figure 4 for mine locations. Whether an orebody from a particular horizon cropped out depended solely on the depth of erosion.
Only one orebody is known that is classified as Deep ore. This lies at depth below the Rayas workings and is being mined at present (1979). Other mineralized zones of the Deep horizon are found below the Sirena and Valenciana orebodies.

Ore shoot locations, controlled by the locations of local shattering, are isolated from one another by long strike distances of relatively little shattered pre-ore stage vein filling and little shattered wall rocks.

An additional vertical zoning, apart from the three levels of ore, also is apparent in the barren stage quartz filling of the Veta Madre. Quartz and calcite filling of the Veta Madre is wide below about the 2300 meter elevation. From the 2300 to the 2350 meter elevation, the vein filling diminishes to a hairline width, and above the 2350 meter elevation, an unfilled fracture and altered wall rocks are all that mark the Veta Madre. In many places, a few tens of meters below portions of the unfilled fracture, a wide, well-formed vein exists, often hosting ore shoots.

**Vein Mineralogy**

Three major mineralization stages are recognized in the district:

1. Pre-Ore Stage,
2. Ore Stage,
   a. Early - Silver Rich Assemblage, called the silver episode.
   b. Late - Silver Deficient Assemblage, called the post silver episode.

3. Post Ore Stage.

Pre-ore stage mineralization filled the veins by replacement of breccia fragments along the fault zones and as minor open space filling. Wall rock breccia fragments may be seen to be partially to completely replaced by milky quartz. The replacement may be so complete as to destroy the original texture and outline of the breccia fragment. Pre-ore stage vein fillings were over 90% white and grey quartz with minor bands of amethyst and adularia, and less than 10% white calcite. Adularia is present as replacements and microveinlets in brecciated wall rock fragments within the quartz-calcite veins. This early barren fault-filling stage also locally contains minor chlorite, calcite, montmorillonite, and sericite in altered wall rock fragments within the vein. Although called the "early barren stage", trace amounts of silver and gold were introduced, and assays of this stage run a few parts per million in silver (Gross, 1975).

Between the early barren stage and the later ore stage,
a period of fracturing occurred in the district. Barren stage vein quartz was fractured and the wall rocks were locally shattered. This period of shattering often left the Veta Medre little fractured. Furthermore, the wall rocks between the local shatter zones were only slightly fractured.

Ore stage mineralization is recognizable as open space fillings, resulting in mineralogically and texturally banded veins, often with vugs in the vein center. These veins often contain sharp-edged breccia fragments showing little evidence of replacement, but occasionally some fragments are slightly to strongly replaced by quartz, adularia, or sericite. Quartz, adularia, sericite, and argentite deposited early in the sequence (silver episode) and calcite and minor quartz deposited later in the sequence (post-silver episode). A period of fracturing occurred after the pre-ore stage mineralization. Ore stage solutions then entered the newly formed fractures and formed ore shoots.

The three levels of ore, outlined by Gross (1975) define a vertical mineral zonation similar to zoning observed in many low to moderate temperature veins. Earlier mining operations, mostly producing from the Upper ore zone or from upper levels of the Lower ore zone, encountered large quantities of native silver (probably a supergene
product), and also minor amounts of cinnabar, sulfosalts, fluorite, guanajuatite, and silver sulfide with high selenium contents (Petruk and Owens, 1974). This assemblage changes at moderate depth to the simpler silver sulfide (with lower selenium values) and pyrite assemblage now being mined at most operating mines, including Las Torres (Petruk and Owens, 1974). Deeper still, in the Deep ore horizon, the ores are sulfide-rich assemblages of chalcopyrite, galena, sphalerite, acanthite, and minor polybasite. No exploration has yet been made to test for a deeper, sulfide-rich ore horizon at Las Torres.

Post ore stage mineralogy is predominately a coarsely crystalline calcite, filling the central parts of many veins. Many veins were closed at the time of the post ore stage fluids and these have solid quartz and adularia fillings or quartz or adularia crystals in central vugs. Some even later dolomite and fluorite have been found in the late stage, and marcasite and zeolites were noted in the very center of some vugs.

Figure 6 presents a paragenetic diagram for the Las Torres Mine orebodies. Figure 6 also illustrates the more general paragenesis of the three stages discussed above.
THE LAS TORRES MINE

General
The Las Torres Mine is 5 kilometers east of the city of Guanajuato, located on what is termed the "southeast extension" of the Veta Madre (Figure 4). Three ore shoots of lower horizon ore are in production.

Previous Work
As the Las Torres Mine is a relatively new mine, few reports have been published. Taylor (1971) studied the local geology and mineral paragenesis. Petruk and Owens (1974) contributed to a study of the mineral paragenesis. Gross (1975) described the theory behind the ore discoveries and discussed some aspects of the wall rock alteration.

Stratigraphy
Shown on Plate 1, the Cedo Formation outcrops in the hanging wall of the Veta Madre, but is only a thin erosional remnant atop successively older formations. The Calderones Formation, below the Cedro Formation, is up to 220 meters thick. The base of the Calderones consists of a zone up to 46 meters thick of mudstone, siltstone, fine-grained sandstone, and minor coarse-grained conglomerate. These sediments were deposited on the unconformity above the Bufa Formation. Below the unconformity is the Bufa
Formation (up to 360 meters thick) and the Losero Formation (up to 40 meters thick). The Guanajuato Formation, below the Losero Formation, is exposed in deep workings and drill holes in the hanging wall. The footwall of the Veta Madre is entirely in the Guanajuato Formation.

**Intrusions**

No large intrusions are present near the Las Torres Mine. A very few dikes are present in the area, primarily in the footwall. The largest, called the Sulfato Dike (see Plate 1 at coordinates 2322980N and 269400E), is a highly propylitized andesite porphyry dike, up to 3 meters wide and over 450 meters long. The dike, with an attitude of N90E 60-70S, fills a fault of the pre-ore fault set. The dike has fractures parallel to its walls which are mineralized with base and precious metals in a gangue of quartz and calcite. Other dikes are considerably shorter and are unmineralized.

**Structure**

It appears that subtle structural changes have played a major role in ore localization, therefore, a detailed discussion of the structure present at the Las Torres Mine is warranted.

The sediments and bedded volcanics of both the hanging wall and footwall dip 10 to 20° NE, except adjacent to the
Veta Madre on the hanging wall, where the dip of the formations lessen slightly. This lessening of dip may be attributed to slight drag folding.

Faults and fractures in the footwall of the Veta Madre are observable on the surface as well as underground. On the surface, they are either uncemented fissures up to a few millimeters wide or may be filled with up to a few centimeters of quartz and calcite. Underground, near the Veta Madre, the fissures appear as well-defined quartz and calcite veins leaving the main Veta Madre at a low angle. Only a very few of the footwall veins and veinlets contain significant silver mineralization, although between 1 and 2 kilometers southeast of the Las Torres Mine, several wide (up to 3 meters) footwall veins were mined in the past.

At the Las Torres surface, three major hanging wall fractures striking N40W to N45W leave the Veta Madre where its strike changes to nearly north (see Plate 1). These three hanging wall splits are part of a large cymoidal loop system which rejoins the Veta Madre 2.5 kilometers to the northwest near the Sirena Mine.

The southernmost of the three, called the San Juan fault, is a poorly developed fracture system with a general attitude of N45W 75N to 75S. It is easily mappable by following quartz and calcite fillings and weak to strong
argillic and phyllic alteration (see Plate 1 at 2323100N and 268800E).

The central hanging wall fracture is the Zamata Vein, a major structure with a strike of N40W and dip of 55 to 70S. The northernmost of the three fractures is the Cocinas Vein, also a major structure with a strike of N36W and a dip of 55S. The Zamata and Cocinas veins have been prospected by several exploration pits and adits, but no production has been recorded. These two well-formed veins are mostly unmineralized cracks on the surface, but locally contain calcite, chalcedony, and very minor crystalline quartz.

Of the three main hanging wall cymoidal splits, only the southernmost, the San Juan, could conceivably project into the Las Torres workings. However, numerous wide, well-formed hanging wall veins do leave the Veta Madre in the underground workings. Most of these hanging wall veins do not reach the surface. The San Juan vein, however, is seen on the surface and probably has been cut by the underground workings, but has not been recognized among the numerous hanging wall veins at depth.

An additional weak veinlet system seen on the surface 600 meters south of the San Juan vein projects downward to a well-formed vein in the hanging wall. This is shown in
Figure 14.

The major structural feature and the major control of ore deposition is the Veta Madre itself. Just north of the Las Torres Mine the Veta Madre strike changes sharply to the north (Plate 1 at 2323000N and 268950E) from its general N20W strike, forming a surface trace concave to the east. Farther south of the mine, near the Cedros Shaft, a second, less pronounced bend concave to the east occurs. Dips apparently do not change appreciably from their 42°SW average anywhere along the surface trace. However, as illustrated in Figure 14, the dip of the Veta Madre steepens to an average of 44°SW at an elevation of about 1840 meters above sea level.

Plate 2 is a structural contour map of the Veta Madre at Las Torres, after the method described by Conolly (1936). This plate depicts changes in both the strike and dip of the Veta Madre, with the contours representing distances, in meters, of the true Veta Madre from an imaginary plane in the footwall. The imaginary plane, with an attitude of N18½W 42W, represents the average attitude of the Veta Madre near Las Torres. The contours illustrate deviations of the Veta Madre from its average attitude.

Certain patterns become clear. The two bends concave to the east appear as asymmetric antiform structures,
raking 60 to 65 SE. The orebodies appear to be spatially related to the more gentle flanks of the antiforms. The lower orebodies occur centered at the point of sudden dip increase. This change in dip is shown on Plate 2 by a change from widely to closely spaced contours. These combined features, the change in strike and the steepening of dip, would result in localized stress concentrations during fault movement at about the 1850 elevation, resulting in more intense fracturing near this level.

These data suggest that the localization of shatter zones and the subsequent localization of more intense alteration, of mineralized veins, and of stockworks are related to simple attitude changes in the Veta Madre. However, it would be more than fortuitous if all changes in dip and strike throughout the district occurred at the one elevation of the Lower ore horizon (2200 to 1700 meters in elevation), therefore, factors in addition to structure must also help control the loci of ore deposition. These additional factors will be discussed in the sections on wall rock alteration and geochemistry.

Orebodies

The Las Torres Mine contains three isolated Lower horizon ore shoots on the hanging wall of the Veta Madre. These ore shoots underlie and are isolated from three Upper
horizon ore shoots, the San Juan, Siglo XX and the Cedros (Plate 2). The Lower horizon ore shoots are opened on four levels: The 310 (2003 meters elevation), the 390 (1923 meters), the 490 (1823 meters) and the 590 (1723 meters).

Few data are available on the Upper horizon ore shoots except that the orebodies were up to 18 meters wide and considered lower grade than "typical" Guanajuato ore shoots (Anonymous, 1909). The three Upper horizon ore shoots project downward towards the Lower horizon ore shoots now being mined, but whether zones of anomalously high but sub-ore grade mineralization connect the upper with the lower horizons is uncertain.

The South orebody, the southeasternmost of the three Lower horizon ore shoots, was not opened at the time of this study, and was defined on the basis of four diamond drill holes.

The Main orebody, developed between the 590 level and the 310 level, is up to 230 meters along strike and up to 45 meters wide. This ore shoot is a stockwork in the Veta Madre hanging wall. The footwall of the ore shoot is formed by the Veta Madre itself.

The northernmost orebody, Block 3-North, is developed from about the 560 level to the 360 level, and is in a stockwork between several fractures in the hanging wall of
the Veta Madre. Only the upper portion of this orebody is adjacent to the Veta Madre itself, the remainder is confined to shattered areas in the hanging wall near and above the Losero-Bufa contact (Plate 2).

The Main and Block 3-North orebodies have a combined 3 million metric tons of ore with an average combined grade of 11.3 ounces Ag and 0.07 ounces Au per ton (Lacana, 1975 annual report). The South orebody values are not well defined and are not included in these figures.

The two accessible stockwork orebodies consist of numerous intersecting and mineralized veins and veinlets in the Bufa and Losero Formations. These veins generally closely parallel the Veta Madre; for example, on the 390 level the Veta Madre average attitude is N27W 42W and the average attitude of over 90% of the mineralized veins is N31W 48W. A second, less well-developed set of mineralized fractures have an average attitude of N19E 68E on the 390 level.

Mineralized veins are seen to be refractured and cut by later mineralized veins. Often, mineralized breccia fragments are enclosed within later mineralized veins. It appears that several episodes of fracturing must have occurred during the mineralizing process. This conclusion is supported by the fluid inclusion data, presented in a
subsequent section.

Orebody Mineralogy

The pre-ore stage mineralization at Las Torres was primarily as a replacement of breccia by clear to milky quartz with clear to yellow calcite and minor adularia and sericite. The adularia and sericite form rims around the walls of breccia fragments. The pre-ore stage mineralization formed essentially barren veins up to several tens of meters wide.

Renewed movement of the major faults of the district resulted in refracturing of previously formed veins and also resulted in the opening of many new fractures. Re-opened and new fractures were then subsequently mineralized by the ore stage solutions.

Ore stage vein mineralogy is highly variable at Las Torres, depending on the lithology of the rocks which are cut by the veins. If the wall rock is the Bufa Formation or if the veins intersect the barren Veta Madre, the ore stage veins have a quartz, calcite, adularia, sericite, electrum, pyrite, acanthite mineralogy. This assemblage will be called "Bufa type" in the remainder of this report. Most "Bufa type" veins are less than 5 centimeters wide. "Bufa type" veins are banded, showing several thin bands of silver sulfide, usually coprecipitated with, and immediately
followed by, adularia and minor sericite. The acanthite often partially replaces pyrite. Quartz is ubiquitous. Calcite forms the vein center, although in some veins calcite coprecipitated with the acanthite. Nevertheless, on average, calcite comprises less than 20% by volume of any vein. Figure 5 shows the relationship of silver mineralization with sericite, adularia, and quartz.

In contrast to the "Bufa type" veins, ore stage veins cutting in or near the Losero Formation have over 50% coarsely crystalline brown, purple, and white calcite. Unlike the ore stage veins of the "Bufa type", veins in or near the Losero Formation have subordinate quartz (under 50%). The quartz is usually well crystallized, forming crystals in vugs, often capped by large, euhedral rhombs of calcite. Pyrite is volumetrically more significant in veins cutting the Losero Formation, and occurs as large euhedral cubes within the veins. Perhaps the most significant difference in mineralogy when compared to the "Bufa type" veins, is the large quantity of chlorite. Chlorite often makes up to 50% of the veins, but averages about 20% by volume, and occurs as thick, green masses enclosing euhedral pyrite crystals. There appears to be an inverse relation between the quantity of chlorite and the quantity of quartz in any one vein, and where volumetrically
Figure 5: Photomicrograph of a portion of an ore stage veinlet (silver episode) from the 490 Level (Sample ALUN) in the Block 3-North orebody. Note shredded appearance of the acanthite (ac), often intimately intergrown with sericite (se) rosettes or surrounded by adularia (ad). Quartz crystals (qt) underlie and are slightly earlier than the acanthite and sericite. Field of view is 1.2 x 0.8 centimeters. Light is plain transmitted light with uncrossed nicols.
large quantities of chlorite (over 20%) occur, the major gangue mineral is calcite. This vein assemblage will be called "Losero type" in the remainder of this report (see Figure 6).

The chlorite is the "swelling chlorite" of Carroll (1970) which expands on glycolation from 14.6 Å to 15.6 Å due to a mixed-layering with montmorillonite. On heating, this same 001 reflection collapses to 12.3 Å. Mixed with the chlorite-montmorillonite are thin, white bands of halloysite and illite, both also showing mixed-layering with montmorillonite.

It may be surprising that veins of such diverse gangue mineralogy as the "Bufa" and "Losero" types are considered to be of the same stage and that the mineralogy differences are ascribed to differences in wallrock. The Losero Formation contains 20% by volume primary calcite as cement around the volcanic grains, and where mineralized by ore stage veins the formation is altered to the potassic or propylitic grades. In these altered zones, calcite content is absent or reduced, respectively. Also, the calcite in unaltered Losero Formation samples fluoresces pink to red under longwave ultraviolet light, as does the calcite in the ore stage veins. The Bufa Formation, in contrast, has no primary calcite, and as may be expected, veins of the "Bufa
type" have a considerably smaller calcite content. It is concluded that the large quantity of calcite in the veins in and near the Losero Formation is due to the calcite cement being remobilized and precipitated in the veins.

One additional line of evidence is used to conclude that "Bufa type" ore stage veins are of the same stage as the "Losero type". Veins in the Losero Formation, with their high calcite and chlorite content, can be traced into the Bufa Formation both vertically and laterally. As the Bufa Formation is entered, the calcite and chlorite contents are observed to decrease until the typical quartz, low calcite, and no chlorite assemblage is reached.

The ore stage at the Las Torres Mine is further divided into two episodes: An early silver depositing episode followed by a later gangue depositing episode. The silver episode deposited quartz, adularia, sericite, chlorite, calcite, and argentite as discreet bands on the vein walls (see Figure 6). Following this episode, calcite and quartz were deposited in the vein center.

A third and final stage of solutions is recognized at the mine. This, a post ore stage, is recognized by minor amounts of calcite, pyrite, and laumontite in fractures and vugs in the veinlets.
FIGURE 6: PARAGENETIC DIAGRAM OF MINERALIZATION AT THE LAS TORRES MINE, GUANAJUATO, MEXICO

<table>
<thead>
<tr>
<th>SPECIES</th>
<th>PRE-ORE</th>
<th>ORE STAGE</th>
<th>POST ORE</th>
<th>POST ORE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Silver Episode</td>
<td>Post Silver</td>
<td>Primary Sec.</td>
</tr>
<tr>
<td>Epidote</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chlorite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adularia</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Illite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrum</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metahalloysite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Montmorillonite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Halloysite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kaolinite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acanthite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sericite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polybasite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agularite (1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Naumanite (1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guanajuatite (1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calcite white</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calcite white pink</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calcite white purple</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluorite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laumontite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hematite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NUMBER OF PEAKS DURING SILVER EPISODE NOT NECESSARILY RESTRICTED TO THREE AS SHOWN

ALL DATA FROM AUTHOR EXCEPT (1)

(1) DATA FROM TAYLOR (1971)
WALL ROCK ALTERATION

General

Despite its over 400 year production history, no detailed alteration study has been made for the Guanajuato District. Now that mostly nonoutcropping ore shoots remain to be discovered, it seemed advisable to make such a study to determine if the alteration patterns: a) may guide exploration programs, and b) may help control the localization of ore shoots. Sixteen kilometers of the Veta Madre were mapped, from La Union on the southeast to Cebada on the northwest. Only data gathered at and near the Las Torres Mine will be presented in this report as the mineralogy and patterns of alteration were remarkably similar throughout the district.

It was found that fresh rock far from major fractures graded into weakly then strongly propylitically altered rocks nearer to the fractures, and this at times graded into a potassic alteration in local areas adjacent to the major veins. Superimposed on this zonal pattern is a cross-cutting, fracture controlled, phyllic and argillic alteration of fresh and previously altered rocks. The intensity of phyllic and argillic alteration at times appeared to be controlled by lithologic contacts.
Previous Work

The earliest and most extensive description of alteration was in 1928 by Wandke and Martinez. They mention that the Esperanza shales are whitened near ore shoots, due to the addition of sericite, quartz, and carbonates. They also reported the propylitic and potassic alteration of the Guanajuato Formation. Of interest are their descriptions of the leaching of vein constituents near the margins of ore shoots, and the absence of leaching in the interior of the shoots. Although expressed in different terms, they were describing the effects of what may have been the passage of an acidic fluid past the margins of the ore shoots. This corresponds well to the argillic alteration, both in chemistry and location, to be discussed later.

An important observation, unfortunately not fully appreciated by Guanajuato geologists, was made by Gomez de la Rosa (1961), who wrote that there was a close spatial association of clay alteration with ore shoots. Gross (1975) mentioned that the bulk of the alteration occurred during a pre-ore stage quartz mineralization.

Definitions

Alteration terminology is after the classification proposed by Meyer and Hemley (1967). Of necessity, modifications are made on their classification by this
author's desire to have a field oriented classification applicable to the mineralogy observable in the field.

**Propylitic Alteration**

Propylitic alteration, as defined here, contains the essential minerals chlorite, calcite, and pyrite, with the accessory minerals quartz and montmorillonite. Epidote may be present in very minute amounts.

Propylitic alteration is the most widespread of alteration types in the district. All rocks in the district are susceptible to propylitization to varying degrees; the degree is usually dependent on the ferromagnesium mineral content of the original rock. The Guanajuato Formation is most readily propylitized, and it is difficult to find an outcrop of this formation which shows no effects of propylitization. The Bufa and Chichindaro rhyolites appear the least susceptible. The normally green color of the Losero and Calderones Formation, with their high content of deuteric chlorite, generally obscures the degree of propylitic alteration, but propylitic alteration may be mapped based on veinlet controlled chlorite and the amount of pyrite in the outcrop.

The main control of intensity or degree of propylitization is the presence of fractures. The more intensely propylitized rocks are close to fractures. As the distance
from a fracture increases, the intensity of alteration usually decreases. For convenience in field mapping, different intensities of propylitic alteration were mapped separately, as shown on the following page:
### PROPYLITIC FIELD MAPPING CRITERIA

<table>
<thead>
<tr>
<th>Formation</th>
<th>Intensity</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guanajuato</td>
<td>Strong</td>
<td>Over 80% of the rock appears green in outcrop, rock flooded with chlorite.</td>
</tr>
<tr>
<td></td>
<td>Weak</td>
<td>From 30 to 80% of the rock appears green in outcrop. Chlorite usually confined to fracture walls.</td>
</tr>
<tr>
<td></td>
<td>Minimal</td>
<td>Under 30% of the rock appears green in outcrop</td>
</tr>
<tr>
<td></td>
<td>to none</td>
<td></td>
</tr>
<tr>
<td>Bufa, Chichindaro,</td>
<td>Strong</td>
<td>Entire rock outcrop is from very dark to very faint green due to chlorite flooding.</td>
</tr>
<tr>
<td>Cedro, La Luz</td>
<td>Weak</td>
<td>Rock color unchanged but some lapilli or phenocrysts colored green and minor chlorite is visible on fractures.</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>No visible chlorite although minor pyrite may be present.</td>
</tr>
<tr>
<td>Calderones, Losero</td>
<td>Strong</td>
<td>Entire rock outcrop is from very dark to very faint green due to chlorite flooding. Calcite content is significant as veinlets and irregular blebs.</td>
</tr>
<tr>
<td></td>
<td>Weak</td>
<td>Chlorite is noticeable along fractures, or replacing a few lapilli or clasts. Vein calcite is 1% to 2% by volume.</td>
</tr>
<tr>
<td>Esperanza</td>
<td>Strong</td>
<td>Normally black color of formation is converted to faint to dark green.</td>
</tr>
<tr>
<td></td>
<td>Weak</td>
<td>Black color remains, but chlorite is visible along bedding planes or fractures.</td>
</tr>
</tbody>
</table>

More detailed subdivisions could have been used, however, the divisions described above were found to adequately demonstrate decreasing intensities of alteration away from
the veins.

Strongly propylitized rocks of any formation were found to contain over 16% by volume chlorite as fracture coatings and as a fine-grained discoloration of the groundmass or matrix of the rocks. A characteristic of all strongly propylitized rocks are their faint to dark green color in hand specimens. Pyrite, as euhedral cubes closely associated with fractures coated with felty chlorite, makes up from 2 to 5% of the rock by volume. Calcite, as irregular blebs between and within clasts and lapilli and as veinlets, makes up from about 1 to 8% by volume.

The groundmasses of all igneous rocks and the matrix of the sedimentary rocks appear to be the first to be altered to chlorite, leaving the crystals and lithic fragments little affected. With increasing intensity, biotite and plagioclase crystals are replaced along crystal and twin axes. Quartz and sanidine are unaltered, except in extremely propylitized samples.

Epidote is very rare. One specimen of drill core (S-18, 663 meters below collar) in the Guanajuato Formation had up to 15% epidote and 1 to 3% pyrite over a 10 centimeter core length. Core samples from the Sirena Mine (see Figure 4) contained strong epidote near the base of some deep drill holes.
Weakly propylitized rocks have up to 16% and rarely as little as 5% chlorite by volume. This chlorite normally fills only microfractures and joints, and is associated with 1 to 2% euhedral pyrite and up to 2% calcite. Normal rock colors are not changed but green coloration along fractures and joints is obvious.

Montmorillonite is ubiquitous in the propylitic zones, usually occurring as layered chlorite-montmorillonite or as illite-montmorillonite phyllosilicates. Every weak to strongly propylitized sample with visible chlorite in hand specimens gave x-ray patterns of expandable chlorite (Carroll, 1970) and expandable illite.

Figure 7 illustrates the textures of various intensities of propylitic alteration in rocks of the district. Note the presence of pyrite in most samples.

Potassic Alteration

Potassic alteration, as defined here, contains only adularia and sericite as essential minerals, and contains illite and quartz as accessory minerals. Montmorillonite is an associated mineral, but is probably present metastably, that is, it is a relict from the previous propylitic stage.

Potassically altered rocks are volumetrically second only to propylitically altered rocks, and are usually but
not always spatially related to orebodies. As with the propylitic alteration, all formations in the district show effects of this alteration. The rhyolites appear to be the more extensively and intensively altered. The major control of intensity of potassic alteration is the proximity of pre-ore stage fractures and the degree or the intensity of fracturing. For example, the sporadic potassic zones normally are adjacent or within 30 meters of the Veta Madre, usually located near junctures of the Veta Madre with hanging wall veins, located at sites of abrupt change in Veta Madre attitude, or are located in highly brecciated areas of the hanging wall or footwall.

Toward the vein, the potassic alteration grades gradually (over scores of meters) into a phyllic zone wherever the latter is present. Away from the vein, the potassic alteration grades gradually (over tens of meters is common) into the propylitic zone.

Strongly potassically altered rocks are orange, pink or yellow-brown, and are hardened and extremely brittle. The groundmass texture is obliterated on megascopic scale, and is partially replaced by a more homogeneous, very fine-grained adularia-quartz-sericite mixture. The adularia is not visible as individual grains under normal microscope examination and is recognized only by etching
Figure 7: Photomicrographs illustrating effects of propylitic alteration. A - Cedro Formation, moderate amounts of chlorite in phenocrysts; B - Calderones Formation, green-brown chlorite along microfractures and within lapilli; C - Bufa Formation, green-brown chlorite in groundmass and on lapilli rims; D - Losero Formation, green-yellow chlorite around lithic fragments; E - Guanajuato Formation, loss of hematite cement, veinlets of carbonate and pyrite, and chlorite flooding of rock. All photographs have field of view of 4.3 x 2.9 millimeters using plain polarized light (except A and D which were photographed under cross nicols).
and staining with sodium cobaltinitrite, described by Heinrich (1965). Minor veinlets of microscopic adularia are present (see Figure 8) but the bulk of the adularia is as flooding of the groundmass. Crystal and lithic fragment edges are converted to illite and rare sericite. Results from point counting indicate from 39 to 79% by volume is adularia, and from 1 to 18% by volume is illite or sericite. A very minor amount of the phyllosilicates may be metahalloysite, as this mineral was noted on a very few x-ray patterns.

The volume percentages of the alteration minerals vary with the lithology. The above figures apply to the volcanic formations and to the Guanajuato conglomerate. The Esperanza Formation, on the other hand, contains more sericite by volume than adularia and illite, except in extremely altered fragments enclosed in the veins where adularia predominates. Sericite and illite average 30% and adularia, 20% in strongly potassically altered areas of the Esperanza Formation. Calcite, as veinlets, can constitute up to 14% by volume of the altered rock, but much, if not all of this may be related to a younger alteration stage affecting the Esperanza Formation. Pyrite, as disseminated euhedral cubes, constitutes up to 11% by volume. The black color of the shales is changed to
lustrous white where sericite predominates, and to creamy white where adularia and some clays predominate.

Field criteria for drawing a border between strong and weak potassic alteration is subjective at best as there exists no sharp natural cutoff. If a rock was hardened, turned deep pink or orange, and the groundmass granularity was obliterated, it was called strongly altered. If original color remains, if hardness is little affected, and if the groundmass retains its textures, the affects of potassic alteration are negligible. Between these two extremes are every gradation of intensity. Usually the border between weak and strong was chosen at the appearance of a strong color change. This is a very subjective division, but it corresponds well to a definite rapid increase in brittleness and hardness, and corresponds less well to an obliteration of groundmass textures.

Argillic Alteration

Argillic alteration, as defined here, contains kaolinite, halloysite, and montmorillonite as the diagnostic or essential minerals. Quartz is the only accessory mineral. Any other mineral present in these zones is probably present as metastable phases. Pyrophyllite was searched for but was not found in any x-ray pattern.
Figure 8: Photomicrographs illustrating effects of potassic alteration. A - Bufa Fm., with flooding by very fine-grained sericite rosettes and adularia crystals along microveinlets, crossed nicols; B - Losero Fm., with yellow-brown rosettes and irregular crystals of sericite and adularia along microveinlets and along grain boundaries, plain light. Both photographs have a field of view of 1.8 x 1.1 millimeters.
Argillic alteration is the least extensive of the alteration grades along the Veta Madre and its distribution bears a very close spatial relation to orebody location. Outcrops of rocks of this alteration grade are thin, short, and irregularly distributed along the Veta Madre and parallel veins, and rarely extend beyond 20 meters into either wall. Where present, this alteration passes rapidly into a phyllic zone (see following section) which in turn passes into either a potassic or propylitic zone or directly into essentially unaltered wall rocks. This crosscutting relation indicates that argillic alteration is not one final front of a series of fronts advancing from a common source. Rather, it resulted from a temporally separate introduction of chemically different hydrothermal fluids which for the most part followed the same channels as the previous altering fluids, but also commonly followed channels which formed after the end of potassic alteration.

All formations altered to the argillic grade are cream, white, or pale yellow in color, no matter what the original color or lithology. Rocks subjected to argillization appear so similar, and textures are so nearly completely destroyed, that field relationships are often the only criteria for naming the altered formation. Kaolinite, halloysite, and montmorillonite comprise from
15 to 98% of the rock by volume. Where the argillic zone cuts potassic zones, specimens contain from 1 to 48% illite and up to 15% adularia by volume. Except for quartz, sanidine is the last mineral to alter to clays, and is normally rimmed with illite, which in turn is rimmed with montmorillonite.

The total amount of kaolinite and halloysite is small, always restricted to vein walls, and grades outwards to montmorillonite. The montmorillonite often grade outwards into sericite and/or illite (passing into the phyllic zone, discussed below). As would be expected, the metastable phases present (adularia and chlorite) are more common near the outer boundaries of the argillic zone, and much more common in the phyllic zone.

The argillic zones are generally restricted to the outer edges of ore zones. Thus, in passing from barren rock, a zone of argillic alteration is normally encountered prior to an ore shoot, and once the argillic zone is passed, ore grade rises and potassic alteration is the primary alteration present. As stated under vein mineralogy, the ore stage fluids also deposited adularia and calcite within the veins, therefore, it is possible to trace vein calcite and adularia from the center of an ore shoot into the argillic zone, where the calcite is removed and the adularia
is converted to clay minerals. The close spatial association of the argillic zones with ore stage veinlets, and the argillization of ore stage adularia in the argillic zones, indicate that at least some of the argillic alteration formed after the ore deposition. It may be the result of a more spatially restricted, more acidic, final phase of the same rising ore fluids, and will be discussed at length in subsequent sections.

Figure 9 illustrates the textures of argillized rocks. Figure 10 illustrates the well crystallized morphology of the halloysite and kaolinite, indicating that the clays are not supergene (weathering) products (Buchanan, 1979).

Flat to gently dipping fractures often have thicker argillic alteration selvages on the hanging wall than on the footwall, possibly indicating that the solutions in these fractures had an uneven pH distribution. Also, these same fractures show an uneven banding of vein minerals, with thick zones of platey minerals such as chlorite and sericite on the hanging wall, often accompanied by thicker masses of ore minerals. Figure 11 illustrates these features.

**Phyllic Alteration**

Phyllic alteration, as defined here, contains sericite, illite, and pyrite as essential minerals. Kaolinite,
Figure 9: Photomicrographs illustrating effects of argillic alteration. A - Cedro Fm., phenocrysts lined with clays, groundmass largely montmorillonite; B - Calderones Fm., complete destruction of deuteric chlorite and obliteration of groundmass textures; C - Bufa Fm., sample now approximately 90% montmorillonite; faint outlines of crystal lapilli visible; D - Losero Fm., groundmass texture destroyed by clays and illite, crossed nicols. All photographs have a field of view of 4.3 x 4.1 millimeters. Photographs A, B, and C were photographed in plain light.
Figure 10: Scanning electron photomicrographs illustrating clay mineral morphology from argillized Bufa Formation. A - Kaolinite rosettes of hexagonal crystals, field of view 0.33 x 0.22 microns; B - Halloysite rods, field of view 1.7 x 1.1 microns.
Figure 11A: View of veins in Block 3-North, 560 level, showing argillic alteration is more intense and wider on the hanging wall than on the footwall.

Figure 11B: Close up of ore stage veinlet (Losero Type) showing uneven banding with thicker chlorite bands on the hanging wall of veinlets. Paper is 1.2 centimeters wide.
halloysite, and montmorillonite may be present as accessories.

Phyllic alteration is characteristically an illite and sericite flooding of the wall rock groundmass, causing the rock to be slightly paler in color. The Bufa Formation is slightly lightened, and the rock is more friable. The Cedro Formation is whitened from its normally grey color, and is made extremely friable. The Chichindaro Formation is converted into a dull white, soft rock, with all textures obliterated in extreme cases of alteration.

At the Las Torres Mine, phyllic alteration is restricted to a sporadic, often missing, border phase between the argillic alteration and the host rocks. Phyllically altered rocks, therefore, grade outwards into fresh, propylitically, or potassically altered host rocks, and grade inwards towards the fracture into argillic alteration. Often, this phyllic zone between argillic alteration and the host rock is missing, especially in deeper levels of the Las Torres Mine. Conversely, the argillic zone is often missing, especially in higher elevations. The location and intensity of phyllic alteration also appears to be controlled by the Calderones contact with the Bufa rhyolite, as is illustrated in Figure 14. At the contact, the phyllic zone spreads out below
the Calderones Formation and the rock is altered for up to 400 meters into the hanging wall. This phyllic blanket below the contact possibly indicates the spread of solutions below a semi-impermeable cap. This impermeable layer would correspond to the shales and fine clastics at the base of the Calderones Formation. The close spatial association of phyllic and argillic alteration strongly suggests that the two alteration types are genetically related, with the phyllic forming as a response to a higher pH front than did the argillic.

The occurrence of such phyllic caps above ore zones are well documented for precious and base metal veins (Sorenson, 1951; Steven and Eaton, 1975; Dreier, 1976) as well as above present day sulfide-depositing vapor-dominated geothermal systems (White, 1970).

Figure 12 illustrates the textural changes in phyllically altered rocks. Note the presence of pyrite.

Other Alteration Types

Silicification: Quartz is a product of not only vein filling but also of propylitic, potassic, argillic and phyllic alteration. Where used in this report, however, the term silicification refers to wall rock which contains hydrothermally introduced quartz as the major component. Silicified Calderones Formation is present on the 310 level
Figure 12: Photomicrographs illustrating effects of phyllic alteration. A - Calderones Fm., crystal rims blurred by illite, and showing chlorite from the earlier propylitic alteration; B - Bufa Fm., strong illite flooding of groundmass and illite within plagioclase crystals; C - Guanajuato Fm., extreme flooding by illite, removal of hematite cement, and obliteration of fine textural detail of clasts. All photographs have field of view of 1.1 x 1.0 millimeters. Photographs A and B taken in plain light, C using crossed nicols.
of the Las Torres Mine, where the formation imperceptibly merges into the hanging wall of the Veta Madre. The rock is extremely hard, dense, and grades outward into propylitized wall rock. A hanging wall zone 6 meters wide and 40 meters long of silicified Buña Formation is present on the 390 level of the mine. The rhyolite is converted into a grey, granular rock with visible sanidine and other crystal lapilli.

Silicification is pre-argillization as the silicified zone on the 390 level has been extensively fractured, mineralized, and subjected to weak to strong argillic alteration.

Figures 13A and 13B illustrate the spatial relationships between the alteration grades on the four levels of the mine and Plate 1 illustrates the surface alteration.

Figure 14 shows the alteration patterns in a cross section through the Las Torres Mine.
FIGURE 13A
WALL ROCK ALTERATION IN THE LAS TORRES MINE,
GUANAJUATO, MEXICO

LEGEND

- ESSENTIALLY FRESH ROCK
- PRE-ORE POTASSIC (STRONG)
- PRE-ORE PROPILITIC (WEAK)
- ORE STAGE PHYLIC
- PRE-ORE PROPILITIC (STRONG)
- ORE STAGE ARGILLIC (WEAK)
- PRE-ORE POTASSIC (WEAK)
- ORE STAGE ARGILLIC (STRONG)
- VISTA MARK
- ORE SHOT
- UNDERGROUND WORKING
- DRILL HOLE INTERCEPT
- FAULT
- DRILL HOLE ON LEVEL

SEE TEXT FOR DESCRIPTIONS OF ALTERATION

SCALE
0 50 100 m.
FIGURE 14: WALL ROCK ALTERATION ALONG SECTION A-A'
LAS TORRES MINE, GUANAJUATO, MEXICO

FOR LEGEND, SEE FIGURE 13A

HORIZONTAL = VERTICAL
FLUID INCLUSION STUDY

General

Part of a study of ore controls must include a study of the physical and chemical state of the ore-forming fluids. Fluid inclusions are the major source of such information, yielding data on the temperature of mineral deposition, the density and salinity of the ore-forming fluids, and the pressure on the system. Under certain circumstances, the depth of formation below the paleo-surface can be determined. It is already concluded that the deposition of the Las Torres ore was controlled by unknown factors in addition to structural and stratigraphic controls; indeed, the neatly arranged three ore horizons (Gross, 1975) might imply some kind of a pressure-temperature-depth relationship. A study of fluid inclusions was deemed necessary to determine what, if any, pressure-temperature-depth relation may have existed.

Fluid inclusions can also yield quantitative chemical data if the liquids are extracted and analysed. Using these data in combination with information on mineral paragenesis, the pH of the solutions and fugacities of various volatile species can be determined. As the ore-related late stage argillic and phyllic alteration is likely a function of pH, such chemical analyses were required to understand the
processes of ore deposition.

Fluid inclusion studies also yield information on the changes in time of solutions, if pre-ore, ore, and post ore samples are analysed and compared. The wall rock alteration at Las Torres formed during at least two discrete stages and not as a series of advancing chemical fronts, and post ore hydrothermal alteration is absent. Temporal changes in the chemical state of the rising fluids must have existed. These changes were studied by comparison of the physical and chemical states of the fluids in the inclusions from the various stages.

Methods

The vocabulary of fluid inclusion studies is completely discussed by Roedder (1967) and his terminology is used in this report. Symbols used in the remainder of this report are listed below:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Th</td>
<td>Homogenization temperature</td>
</tr>
<tr>
<td>Tf</td>
<td>Last melting temperature</td>
</tr>
<tr>
<td>v</td>
<td>Vapor phase</td>
</tr>
<tr>
<td>l</td>
<td>Liquid phase</td>
</tr>
<tr>
<td>P</td>
<td>Primary fluid inclusion</td>
</tr>
<tr>
<td>S</td>
<td>Secondary fluid inclusion</td>
</tr>
<tr>
<td>PS</td>
<td>Pseudosecondary fluid inclusion</td>
</tr>
<tr>
<td>Sp</td>
<td>Sphalerite</td>
</tr>
<tr>
<td>Cp</td>
<td>Chalcopyrite</td>
</tr>
<tr>
<td>El</td>
<td>Electrum</td>
</tr>
<tr>
<td>Ha</td>
<td>Halloysite</td>
</tr>
<tr>
<td>Ac</td>
<td>Acanthite</td>
</tr>
<tr>
<td>Py</td>
<td>Pyrite</td>
</tr>
<tr>
<td>Ad</td>
<td>Adularia</td>
</tr>
<tr>
<td>Se</td>
<td>Sericite</td>
</tr>
<tr>
<td>Qt</td>
<td>Quartz</td>
</tr>
<tr>
<td>Ca</td>
<td>Calcite</td>
</tr>
<tr>
<td>Fl</td>
<td>Fluorite</td>
</tr>
<tr>
<td>Gn</td>
<td>Galena</td>
</tr>
<tr>
<td>Ch</td>
<td>Chlorite</td>
</tr>
<tr>
<td>Ka</td>
<td>Kaolinite</td>
</tr>
<tr>
<td>Mo</td>
<td>Montmorillonite</td>
</tr>
</tbody>
</table>
Careful sample selection is of the utmost importance in any fluid inclusion study. Each sample used in this study was classified as pre-ore, ore stage, or post ore, depending on its paragenetic position, and ore stage samples were further subdivided into silver deposition and gangue deposition stages. Fluid inclusions in the samples were tested for temperatures of homogenization (Th) and last melting temperatures (Tf) prior to extraction of the liquids. Pre-ore samples which were uncontaminated by microveinlets of later ore stage mineralization were difficult to find, in fact, only one such sample was found and even it had a very minor amount of ore stage mineralization. Ore stage (silver episode) samples were readily found, as were post silver fillings of vein centers.

Once a sample was selected for extraction of the inclusion liquids, cleaning procedures were followed, as outlined in Appendix B. Locations of all samples used in all tests are shown on Plate 2.

Pre-Ore Inclusions

All pre-ore samples contained fluid inclusions. Measurements of their sizes using a calibrated graduated ocular indicated that usable primary inclusions averaged 28 microns in largest dimension; rarely an inclusion as large as 100 microns was found. Even at 450x magnification,
clear resolution of the small inclusion interiors was seldom obtained. For homogenization temperature (Th) measurements, only the larger inclusions were studied (at up to 320x magnification) and visibility and clarity of view were found to be quite adequate to make precise temperature readings. However, for the last melting temperature (Tf) measurements to determine salinities, measurements were found to be nonreproducible and not in agreement with analysed fluids, because the poor visibility of inclusion interiors precluded observation of nearly invisible ice crystals. The temperatures attending rapid expansion in vapor phase sizes or in changes in vapor phase position were recorded as the Tf, but as some ice obviously must still have existed, the majority of these temperature readings were too low. This would have indicated salinities grossly larger than actually existed. For this reason, freezing tests were discontinued on pre-ore samples.

Pre-ore fluid inclusion shapes were irregular, often elongated perpendicular to crystal growth planes. Most pre-ore Th readings are on pseudosecondary fluid (PS) inclusions. All pre-ore inclusions had only two phases: vapor and liquid. Vapor phase volumes were variable from 4 to 99% of total inclusion volume, indicative of trapping
of a nonhomogeneous (a boiling) solution. Trapping of a solution undergoing boiling is also indicated by the wide range in Th readings, from 231°C to over 360°C. These figures are tabulated on Table 1. Under boiling conditions, the lower Th is normally selected as being closest to the true temperature of formation, assuming that the primary inclusions that homogenize at the lowest temperature are those that trapped the smallest amount of vapor during crystal growth. It is concluded that the temperature of formation of pre-ore vein material at Las Torres is 231°C. Based on the analysed salinity of pre-ore solutions (see Table 3), a solution density of 0.85 grams per cubic centimeter is calculated (Haas, 1976).

Ore Stage Inclusions

All ore stage samples contained numerous inclusions. Measurements of their sizes indicated that usable primary fluid inclusions averaged only 11 microns in maximum dimension. The largest inclusion was 40 microns across. Inclusions used were considerably smaller than those of the pre-ore stage, and the limitations on arriving at meaningful salinity data that apply to the pre-ore stage also apply to the ore stage samples.

Ore stage (silver episode) inclusions have a widely variable salinity as indicated by daughter minerals in
<table>
<thead>
<tr>
<th>SAMPLE NUMBER</th>
<th>MINERAL</th>
<th>FI TYPE</th>
<th>R RANGE °C</th>
<th>NUMBER OF READINGS</th>
<th>% VAPOR RANGE</th>
<th>EVIDENCE OF BOILING</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRE-ORE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FI-19-B</td>
<td>Qt</td>
<td>P</td>
<td>231-360</td>
<td>11</td>
<td>4-65</td>
<td>(4)</td>
<td>Extracted sample.</td>
</tr>
<tr>
<td>0809</td>
<td>Ca</td>
<td>PS</td>
<td></td>
<td></td>
<td>18-40</td>
<td>(4,5)</td>
<td></td>
</tr>
<tr>
<td>ORE-SILVER EPISODE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALUN</td>
<td>Qt</td>
<td>P</td>
<td>284</td>
<td>1</td>
<td>11-22</td>
<td>(1)</td>
<td>Much ad in vein.</td>
</tr>
<tr>
<td>B-3</td>
<td>Qt</td>
<td>P</td>
<td>254-265</td>
<td>3</td>
<td>2</td>
<td>none</td>
<td>Liquid CO₂ in S incl.</td>
</tr>
<tr>
<td>B-145</td>
<td>Ca</td>
<td>S</td>
<td>29</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ca</td>
<td>S</td>
<td>82</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ca</td>
<td>S</td>
<td>200-202</td>
<td>2</td>
<td>10-17</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ca</td>
<td>P</td>
<td>234-360</td>
<td>6</td>
<td>20-50</td>
<td>(4,5)</td>
<td>At base of main ore-body.</td>
</tr>
<tr>
<td>F-2</td>
<td>Qt</td>
<td>P</td>
<td>246-287</td>
<td>4</td>
<td>18-99</td>
<td>(4)</td>
<td></td>
</tr>
<tr>
<td>F-9</td>
<td>Qt</td>
<td>P</td>
<td>282</td>
<td>1</td>
<td>15</td>
<td>(4)</td>
<td></td>
</tr>
<tr>
<td>F-11</td>
<td>Qt</td>
<td>P</td>
<td></td>
<td></td>
<td>20-99</td>
<td>(4)</td>
<td></td>
</tr>
<tr>
<td>FI-15</td>
<td>Qt</td>
<td>P</td>
<td>246-372</td>
<td>10</td>
<td>11-40</td>
<td>(4,5)</td>
<td></td>
</tr>
<tr>
<td>FI-17</td>
<td>Qt</td>
<td>P</td>
<td></td>
<td></td>
<td>4-20</td>
<td>(4)</td>
<td></td>
</tr>
<tr>
<td>FI-18</td>
<td>Ca</td>
<td>P</td>
<td>257</td>
<td>1</td>
<td>10-30</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ca</td>
<td>S</td>
<td>212-217</td>
<td>3</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FI-19-0</td>
<td>Qt</td>
<td>P</td>
<td>271</td>
<td>1</td>
<td>6-55</td>
<td>(4)</td>
<td></td>
</tr>
<tr>
<td>F-35-0</td>
<td>Qt</td>
<td>P</td>
<td>346</td>
<td>1</td>
<td>7-44</td>
<td>(4)</td>
<td></td>
</tr>
<tr>
<td>S-16-1730</td>
<td>Ca</td>
<td>P</td>
<td>235-261</td>
<td>7</td>
<td>13-27</td>
<td>(3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ca</td>
<td>S</td>
<td>219-230</td>
<td>4</td>
<td>7-15</td>
<td>(3)</td>
<td></td>
</tr>
<tr>
<td>390SEX</td>
<td>Qt</td>
<td>P</td>
<td>228-265</td>
<td>5</td>
<td>9-20</td>
<td>(4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Qt</td>
<td>S</td>
<td>203-217</td>
<td>3</td>
<td>13-15</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>472</td>
<td>Ca</td>
<td>P</td>
<td>258-320</td>
<td>5</td>
<td>6-25</td>
<td>(4,5,6)</td>
<td>Many P inclusions have 2% by vol. NaCl and 1% KCl daughters.</td>
</tr>
<tr>
<td></td>
<td>Ca</td>
<td>S</td>
<td>174-180</td>
<td>3</td>
<td>9-13</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>5D</td>
<td>Qt</td>
<td>P</td>
<td>&gt;360</td>
<td>4</td>
<td>18-99</td>
<td>(2,3,4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ca</td>
<td>P</td>
<td>261-276</td>
<td>5</td>
<td>17-33</td>
<td>(2,3)</td>
<td></td>
</tr>
<tr>
<td>Sample</td>
<td>Type</td>
<td>Size</td>
<td>Quantity</td>
<td>Molar Composition</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
<td>------------</td>
<td>----------</td>
<td>-------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>517</td>
<td>Ca</td>
<td>234-356</td>
<td>6</td>
<td>20-99</td>
<td>(1,4,7)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>524</td>
<td>Qt</td>
<td>174-214</td>
<td>5</td>
<td>10-90</td>
<td>(4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>534</td>
<td>Qt</td>
<td>335</td>
<td>1</td>
<td>10-99</td>
<td>(4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>541</td>
<td>Qt</td>
<td>232-299</td>
<td>14</td>
<td>10-40</td>
<td>(4,5,6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>77-4</td>
<td>Qt</td>
<td>217</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>77-7</td>
<td>Qt</td>
<td>267-312</td>
<td>10</td>
<td>10-99</td>
<td>(1,4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0804</td>
<td>Qt</td>
<td>225≤360</td>
<td>67</td>
<td>8-99</td>
<td>(1,2,4,5,7) See text.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0807-1</td>
<td>PS</td>
<td>241</td>
<td>1</td>
<td>10-99</td>
<td>(4,6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Qt</td>
<td>222-225</td>
<td>2</td>
<td>10-80</td>
<td>(4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0813</td>
<td>Qt</td>
<td>243-339</td>
<td>4</td>
<td>8-99</td>
<td>(3,4,5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0828</td>
<td>Qt</td>
<td></td>
<td></td>
<td>70-99</td>
<td>(4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FI-20</td>
<td>Ca</td>
<td>228-249</td>
<td>4</td>
<td>4-9</td>
<td>none</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FI-21-0</td>
<td>Qt</td>
<td>248≤360</td>
<td>3</td>
<td>12-25</td>
<td>(5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ca</td>
<td>200-206</td>
<td>2</td>
<td>10-30</td>
<td>none</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FI-23-0</td>
<td>Qt</td>
<td>236-237</td>
<td>6</td>
<td>14-25</td>
<td>none</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FI-24-0</td>
<td>Ca</td>
<td></td>
<td></td>
<td>12-75</td>
<td>(4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FI-26-0</td>
<td>Qt</td>
<td>248-340</td>
<td>14</td>
<td>7-95</td>
<td>(4,5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FI-29-0</td>
<td>Ca</td>
<td>234≤360</td>
<td>5</td>
<td>10-60</td>
<td>(4,5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Qt</td>
<td>215</td>
<td>1</td>
<td>10-26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FI-30-0</td>
<td>Qt</td>
<td>244≤360</td>
<td>9</td>
<td>9-40</td>
<td>(4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FI-31-0</td>
<td>Qt</td>
<td>270-290</td>
<td>10</td>
<td>20-28</td>
<td>none</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FI-32-0</td>
<td>Qt</td>
<td>248≤360</td>
<td>7</td>
<td>12-99</td>
<td>(2,4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FI-33-0</td>
<td>Qt</td>
<td></td>
<td></td>
<td>7-52</td>
<td>(4,6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FI-34-0</td>
<td>Qt</td>
<td>288-318</td>
<td>8</td>
<td>15-99</td>
<td>(2,3,4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0838</td>
<td>Qt</td>
<td>261-263</td>
<td>2</td>
<td>9-30</td>
<td>(1,4)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A few inclusions have numerous daughters, all dissolve at under 230°C.

One inclusion has 2 v. small daughters, unidentified.

One inclusion has a v. small daughter, unidentified.

Cloudy liquid phase.
<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Qt</td>
<td>P</td>
<td>269±360</td>
<td>3</td>
<td>10-80</td>
<td>(1,4,5)</td>
</tr>
<tr>
<td>Qt</td>
<td>S</td>
<td>190</td>
<td>1</td>
<td>11-40</td>
<td>(4)</td>
<td></td>
</tr>
<tr>
<td>Qt</td>
<td>P</td>
<td>297-350</td>
<td>2</td>
<td>10-47</td>
<td>(4,5)</td>
<td></td>
</tr>
<tr>
<td>Qt</td>
<td>S</td>
<td>176</td>
<td>2</td>
<td>10</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>Qt</td>
<td>P</td>
<td>242-310</td>
<td>3</td>
<td>20-99</td>
<td>(4,5)</td>
<td></td>
</tr>
<tr>
<td>Qt</td>
<td>P</td>
<td>245±360</td>
<td>7</td>
<td>18-99</td>
<td>(4,5)</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>P</td>
<td>270</td>
<td>1</td>
<td></td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>PS</td>
<td>269</td>
<td>1</td>
<td></td>
<td>15-28</td>
<td></td>
</tr>
<tr>
<td>Qt</td>
<td>P</td>
<td></td>
<td></td>
<td>8-28</td>
<td>(4)</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>P</td>
<td>239-269</td>
<td>6</td>
<td>15-80</td>
<td>(1,4)</td>
<td></td>
</tr>
<tr>
<td>Qt</td>
<td>P</td>
<td>239-269</td>
<td>6</td>
<td>15-80</td>
<td>(1,4)</td>
<td></td>
</tr>
</tbody>
</table>

ORE - POST SILVER EPISODE

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>F-9</td>
<td>Ca</td>
<td>P</td>
<td>257-268</td>
<td>3</td>
<td>20</td>
<td>none</td>
</tr>
<tr>
<td>FI-27</td>
<td>Ca</td>
<td>P</td>
<td>255-261</td>
<td>7</td>
<td>2-60</td>
<td>(4)</td>
</tr>
<tr>
<td>FI-31-0</td>
<td>Ca</td>
<td>P</td>
<td>360</td>
<td>1</td>
<td>9-28</td>
<td>(4)</td>
</tr>
<tr>
<td>0813</td>
<td>Ca</td>
<td>P</td>
<td>265-333</td>
<td>3</td>
<td>15</td>
<td>(5)</td>
</tr>
<tr>
<td>0845</td>
<td>Ca</td>
<td>P</td>
<td>231-234</td>
<td>3</td>
<td>6-90</td>
<td>(2,4)</td>
</tr>
<tr>
<td>FI-20</td>
<td>Ca</td>
<td>S</td>
<td>97</td>
<td>2</td>
<td>1</td>
<td>none</td>
</tr>
<tr>
<td>Ca</td>
<td>S</td>
<td>210-221</td>
<td>3</td>
<td>4-9</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>330</td>
<td>Ca</td>
<td>P</td>
<td>250-369</td>
<td>6</td>
<td>10-40</td>
<td>(4,5)</td>
</tr>
<tr>
<td>390-78</td>
<td>Ca</td>
<td>P</td>
<td>238-317</td>
<td>4</td>
<td>2-36</td>
<td>(4,5)</td>
</tr>
<tr>
<td>Ca</td>
<td>PS</td>
<td>233-303</td>
<td>6</td>
<td>9-29</td>
<td>(5)</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>S</td>
<td>223-225</td>
<td>2</td>
<td>7-17</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>4-10</td>
<td>Ca</td>
<td>S</td>
<td>89-105</td>
<td>3</td>
<td>2-20</td>
<td></td>
</tr>
<tr>
<td>505</td>
<td>Ca</td>
<td>PS</td>
<td>243±360</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>S</td>
<td>208</td>
<td>1</td>
<td></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>533</td>
<td>Ca</td>
<td>P</td>
<td>234-271</td>
<td>5</td>
<td>5-15</td>
<td></td>
</tr>
<tr>
<td>FI-35</td>
<td>Ca</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>77-1</td>
<td>Ca</td>
<td>S</td>
<td>201-205</td>
<td>6</td>
<td>5-25</td>
<td>(4)</td>
</tr>
<tr>
<td>77-7</td>
<td>Ca</td>
<td>P</td>
<td>266-297</td>
<td>3</td>
<td>13-44</td>
<td>(1,4,5)</td>
</tr>
<tr>
<td>Ca</td>
<td>S</td>
<td>85-113</td>
<td>7</td>
<td>1-8</td>
<td>none</td>
<td></td>
</tr>
</tbody>
</table>
TABLE 1, CONTINUED

<table>
<thead>
<tr>
<th></th>
<th>Ca</th>
<th>PS</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0807-2</td>
<td>Ca</td>
<td>PS</td>
<td>252-333</td>
<td>5</td>
<td>(5)</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>S</td>
<td>90-93</td>
<td>4</td>
<td>1</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>P</td>
<td>267-293</td>
<td>4</td>
<td>none</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>S</td>
<td>180-193</td>
<td>2</td>
<td>8</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>0804</td>
<td>Ca</td>
<td>P</td>
<td>235±360</td>
<td>25</td>
<td>8-99</td>
<td>(1,2,4,5)</td>
</tr>
</tbody>
</table>

Notes:

1 Quartz (Qt); Calcite (Ca)

2 Evidence of boiling:
   (1) Inclusions aligned in bands
   (2) Highly shredded ore and gangue
   (3) Megascopic evidence (uneven banding, uneven argillic alteration in/on vein)
   (4) Variable vapor percent
   (5) Variable Th
   (6) Widely variable salinities
   (7) Inclusions spatially related to silver deposition
some inclusions (in samples FI-34-0, 807-1, 77-4, and 472). All daughters were very small (less than 2% of the total inclusion volume), and could not be identified (the solid phases were in Brownian motion and appeared to be thin, transparent, hexagonal (?), plates, possibly phyllosilicates). However, by far the majority of inclusions had no daughters (Table 1). Those few samples with solid phases are believed to contain accidentally trapped mineral grains, and do not contain true daughter salts. Table 1 lists details of fluid inclusion heating runs. Figure 15 shows the data in histogram form.

Ore stage fluid inclusion shapes were irregular, and often elongated perpendicular to growing crystal faces. The elongation results in either subparallel bands of inclusions with each inclusion aligned perpendicular to the band, or in nearly circular clusters of inclusions radiating outward from a central growing crystal (Figures 16 and 17). These bands indicate increases in the number of fluid inclusions which were trapped, followed by periods of crystal growth which trapped few inclusions. On inspection of these bands at higher magnification, it is noted that the inclusions have highly variable degrees of fill (see Figure 18), indicating that a vapor phase must have been present during the time the band was forming.
Figure 15: Histograms of the data presented in Table 1, showing the temperatures of mineral deposition (dashed lines) for the pre-ore stage, the silver episode of the ore stage, and the post silver episode of the ore stage.
Figure 16: Photomicrograph of sample 0804 showing traverse line of Figure 19. Note bands of acanthite (black) and cloudy bands of primary fluid inclusions separated by clear areas of few inclusions. Length of traverse is 1.06 cm. Potassically altered wall rock is in lower left corner, vein center is at right end of the traverse line.
Figure 17: Close-up of radiating bands of primary fluid inclusions from sample 0804, view is nearly parallel to the c axis of a quartz crystal. Note the inclusions are elongated perpendicular to the crystal faces. Field of view is 300 x 200 microns.
Figure 18: Close-up of primary fluid inclusions in quartz from sample 0804 showing variable degrees of fill of inclusions. The inclusion at A has approximately 18% vapor by volume, but the inclusion at B is approximately 99% vapor. For scale, the inclusion at A is 8 microns in maximum dimension.
Any irregularity on the face of a growing crystal can initiate the trapping of a fluid inclusion. If a separate vapor phase (in the form of bubbles) was present during the crystal growth, it can be assumed with confidence that small bubbles adhering to the crystals caused more frequent fluid inclusion entrapment as these bubbles served as nucleation centers. As the crystal face grew, the bubble could ride outwards on the surface of the face, forming an elongated cavity behind it. Considerable evidence supporting this mechanism is given by Roedder (1972). If it is accepted that the bubbles helped cause the bands of fluid inclusions observed in most samples, then an additional conclusion is that the intensity of bubbling (another way of saying the intensity or degree of boiling) was highly episodic. The degree of boiling passed through several peaks, recognized as bands of greater fluid inclusion frequency. Intervening were periods of less intense boiling.

In order to test this conclusion, a point count of the number of fluid inclusions across a veinlet was made. The traverse was perpendicular to the vein wall to the vein center on sample 0804. The number of inclusions intercepted by a 3 micron grid along the line of traverse was recorded and plotted on Figure 19. Th values recorded
FIGURE 19

VARIATION IN THE NUMBER OF FLUID INCLUSIONS IN EACH 126 MICRON INTERVAL ACROSS ORE STAGE VEINLET IN SAMPLE 0804, SHOWING THE VALUES OF PRIMARY INCLUSIONS FROM THE WALL ROCK TO VEIN CENTER ALONG TRAVERSE LINE. ALSO SHOWING BANDS OF Ac, Ad, Se, and Qt ALONG TRAVERSE LINE
along the same traverse line were plotted, as were mineralogical variations.

Note that the density of fluid inclusions is not constant and that a correlation exists between silver sulfide deposition and high densities of fluid inclusions. Also note the very close correlation between deposition of the silver minerals and deposition of adularia and sericite.

These features indicate that periodic boiling was accompanied by argentite, adularia, and sericite precipitation. The temperatures shown on Figure 19 indicate a very gradual temperature rise from 225°C at the wall rock to 240°C at the vein center. The gentle slope of the temperature curve strongly suggest that fluctuations in temperature played no role in silver deposition. Also suggested is that the post silver episode was accompanied by only minor boiling.

Not all ore stage samples had the same number of acanthite bands as sample 0804. Those veins that were permeable during numerous periods of boiling would be expected to have numerous acanthite bands; those that were sealed would have only one or a few bands. Nevertheless, as shown in Table 1, primary fluid inclusions in all samples invariably showed strong evidence of boiling except for two samples from deep in the system (numbers FI-20-0
and FI-21-0). These two samples may mark the deepest level reached by boiling.

The values indicate that the ore stage precipitated at 225°C up to 235°C during silver mineralization, and calcite and quartz gangue continued to precipitate up to 240°C. Ore stage samples from both the upper and lower ore horizons showed the same Th and samples from both horizons indicated boiling occurred.

As the solutions were boiling during mineralization, no pressure correction to the Th values is necessary. At an average temperature of 230°C, a solution with the salinities shown on Table 3 will boil at a depth of 340 meters (Haas, 1976), assuming hydrostatic conditions. However, a serious difficulty immediately arises: Samples at a depth of over 650 meters below the present surface are shown to have been boiling (see Plate 2 and Table 1), and under a 650 meter hydrostatic head, the pressure would be too great to allow boiling. Obviously, the Las Torres deposits were not formed under a simple hydrostatic condition. Only temperature changes, pressure changes, or major changes in solution chemistry can initiate boiling at a fixed elevation. Since the temperature is relatively stable, and the salinity varies only slightly (Table 3), the obvious conclusion must be that pressure fluctuated...
episodically. This would allow the observed episodic boiling.

It can be argued that a high partial pressure of dissolved gases within the solution would allow boiling at depths in excess of 340 meters. CO$_2$ would be the most common such gas. At a depth of 650 meters, a temperature of 230°C, and a salinity of approximately 5260 ppm (see Table 3), the CO$_2$ partial pressure would have to be greater than 26 atmospheres (Haas, 1976). As will be shown, the fugacity of CO$_2$ had been calculated at $10^{-1.43}$, giving a partial pressure of only 0.037 atmospheres.

This small amount may be due to previous loss of CO$_2$ to the vapor phase, or just as likely, may be due to a very low initial amount of CO$_2$ in the fluids. The former (most CO$_2$ is lost to the vapor phase during boiling) seems unlikely in that: a) most fluid inclusions are dominated by water vapor and liquid, with no observable liquid CO$_2$, and b) if large amounts of CO$_2$ had originally been present, allowing the fluids to boil at depths in excess of 340 meters, why would boiling have been episodic? It is assumed that the low CO$_2$ fugacity is indicative of a very low original CO$_2$ content, and the conclusion must be that CO$_2$ was not present in sufficient concentrations to allow boiling at the depths studied. Again, this leaves
pressure fluctuations as the most simple cause of the observed boiling.

Fluid Inclusions of the Deep Ore Horizon

As stated previously, no Deep ore horizon has yet been searched for at Las Torres. The only good exposure of a deep ore zone is at the Rayas Mine, 7 kilometers northwest of the Las Torres Mine. This mine is also on the Veta Madre. Fluid inclusion samples of all levels of ore at Rayas were studied to determine the physical state of the fluids during precipitation of deep sulfide assemblages and higher Ag-Au ores. Results are tabulated in Table 2.

Prior to discussing these data, it is important that the reader understand that it is reasonable that significant differences may exist in the chemical and physical state of fluids between two sample sites so far apart. This is true even though both sites are on the same fracture system and mineralization at both sites formed within the same geothermal system.

Obviously, a major point of departure between Rayas and Las Torres is the temperature of precipitation of the ore stages (Table 2), very strongly suggesting a horizontal thermal gradient along strike of the fracture system. Nevertheless, the data clearly indicate that at Rayas, just as at Las Torres, the Upper and Lower ore horizons
<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Mineral</th>
<th>Sample Elevation</th>
<th>Temp. (^\circ\text{C})</th>
<th>Number of Readings</th>
<th>% Elevation</th>
<th>Evidence of Boiling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FROM DEEP ORE HORIZON:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ray-2 (Qt)</td>
<td>1745 m.</td>
<td>284</td>
<td><em>(1)</em></td>
<td>22</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>Ray-5 (Sp)</td>
<td>1705 m.</td>
<td>282</td>
<td><em>(1)</em></td>
<td>25</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>Ray-5 (Qt)</td>
<td>1705 m. 297-317</td>
<td><em>(3)</em></td>
<td>20</td>
<td>none *</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ray-5 (Qt)</td>
<td>1705 m. 261-287</td>
<td><em>(8)</em></td>
<td>20-25</td>
<td>none</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3588 (Qt)</td>
<td>1705 m. 290-385</td>
<td><em>(5)</em></td>
<td>25-30</td>
<td>possibly <em>(4)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>FROM ABOVE DEEP ORE HORIZON:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3572 (Qt)</td>
<td>2090 m. 290-360</td>
<td><em>(3)</em></td>
<td>15-80</td>
<td><em>(4,5)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3573 (Qt)</td>
<td>2100 m. 329-360</td>
<td><em>(2)</em></td>
<td>30-99</td>
<td><em>(4,5)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3575 (Qt)</td>
<td>2130 m. 258-261</td>
<td><em>(3)</em></td>
<td>13-67</td>
<td><em>(4)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3578 (Qt)</td>
<td>1900 m. 278</td>
<td><em>(1)</em></td>
<td>10-90</td>
<td><em>(4)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3579 (Qt)</td>
<td>1900 m. 262-360</td>
<td><em>(7)</em></td>
<td>6-20</td>
<td><em>(5)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3580 (Qt)</td>
<td>1875 m. 323-351</td>
<td><em>(6)</em></td>
<td>15-90</td>
<td><em>(4)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3581-1 (Qt)</td>
<td>1840 m.</td>
<td></td>
<td></td>
<td>10-30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3581-2 (Qt)</td>
<td>1840 m.</td>
<td></td>
<td></td>
<td>20-55</td>
<td><em>(4)</em></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
1. Quartz (Qt); Sphalerite (Sp); Homogenization temperature (Th)
2. For evidence of boiling, see bottom of Table 1.
*Contain NaCl daughters.*
formed from boiling solutions. However, the Deep ore solutions were not boiling, were slightly warmer, and were considerably more saline than the solutions of the higher Ag-Au ores. Also, a nearly horizontal line may be drawn at approximately 1800 meters above sea level at Rayas separating the zone of boiling from the zone of nonboiling. Below the line the ores are base metal-rich, above the line the ores are sulfur-poor assemblages containing Ag and Au.

How may these data from Rayas be applied to Las Torres, assuming a general decrease in temperature of all levels of solution? Could it be that Deep ore horizon sulfides (if they exist at Las Torres) will be found to have precipitated from similarly saline, slightly warmer, nonboiling solutions? And if so, then the mineral assemblages and the salinity differences between the deep and the higher ores may suggest two different fluid sources. Evidence for this exists in the extraction data presented later in this section.

**Extraction of Fluid Inclusions**

The liquid enclosed in a fluid inclusion is a minute sample of the mineral-depositing solution, and if analysed, this liquid can yield information on the chemical state of the aqueous system. Ten samples were analysed: 1 pre-ore, 6 ore stage (silver episode) and 3 ore stage (post silver
episode) samples, following the methods outlined in Appendix B. Results are tabulated in Table 3, below. The data presented in Table 3 are semi-quantitative as the MIBK extraction method extracts close to but not exactly 100% of the metals. Also leading to a small error (estimated to be a minor factor) is the method used to estimate volume percent of fluid inclusion within the original sample. An additional minor factor leading to nonquantitative results may be the presence of metallic ions adhering to defects in the crystal lattice. As the quantitative aspects of these minor variables are not determined, the results of Table 3 must be considered as semi-quantitative, estimated by this author to have an error of much less than 10%.

The pre-ore stage sample has the highest salinity, approximately 29,200 parts per million dissolved solids, with a Ca:Na:K:Mg ratio of 96:2:2:0. Cu, As, Mn, Pb, and Au are higher by a factor of 9, 5, 14, 43, and 5, respectively than the values in the ore stage solutions. Ag, Fe, and Bi are lower by a factor of 10, 2, and 6, respectively.

The exact age of the Deep ore horizon (deposits of which are high in Cu, Pb and Zn sulfides and low in acanthite) relative to the higher horizons is not absolutely established. We cannot rule out the possibility that some of the base metal sulfides of the Deep horizon may have
### TABLE 3
SOME SPECIES IN GUAMAJUTO HYDROTHERMAL FLUIDS

<table>
<thead>
<tr>
<th>SAMPLE TYPE</th>
<th>Ca (ppm)</th>
<th>Na (ppm)</th>
<th>K (ppm)</th>
<th>Mg (ppm)</th>
<th>F (ppm)</th>
<th>Ag (ppm)</th>
<th>Se (ppm)</th>
<th>Cu (ppm)</th>
<th>Pb (ppm)</th>
<th>Zn (ppm)</th>
<th>Fe (ppm)</th>
<th>Bi (ppm)</th>
<th>Sb (ppm)</th>
<th>As (ppm)</th>
<th>Mn (ppm)</th>
<th>Au (ppm)</th>
<th>Total Sulfur</th>
<th>Cl^-</th>
<th>Total Species</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFF-ORE</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>TYPE 1 (ORE)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0807-1</td>
<td>1422</td>
<td>170</td>
<td>156</td>
<td>99</td>
<td>94.0</td>
<td>70</td>
<td>5.6</td>
<td>1.11</td>
<td>5.7</td>
<td>14.5</td>
<td>32.75</td>
<td>2.76</td>
<td>30.39</td>
<td>0.41</td>
<td>0.04</td>
<td>0.06</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>77-4</td>
<td>455</td>
<td>143</td>
<td>944</td>
<td>22</td>
<td>6.7</td>
<td>1</td>
<td>0.5</td>
<td>0.02</td>
<td>0.8</td>
<td>21.5</td>
<td>40.12</td>
<td>1.41</td>
<td>99.71</td>
<td>0.37</td>
<td>0.11</td>
<td>0.09</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>77-7</td>
<td>2815</td>
<td>102</td>
<td>398</td>
<td>0</td>
<td>14.2</td>
<td>20</td>
<td>6.9</td>
<td>0.94</td>
<td>12.9</td>
<td>49.5</td>
<td>93.63</td>
<td>8.36</td>
<td>1.97</td>
<td>2.76</td>
<td>0.16</td>
<td>0.08</td>
<td>0.01</td>
<td></td>
<td>171</td>
</tr>
<tr>
<td>0804</td>
<td>70</td>
<td>139</td>
<td>395</td>
<td>0</td>
<td>151.7</td>
<td>4</td>
<td>34.7</td>
<td>1.97</td>
<td>8.9</td>
<td>73.0</td>
<td>70.21</td>
<td>7.01</td>
<td>2.10</td>
<td>2.15</td>
<td>0.20</td>
<td>0.05</td>
<td>0.02</td>
<td></td>
<td>116</td>
</tr>
<tr>
<td>50</td>
<td>267</td>
<td>192</td>
<td>157</td>
<td>28</td>
<td>3.6</td>
<td>9.6</td>
<td>0.02</td>
<td>21.0</td>
<td>130.1</td>
<td>70.08</td>
<td>4.12</td>
<td>7.30</td>
<td>1.42</td>
<td>0.13</td>
<td>0.05</td>
<td>0.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average of 5</td>
<td>1006</td>
<td>149</td>
<td>410</td>
<td>30</td>
<td>54.0</td>
<td>24</td>
<td>11.5</td>
<td>0.81</td>
<td>11.5</td>
<td>57.7</td>
<td>61.36</td>
<td>4.73</td>
<td>22.49</td>
<td>1.42</td>
<td>0.13</td>
<td>0.07</td>
<td>0.02</td>
<td></td>
<td>107</td>
</tr>
<tr>
<td>TYPE 2 (ORE)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POST SILVER CALCITE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
precipitated during the "pre-ore" stage. The high metal values and the high sulfur contents of this stage (shown in Table 3) certainly suggest this as a possibility. The pre-ore samples at Las Torres all indicated that boiling occurred (Table 3) but these samples were all collected from above the deep level of suspected base metal deposition. As shown in Table 2, at the level of the Deep ore horizon, the solution salinity was high and the solutions did not boil. If we assume the "pre-ore" stage actually did deposit the base metals of the deep horizon from nonboiling solutions, then at some elevation above the deep horizon those same solutions would have boiled as the solutions passed hydrostatic conditions. Thus, salts will concentrate below the level of "pre-ore" boiling making solutions below this level more saline than those above the level. If correct, this explains the relatively low salinity of the "pre-ore" sample analysed in Table 3, and offers an explanation for the evidence of boiling in the pre-ore samples studied.

Ore stage (silver episode) samples are divided into two types: the Bufa type and the Losero type. Bufa type samples have a total average salinity of 5260 parts per million, with an average Ca:Na:K:Mg ratio of 63:9:26:2, considerably different than pre- and post-silver solutions.
The Losero type ore stage sample has a total average salinity of 26,000 parts per million, with Ca:Na:K:Mg ratios of 66:11:15:7. Losero type ore has a much higher total salinity due largely to the higher Ca and Mg values. These high values may be explained by the solution of the calcite cement of the Losero Formation, which is absent in the Bufa Formation. Also, the high Ca and Mg values may help explain the much higher volume percent of calcite and chlorite in veins of the Losero type. As the bulk of the veins have a Bufa type mineralogy, and the Losero type is spatially restricted to in and near the Losero Formation, all calculations based upon the analysed inclusion liquids will use the values obtained from the Bufa type mineralogy.

Post-silver episode samples are dilute, averaging a total of 6910 ppm total dissolved solids. Ca:Na:K:Mg ratios average 95:2:2:5, surprisingly similar to the pre-ore stage ratios, but the total sulfur and metal content is considerably less. The drastic depletion of metals in solution is quite evident from Table 3.

Summary

It appears that the pre-ore stage minerals were deposited by sulfur and base metal-rich solutions. From studies reported in earlier sections, these solutions also altered the wall rocks up through the potassic grade.
Deposition of base metal sulfides by this solution is strongly suggested.

Ore stage (silver episode) solutions were base metal and H₂S low, but were enriched in silver and chloride relative to the earlier stage. H₂S is presumed to be the dominant sulfur species, an assumption based on the data presented in Figure 20. This solution deposited silver sulfides and electrum as a result of repeated boiling episodes.

In time, the ore stage solution chemistry changed to a metal and sulfur deficient solution, and was responsible for deposition of calcite and quartz, but no sulfides.

We can see in the chemistry a drastic chemical difference between the pre-ore and the ore stage solutions, suggesting a different source for the solutions and/or a different path of fluid flow within the geothermal cell. An alternative possibility must be considered: Instead of two different fluids forming the Deep and the higher levels of ore, it is possible that the boiling may result in both the deposition of the base metals at depth as well as the higher silver-gold ores. Recent data (Drummond and Ohmoto, 1979) suggest that only 10% water loss due to vapor escape will precipitate essentially all base and most precious metals. This is largely due to the loss of
dissolved gases and consequent pH rise. On the other hand, White (1970) and Wahl (1977) present strong evidence that at and below the boiling interface in a geothermal system the salinity of the fluid greatly increases due to loss of water as vapor. Thus, the ionic strength should increase and the resultant greater degree of complexing will tend to restrict sulfide deposition. It is unsure which of these two contrasting mechanisms will predominate at any given boiling interface. Although not completely discarded as a possibility, this alternative (boiling converted a homogeneous fluid into the two chemically distinct fluids as shown on Table 3) is unlikely when the data of Table 3 are studied. It seems geologically unreasonable that certain species would be selectively concentrated, and others depleted. The analyses of sample 0809 (pre-ore and possibly related to base metal deposition) when compared to the average analyses of the Bufa type silver ores show that there is no systematic concentration or depletion of species. Therefore, this alternative possibility is discarded, and it is assumed that the pre-ore stage solutions were indeed of a different stage and age than were the precious metal depositing solutions.
GEOCHEMISTRY OF ORE DEPOSITION

General

The fluid inclusion study, just discussed, yielded significant data on the temperature of ore deposition (230°C ± 5°C); on the density of the fluids (0.83 g/cc); on the fluid salinity (5360 ppm); on the physical state of the fluids (episodic intense boiling); and on the chemical composition of the ore-depositing solutions (Table 3). Thin and polished sections indicated a close spatial relationship between acanthite, adularia, sericite, and quartz deposition. These data may be used to calculate the pH of ore deposition, the quantity of SiO₂ in solution, and the fugacities of CO₂ and O₂. These calculations should result in geologically reasonable values and will serve as tests of the techniques used in fluid inclusion nondestructive and chemical analyses.

Ionic Strength

If complex speciation is ignored, the ionic strength, I, is equal to \( \frac{1}{2} \sum (m_i z_i^2) \), where \( m_i \) is the molality of ion i and \( z_i \) is the charge of ion i. Bufa type ore stage solutions have the following average values (taken from Table 3):
<table>
<thead>
<tr>
<th>Species</th>
<th>PPM</th>
<th>Molality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>1006</td>
<td>0.0251</td>
</tr>
<tr>
<td>Na</td>
<td>149</td>
<td>0.0065</td>
</tr>
<tr>
<td>K</td>
<td>410</td>
<td>0.0105</td>
</tr>
<tr>
<td>Mg</td>
<td>30</td>
<td>0.0012</td>
</tr>
<tr>
<td>Li</td>
<td>54</td>
<td>0.0078</td>
</tr>
<tr>
<td>F</td>
<td>24</td>
<td>0.0013</td>
</tr>
<tr>
<td>Se</td>
<td>0.81</td>
<td>1.0 x 10^{-5}</td>
</tr>
<tr>
<td>Cu</td>
<td>11.5</td>
<td>1.8 x 10^{-4}</td>
</tr>
<tr>
<td>Pb</td>
<td>57.7</td>
<td>2.8 x 10^{-4}</td>
</tr>
<tr>
<td>Zn</td>
<td>61.4</td>
<td>9.4 x 10^{-4}</td>
</tr>
<tr>
<td>Fe</td>
<td>4.7</td>
<td>8.5 x 10^{-5}</td>
</tr>
<tr>
<td>Bi</td>
<td>22.5</td>
<td>1.4 x 10^{-4}</td>
</tr>
<tr>
<td>Ag</td>
<td>11.5</td>
<td>1.1 x 10^{-4}</td>
</tr>
<tr>
<td>As</td>
<td>0.13</td>
<td>1.7 x 10^{-6}</td>
</tr>
<tr>
<td>Cl</td>
<td>2780</td>
<td>0.078</td>
</tr>
<tr>
<td>Sb</td>
<td>1.42</td>
<td>1.2 x 10^{-5}</td>
</tr>
<tr>
<td>Mn</td>
<td>0.07</td>
<td>1.2 x 10^{-6}</td>
</tr>
<tr>
<td>Au</td>
<td>0.02</td>
<td>1.1 x 10^{-7}</td>
</tr>
<tr>
<td>S (total)</td>
<td>107</td>
<td>0.00033</td>
</tr>
</tbody>
</table>

Substituting the molal values into $I = \frac{1}{2} \sum (m_i z_i^2)$ yields:

$I = 0.11137$

By using the ionic strength in the modified Debye-
Huckel expression, values of the activity coefficients of ions may be calculated (Garrels and Christ, 1965):

\[
\log \gamma = \frac{-A(z)^{2}(I)^{\frac{1}{2}}}{1 + gB(I)^{\frac{1}{2}}} + \delta I
\]

where:

- \( \gamma \) = activity coefficient of ion \( i \)
- \( A \) = molal parameter, a function of dielectric constant of water, water density, and temperature; from Helgeson (1969)
- \( z \) = charge of ion \( i \)
- \( g \) = hydrated ionic diameter, from Garrels and Christ (1965)
- \( B \) = molal parameter, a function of dielectric constant of water, water density, and temperature; from Helgeson (1969)
- \( \delta \) = deviation function, from Helgeson (1969)

Activity coefficients determined from the modified Debye-Huckel expression will be used in the calculation of pH, \( f(O_2) \), and \( f(CO_2) \).

**pH**

The interlayering of acanthite and sericite with adularia, shown in Figures 5 and 19, suggests coprecipitation under equilibrium conditions. Therefore, the pH of argentite precipitation must lie near the sericite-adularia stability boundary. This pH, at 230°C, is determined in the following steps:
1) (adularia) (sericite)

$$3\text{KAl}_2\text{Si}_3\text{O}_8 + 2\text{H}^+ = \text{KA}_3\text{Si}_3\text{O}_{10} (\text{OH})_2 + 2\text{K}^+ + 6\text{SiO}_2$$

2) The equilibrium constant at 230°C for this reaction is:

$$K = \frac{(\gamma_{Km_K})^2}{(\gamma_{Hm_H})^2} = 10^{8.26} \quad \text{(Helgeson, 1969)}$$

3) pH may then be determined by:

$$\log K = (2) \log(\gamma_{Km_K}) - (2)\log(\gamma_{Hm_H}) = 8.26$$

but, $$-\log(\gamma_{Hm_H}) = \text{pH}$$, therefore,

$$\text{pH} = 4.13 - \log(\gamma_{Km_K})$$

4) $$\gamma_K = 0.59303 \quad \text{(from the modified Debye-Huckel expression and effective ionic diameters listed in Garrels and Christ, 1965)}. \quad m_K = 0.0105$$

5) Therefore, pH = 6.3, a geologically reasonable value. This pH is slightly on the alkaline side of neutral under the given conditions. Neutral pH at 230°C is 5.6.

As the rate of boiling was not constant, it is unlikely that the solution pH remained constant. That is, if wall rock reactions with the solutions were negligible, then during periods of nonboiling the pH would drop as the H₂S and CO₂ would no longer partition into a vapor phase. 

Calcite exists in equilibrium or in close equilibrium
with acanthite. From the reaction below a minimum value of $f(CO_2)$ may be determined:

$$\text{CaCO}_3 + 2H^+ = \text{Ca}^{2+} + \text{H}_2\text{O} + \text{CO}_2(\text{vap})$$

$$\text{Log } K = 8.86 \quad (\text{Helgeson, 1969})$$

$$8.86 - \log(\gamma_{\text{Ca}} m_{\text{Ca}}) - 2pH = \log f(CO_2)$$

and $m_{\text{Ca}} = 0.0251$ and $\gamma_{\text{Ca}} = 0.19724$ (from the modified Debye-Huckel expression), therefore,

$$f(CO_2) = 10^{-1.43},$$

a low value discussed on page 95.

$f(O_2)$

The value of the fugacity of $O_2$ is much more difficult to determine. Maximum and minimum limits of $f(O_2)$ may be placed with some certainty by plotting mineral equilibria on a $\log f(O_2) - \text{pH}$ diagram. This diagram is shown in Figure 20. Knowing that $\text{Fe}_2O_3$, $\text{Ag}_2\text{CO}_3$, $\text{FeS}$, and $\text{Cu}_5\text{FeS}_4$ are absent from the Las Torres ores, the log of the $f(O_2)$ lies between -36.5 and -45.2. This value is geologically reasonable.

$SiO_2$ in Solution

The amount of $SiO_2$ in solution at a given temperature may be calculated based on the assumption that the $SiO_2$ content is dependent on the temperature of the solution and that $SiO_2$ as quartz is in excess in the system. The following equation is used to calculate the concentration
of SiO₂ remaining in solution after boiling (Reed, 1975):

\[ T(°C) = \frac{1522}{5.75 - \log(\text{SiO}_2)} - 273.15 \]

Using \( T = 230°\text{C} \), the concentration of SiO₂ is calculated to be 531 ppm for the ore stage solutions. This is in very good agreement with many modern geothermal systems (Wahl, 1977).

**Total Sulfur in Solution**

Table 3 lists the total sulfur in the ore stage solution as 107 ppm. This sulfur will be present as \( \text{H}_2\text{S} \) (see Figure 20). This corresponds to \( 10^{-2.5} \) moles sulfur.

**Summary**

As all values are geologically reasonable, it is assumed that the results of the fluid inclusion heating tests and the extraction analyses are reliable.
Figure 20: Log $f(O_2)$ - pH diagram for the silver episode of the ore stage solutions, Las Torres Mine, Guanajuato, Mexico.
MODEL OF ORE DEPOSITION

General

All previous sections were purposefully kept as specific as possible. An attempt was made to present only observable data or data easily calculated from observations, keeping interpretations to a minimum. This section will reconstruct the sequence of events that led to ore deposition, and of necessity, some assumptions will be necessary. When assumptions are made, supportive data will be supplied.

A model explaining the Las Torres ore shoots must account for the following observations:

I. Structures:
   a) Ore shoots are on and near the Veta Madre.
   b) Ore shoots are known to exist on two levels (Upper horizon and Lower horizon) separated by barren to nearly barren zones.
   c) The Lower horizon ore shoots occur in the hanging wall of the Veta Madre at zones of dip increase and in areas of strike changes.
   d) A third level of base metals (Deep horizon) exists below many deposits in the district, but may or may not exist below the Las Torres Mine.

II. Alteration:
   a) Propylitic and potassic alteration are pre-ore.
   b) Lower horizon ore shoots are in potassically altered host rocks.
c) Argillic alteration forms a halo around and a cap above ore shoots, but does not form within ore shoots.

d) Phyllic alteration forms a cap around and above the argillic alteration.

e) Argillic and phyllic alteration is contemporaneous with and slightly post ore.

III. Chemistry

a) Pre-ore stage:
1. Solutions were high in sulfur and base metals.
2. The solutions were boiling at approximately 230°C at the level of the upper and lower ore horizons but probably were not at the level of the deep horizon.
3. These solutions filled the Veta Madre and precipitated barren quartz and minor calcite. There is some suggestion (based on the chemistry of the solutions) that they may have deposited some of the Deep horizon base metal ores now being mined at the Rayas Mine. It is unknown if any such base metal deposits exist at Las Torres.

b) Ore Stage (Silver Episode):
1. The solutions were repeatedly boiling at approximately 230°C with an average salinity of 5260 parts million. These solutions were relatively high in Ag, but base metal and \( \text{H}_2\text{S} \) deficient.
2. Samples showing evidence of boiling are found at depths below the present Veta Madre surface outcrops in excess of 650 meters, precluding a simple hydrostatic system.
3. Argentite deposition was accompanied by adularia and sericite, which are much less abundant when argentite is absent.
4. Argentite precipitation was at the same time as boiling episodes.
5. The upper two levels of ore have essentially the same mineralogy, the deep ore horizon (if present at Las Torres) would have a greatly different mineralogy. The upper two ore levels are sulfur poor assemblages, the deep ore (if present) would be sulfur rich.

c) Ore Stage (Post-Silver Episode):
1. The solutions were boiling but the intensity was greatly diminished compared to previous stages.
2. Solutions were metal deficient, low in sulfur, and relatively high in calcium and chloride.
3. Temperatures of precipitation of minerals of this stage (primarily calcite) averaged 230°C.

All of these observations will be incorporated in the reconstruction of the ore-forming process.

Pre-Ore Events

The Veta Madre fracture and subparallel systems of fractures at Las Torres were permeable throughout most of their lengths, with the fractures partially filled with breccia fragments and gouge. Sulfur and base metal rich solutions rose up the fractures and replaced the breccia fragments with quartz and minor calcite and adularia. During this process, minor amounts of Au and Ag, and perhaps major amounts of base metal sulfides were deposited. The precious metals were sparsely distributed throughout the quartz vein filling (Gross, 1975) and if deposited, the
base metal sulfides were restricted to below an elevation of 1700 meters above sea level.

Boiling was common in these solutions above approximately 1700 meters at a temperature of 230°C. With an average total dissolved solid content of 29,200 ppm, the boiling depth (assuming a hydrostatic condition) is calculated to be 330 meters (Haas, 1976) below the paleosurface. Obviously, hydrostatic conditions could not have prevailed, and the mechanism responsible for boiling is likely a lithostatic pressure release. A complete example of this mechanism is discussed under the next section, titled "Ore Stage Events".

Boiling would result in a pH rise in the solutions remaining at depth, a temperature drop (Barton and Toulmin, 1961), a rise in concentration of metal complexes at depth (Wahl, 1977) and lead to a rise in f(O₂). Many combinations of these factors may promote base metal deposition at and below the level of boiling.

Quartz deposition, largely a function of a temperature drop as the solutions rose to the paleosurface, ceased at approximately 2350 meters above present sea level. This is probably a result of: 1) a mixing of the rising hydrothermal solutions with cooler and more dilute groundwaters; and b) precipitation of quartz at greater depths due to cooling of
the solutions caused by the loss of the heat of vaporization. These two factors may result in near depletion of quartz in solution at the 2350 meter elevation. Regardless of which of these two possible causes predominated, the result is that quartz filling is essentially absent at and above 2350 meters above sea level. Very minor amounts of calcite are present above this elevation, as are minor amounts of opal and jasper.

Wall rock alteration accompanying this stage resulted in a zonal pattern of inner intense potassic alteration surrounded by a propylitic halo. The potassic alteration is characterized by the assemblage adularia, illite, and sericite, and by the formation of quartz. The resulting rock was made extremely brittle. The propylitic alteration is characterized by the formation of chlorite, carbonate, pyrite, montmorillonite, minor quartz, and rare epidote. The resulting rocks were softened. Alteration was more intense, and the potassic grade localized, in areas of greater fracture permeability. Such sites are found in areas of rapid dip or strike change of the Veta Madre, and/or in areas of intersection of the Veta Madre with other fractures.

**Ore Stage (Silver and Post-Silver Episodes) Events**

The Veta Madre and the altered host rocks were...
fractured at an unknown, but probably short, time after the pre-ore stage mineralization. A short time interval between the pre-ore and the ore stage fluid passages is considered probable as the two solutions were at the same temperatures. Fractures formed along pre-existing veins as well as formed in previously unfractured wall rocks. Most fractures in fresh or in propylitically altered rocks were tight or gouge-filled (as seen by lack of subsequent mineralization and alteration), whereas fractures in the potassically altered rocks were open and free of gouge (as seen by lack of gouge in subsequently mineralized veins). Fractures were more numerous and more open in the hanging wall of the Veta Madre because these were the areas of potassic alteration, resulting in hanging wall fracture stockworks. Several such zones of high fracture permeability resulted, with each stockwork isolated from one another along strike by zones of very low permeability.

Ore stage solutions rose up the various isolated stockwork areas to the paleosurface. The solutions, at an average temperature of 230°C and with an average salinity of 5260 ppm, would boil at a depth of 340 meters below the paleosurface (Haas, 1976). The depth of 340 meters below the paleosurface is based on the assumption of pressure controlled by the hydrostatic head. It is assumed that the
upper horizon ore shoots were formed by this simple boiling process. This assumption has only a little supportive evidence: a) Samples from the upper horizon contain fluid inclusion evidence of boiling (see Table 1), b) boiling under hydrostatic conditions, leading to a pH rise and deposition of metals, is a commonly observed feature of hydrothermal systems (Weissberg, 1969; White, 1970), c) at a rather constant solution temperature of 230°C, boiling at 340 meters below the paleosurface must have occurred. Boiling occurred during ore deposition in the upper horizon, thus the assumption that the base of the upper horizon ore shoots is at the boiling level is not prohibitive at least and strongly supportive at best. Also, this mechanism is the only one known to this author that would adequately explain the presence of lower horizon ore shoots, as will be fully explained in the following paragraph.

Boiling at 340 meters below the paleosurface would result in calcite, adularia, phyllosilicates, and metal sulfide deposition. In time, a self-sealing of the system would occur both above the level of boiling (due largely to calcite and adularia precipitation) and below the level (due largely to quartz, calcite, and adularia precipitation). Such self-sealing is well documented in modern geothermal systems (Facca and Tonani, 1967; Keith and others, 1978),
and acts to effectively halt fluid flow. Thus, the act of mineralization at the upper horizon also acts to stop solution movement in that particular isolated stockwork. As the sealing occurs around and above the boiling level, the fractures at depth remain open and filled with ore stage solutions, however, fluid movement is essentially stopped.

If for any reason (regional tectonism, hydrofracturing, etc.) the sealed cap should fracture, the solutions at depth will experience a rapid pressure drop and much of the liquid will flash into vapor. At 230°C and a salinity of 5260 ppm, these solutions will flash to a depth of approximately 340 meters below the average base of the sealing cap. This act of flashing, just as in the earlier and higher boiling, will cause a rise in pH and in $f(O_2)$, a drop in $f(CO_2)$, a drop in temperature, and lead to precipitation of metal sulfides, adularia, quartz, calcite, and sericite. The lower horizon area is thereby mineralized and should experience mineralization over a vertical interval of approximately 340 meters. The main ore shoot at Las Torres has a vertical extent of 330 meters although the base of the ore zone is not fully delineated.

Of course, immediately after flashing, the solutions will rise up the newly-opened channels to the paleosurface.
The amount of time spent during a lower horizon flash will be less than that spent in upper horizon boiling; for this reason it is likely that the deeper fractures will not seal as efficiently or as quickly as the near surface fractures.

Once the solutions rise to approximately 340 meters below the paleosurface, boiling will continue as before, and the new fractures will eventually seal. The sequence repeats itself: Boiling, self-sealing, fracturing, flashing, boiling, self-sealing, fracturing...... This sequence must have been repeated a minimum of six times (shown in Figure 19). It may have been repeated considerably more times than six as what is recorded in any single veinlet is a record of flashing events up to the time that particular veinlet became sealed. After that time, no solution would be in that part of the veinlet and flashing events would have no effects. Batzle and Simmons (1976) present detailed evidence that similar episodic fracture sealing and refracturing occurs in modern geothermal systems.

During flashing and boiling, volatiles are partitioned into the vapor phase. If these vapors condense at a higher level in the system, a low pH liquid will result. This low pH liquid will react with the walls of the fractures to form alteration minerals stable at a low ph. Effects of this are observed around and above the lower
horizon ore shoots as a halo and cap of argillic and phyllic alteration. It is not difficult to visualize a mechanism where the vapors move upward through the breccia column of the stockwork, becoming trapped in the increasingly closed fractures at the margins of the stockworks where the open fractures in the potassic zone pass into gouge-filled fractures of the propylitic zone. Here, in the areas of vapor trapping on the margins of the ore shoots, the vapor in time will condense. Vapors rising up the center of the stockwork, on the other hand, have a relatively high permeability path to the surface, and do not become trapped, and do not condense as readily. White (1970) describes this mechanism for modern geothermal systems, a mechanism he describes as resulting in a low-pH alteration assemblage on the margins of a breccia column and not in its center. This perfectly describes the Las Torres orebodies.

As several episodes of boiling are recorded (at least six), some minerals deposited in an earlier flashing event may be altered by the acids produced by a later flashing event. In this way, some of the earlier vein adularia is converted into kaolinite.

The upper horizon and the lower horizon ore shoots are formed from the same solutions at the same temperatures and actually at the same pressure (in terms of hydrostatic head).
and it is not surprising, therefore, that the mineralogy of the two levels of ore are so similar (Petruk and Owens, 1974). The two boiling levels are shown in Figures 21A through 21C.

A change in solution chemistry occurred after the ores were accumulated: The solution salinity increased slightly from 5260 ppm to 6910 ppm, but the metal content drastically decreased as did the \( \text{H}_2\text{S} \) content (Table 3). The temperature of these solutions was 230°C or slightly warmer (Figure 19). These solutions also continued to boil probably under the same mechanism as the silver episode, but unlike the earlier solutions, this episode had little metal to precipitate. Calcite, quartz, and minor fluorite were deposited. The number of boiling events appears to have rapidly decreased in time (see Figure 19).

**Later Events**

A post-ore stage is marked by deposition of calcite, marcasite, and laumontite. This very late stage has not been studied in detail, but the presence of laumontite would indicate a temperature less than approximately 200°C (Coombs and others, 1959; Averyev and Noboko, 1962; Senderov, 1973), an alkaline pH, and may well be attributed to circulating ground waters.
FIGURE 21A: LONGITUDINAL SECTION OF THE VETA MADRE SHOWING A SCHEMATIC REPRESENTATION OF FRACTURES PRIOR TO PRE-ORE STAGE MINERALIZATION

LINE OF SECTION: N18.5W
FIGURE 21B: LONGITUDINAL SECTION OF THE VETA MADRE SHOWING A SCHEMATIC REPRESENTATION OF PRE-ORE STAGE ALTERATION AND POSSIBLE MINERALIZATION

LINE OF SECTION: N18.5W

Color Scheme Same as Fig. 13
FIGURE 2IC: LONITUDINAL SECTION OF THE VETA MADRE SHOWING SCHEMATIC REPRESENTATIONS OF ORE STAGE ALTERATION, MINERALIZATION, AND LEVELS OF BOILING, SEALING, FLASHING, AND NON-BOILING.
LINE OF SECTION: N18.5W  Color Scheme Same as Fig. 13
Implications of Suggested Process

Ore deposits at Las Torres resulted from a very simple process. As such, there should be numerous examples throughout the world which have similar vertically stacked ore shoots, similar vertical zoning of gangue and ore minerals, and similar wall rock alteration patterns. A review (field and literature) of 92 precious metal deposits (with and without base metals) hosted by volcanics indicates that:

1. Vertically stacked ore deposits are probably present at:
   a. Guanajuato, Mexico (This study)
   b. Oatman, Arizona (Personal study)
   c. Golden Plateau, Australia (Brooks, 1970)
   d. Comstock, Nevada (Bastin, 1923; Bonham, 1969; Whitehead, 1976)
   e. Republic, Washington (Bancroft, 1914; Full, 1968)
   f. Waihi, New Zealand (Emmons, 1937)
   g. although not hosted by volcanics, there is evidence of two ore horizons in the Mother Lode, California (Knopf, 1929)

2. Mineral deposition is in part controlled by boiling at:
   a. Red Mountain, Colorado (Burbank, 1950)
   b. Lake City, Colorado (Slack, 1976)
   c. Comstock, Nevada (Tolman and Clark, 1914)
   d. National, Nevada (Tolman and Clark, 1914)
   e. Creede, Colorado (Wetlaufer and others, 1978)
   f. Oatman, Arizona (Personal study)
   g. Katherine, Arizona (Personal study)
   h. Silver Peak (16 to 1 Mine), Nevada (Personal study)
   i. Mogollon, New Mexico (Personal study)
   j. probably Tonopah, Nevada (Nolan, 1935)
   k. Tayoltita, Mexico (Sawkins, F.J., verbal communication, 1979)
l. Guanajuato, Mexico (This study)
m. Pachuca, Mexico (Dreier, 1976)
n. Finlandia, Peru (Kamilli and Ohmoto, 1977)
o. Pasto Bueno, Peru (Landis and Rye, 1974)
p. Casapalca, Peru (Rye and Sawkins, 1974)
q. Bulancak, Turkey (Akinci, 1976)
r. Kamchatka, U.S.S.R. (Shchepot'ev and Andrusenko, 1975)
s. Transbaikal'ye, U.S.S.R. (Grigorchuk and Ivasiv, 1976)
t. Chukotka, U.S.S.R. (Kalyuzhnyi and others, 1975)
x. and, although not directly hosted by a volcanic pile, these additional Au-Ag deposits were in part controlled by boiling solutions:
  i) Carlin, Nevada (Radtke and others, 1974)
  ii) Leadville, Colorado (Thompson, T., verbal comm., 1979)
  iii) Toyoha, Japan (El Shatoury and others, 1974)
  iv) Naica, Mexico (Erwood, 1978)
  v) Hokuraku, Japan (Takenouchi, 1978)
  vi) Santa Eulalia, Mexico (Hewett, 1968)
  vii) Ashio, Japan (Imai and others, 1975)
  viii) Mother Lode, California (Knopf, 1929)

These lists indicate that Guanajuato is not unique.
In fact, the process of ore formation (boiling with or without the episodic sealing cap) appears to be a major control of most precious metal deposits hosted by volcanics. This assumption can lead to new ore discoveries if:

1. In districts where the known precious metal ore shoots do not pass to base metals at the lowest productive levels:
a. It is hard to visualize a geothermal system in which the solutions can leach and transport sufficient quantities of gold and silver to form an ore deposit, but can carry only negligible amounts of base metals. Therefore, a deeper base metal (with silver) zone possibly exists.

b. If samples from well beneath the productive horizon are found to indicate boiling occurred, then the level of boiling is below the known ore, and an additional mineralized horizon probably exists.

c. If phyllic and/or argillic altered wall rock (especially in the hanging wall) extends to depth well below the bottom of the known ore shoots, then a deeper level of mineralization probably exists. The alteration is the higher cap above that deeper level of mineralization.

2. In districts where the known ore shoots do show a base metal (or simply pyrite) increase with depth there probably is little chance of a deeper level of boiling existing within the vein system. However, other factors (structure, reactive host rocks, permeable horizons, etc.) may form base metal deposits at depth.

3. In unexplored vein systems:

a. If orebodies exist as a result of boiling solutions, then phyllic and/or argillic altered zones (especially in the hanging wall) may serve as useful drilling guides.

b. A fluid inclusion study may indicate that boiling occurred at isolated zones along the strike of the vein, which may yield drill targets.

c. Extraction and analysis of fluid inclusion liquids may give an indication of the kinds of ores to be expected (base or precious metals).
It is suggested that new ore producing zones may be discovered well beneath "worked out" districts if the geothermal model is applied. It is also suggested that a major and exceedingly practical exploration tool may lie in simple fluid inclusion research.
REFERENCES CITED


Cathles, L.M., 1977, An analysis of the cooling of intrusives by ground-water convection which includes boiling: Econ. Geol., v. 72, no. 5, p. 804-826.


Crerar, D.S., Barnes, H.L., 1976, Ore solution chemistry IV. Solubilities of chalcopyrite and chalcocite assemblages in hydrothermal solution at 200°C to 350°C: Econ. Geol., v. 71, p. 772-794.

De Cserna, Z., 1960, Orogenesis in time and space in Mexico: Geol. Rundschau, v. 50, p. 595-605.


Drummond, S.E., Ohmoto, H., 1979, Effects of boiling on mineral solubilities in hydrothermal solutions (abs.):


Erwood, R.J., 1978, Supersaline, hypothermal main-stage mineralization solutions, Naica chimney-manto deposit, Chihuahua, Mexico: Econ. Geol., v. 73, no. 2, p. 310.


Garcia, T., 1895, Los mineros Mexicanos: Sec. de Fomento, Mex., D.F.


Grigorchuk, G.Y., Ivasiv, S.M., 1976, Types of metasomatic columns bordering veins of various Au content and thermobaric conditions (at a certain deposit at Transbaikal'ye): Abstr. in Fluid Inclusion Research - Proc. of COFFI, v. 9, p. 51.


Kamilli, R.J., Ohmoto, H., 1977, Paragenesis, zoning, fluid inclusion, and isotopic studies of the Finlandia Vein, Colqui District, Central Peru: Econ. Geol., v. 72, no. 6, p. 950-982.


Petruk, W.; Owens, D., 1974, Some mineralogical characteristics of the silver deposits in the Guanajuato Mining District, Mexico: Econ. Geol., v. 69, no. 7, p. 1078-1085.


Roedder, E., 1958, Technique for the extraction and partial chemical analysis of fluid-filled inclusions from minerals: Econ. Geol., v. 53, no. 3, p. 235-269.


Rye, R.O., Sawkins, F.J., 1974, Fluid inclusion and stable isotope studies on the Casapalca Ag-Pb-Zn-Cu deposit, Central Andes, Peru: Econ. Geol., v. 69, no. 4, p. 181-205.


Takenouchi, S., 1978, High salinity fluid inclusions in breccias of intrusive breccia dikes in the Hokuroku area, Japan: Abstr. in Pgms. and Abstr., Symp. of IAGOD, 5th, Snowbird, Utah, p. 188.

Tolman, C.F., Clark, J.D., 1914, The oxidation, solution, and precipitation of copper in electrolytic solutions and the dispersion and precipitation of copper sulfides from colloidal suspensions, with a geological discussion: Econ. Geol., v. 9, p. 559-592.


# APPENDIX A, TABLE A-1

## CALIBRATION OF HEATING/FREEZING STAGE

<table>
<thead>
<tr>
<th>STANDARD USED</th>
<th>TRUE MELTING TEMPERATURE</th>
<th>ACTUAL MELTING TEMPERATURE</th>
<th>THERMOMETER NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triple Distilled Water</td>
<td>0.00°C</td>
<td>1.5, 1.5, 1.5, 1.5</td>
<td>1</td>
</tr>
<tr>
<td>Water w/ 0.98 wt % NaCl</td>
<td>-0.60</td>
<td>1.15, 1.35, 1.30, 1.20</td>
<td>1</td>
</tr>
<tr>
<td>Water w/ 1.97 wt % NaCl</td>
<td>-1.20</td>
<td>0.80, 0.60, 0.50, 0.50</td>
<td>1</td>
</tr>
<tr>
<td>Water w/ 4.92 wt % NaCl</td>
<td>-3.00</td>
<td>-1.4, -1.6, -1.3, -1.55</td>
<td>1</td>
</tr>
<tr>
<td>Water w/ 9.83 wt % NaCl</td>
<td>-6.00</td>
<td>-3.9, -4.1, -4.3</td>
<td>1</td>
</tr>
<tr>
<td>Omega Engineering Inc. Standard</td>
<td>52</td>
<td>51.5, 51.7, 50.6</td>
<td>1</td>
</tr>
<tr>
<td>&quot;</td>
<td>66</td>
<td>65.5, 65.5, 66.0</td>
<td>1</td>
</tr>
<tr>
<td>&quot;</td>
<td>79</td>
<td>80.5, 82.1, 82.5</td>
<td>1</td>
</tr>
<tr>
<td>&quot;</td>
<td>93</td>
<td>91.5, 88.5, 92.5</td>
<td>1</td>
</tr>
<tr>
<td>&quot;</td>
<td>107</td>
<td>102, 104, 101, 105.5, 107.5, 106.5</td>
<td>1</td>
</tr>
<tr>
<td>&quot;</td>
<td>121</td>
<td>111.5, 109.5, 113.5, 120.5, 121.5, 121.0</td>
<td>2</td>
</tr>
<tr>
<td>&quot;</td>
<td>135</td>
<td>137.5, 136.0, 136.0, 135.0</td>
<td>2</td>
</tr>
<tr>
<td>&quot;</td>
<td>163</td>
<td>163.0, 163.5, 162.0</td>
<td>2</td>
</tr>
<tr>
<td>&quot;</td>
<td>191</td>
<td>192.5, 192.0, 191.5</td>
<td>2</td>
</tr>
<tr>
<td>&quot;</td>
<td>218</td>
<td>216, 217, 216</td>
<td>2</td>
</tr>
<tr>
<td>&quot;</td>
<td>232</td>
<td>229, 229, 227</td>
<td>2</td>
</tr>
<tr>
<td>&quot;</td>
<td>246</td>
<td>228.5, 228.0, 229.5</td>
<td>3</td>
</tr>
<tr>
<td>&quot;</td>
<td>253</td>
<td>240, 245, 244, 242, 245, 243, 245</td>
<td>3</td>
</tr>
<tr>
<td>&quot;</td>
<td>260</td>
<td>250, 248.5, 249.5</td>
<td>3</td>
</tr>
<tr>
<td>&quot;</td>
<td>288</td>
<td>250.0, 249.5, 253.0</td>
<td>3</td>
</tr>
<tr>
<td>&quot;</td>
<td>316</td>
<td>279.5, 280.0, 280.5</td>
<td>3</td>
</tr>
<tr>
<td>&quot;</td>
<td>329</td>
<td>296.5, 290.0, 295.0</td>
<td>3</td>
</tr>
</tbody>
</table>
APPENDIX B

FIGURE B-1 FLOW CHART OF EXTRACTION TECHNIQUE

CLASSIFY SPECIMEN ACCORDING TO PARAGENETIC POSITION AND NON-DESTRUCTIVE HEATING AND FREEZING TESTS

DETERMINE VOLUME % OF FLUID INCLUSIONS IN SAMPLE

CRUSH TO 1/4" SAMPLE FRAGMENTS

WASH IN TRIPLE DISTILLED H2O

SOAK IN ACETONE

IN SAMPLE SOLUBLE IN CONC. HNO3?

NO

SOAK IN CONC. HNO3 UNTIL REACTS TO STOP

YES

PLACE IN ELECTROLYTIC UNIT (50 V. 3.0) FOR AT LEAST 16 HOURS. UNTIL AMMONIUM DROPS TO EQUAL THAT OF PURE WATER

MASH IN TRIPLE DISTILLED H2O

DRY SAMPLE AND WEIGHT

PLACE IN CERAMIC MILL* AND GRIND UNTIL FINE POWDER. AT LEAST 16 HOURS

ADD CAREFULLY MEASURED (200 to 500 ml.) TRIPLE DISTILLED WATER

SOAK 10-15 MINUTES, MINOR STEERING

TO 200 ml. TRIPLE DISTILLED WATER, AS USED IN PREVIOUS STEPS. FOLLOW THE STEPS BELOW TO CHECK FOR CONTAMINATION FROM WATER SOURCE

WITHDRAW 10 ml. OF SAME TRIPLE DISTILLED WATER USED IN PREVIOUS STEP, PUT IN POLYSTYRENE TEST TUBES

CENTRIFUGE IN POLYSTYRENE TUBES, SEND THE STEPS BELOW TO CHECK FOR CONTAMINATION FROM WATER SOURCE

WITHDRAW 10 ml. OF THE CENTRIFUGED WATER FOR MAJOR ION ANALYZER. PUT IN POLYSTYRENE TEST TUBES

ADD: 20 g. CI

20 g. TACL

5 ml. KI

50 ml. CONC. HCL

SNOW. LET SEPARATE AT LEAST 1-hour

WITHDRAW ORGANIC LAYER INTO GLASS TEST TUBE. AMOUNT USUALLY FROM 1 TO 2 ml. MEASURE THE EXTRACT VOLUME

FROM EACH SAMPLE, SELECT 1 ml., ADD 1 ml. OF 15 LAC SOLUTION. ALL BLANKS MUST GO THROUGH THIS STEP

TO 0.2 ml. OF ABOVE EXTRACT ADD 5 ml. OF KI

ADD: 1.0 ml. TRIPLE DISTILLED WATER

0.1 ml. CONC. HNO3

30 microliters 30% H2O2**

TO A. A. FOR:

Ag (ORGANIC PHASE)

Ca (ORGANIC PHASE)

Cu (ORGANIC PHASE)

Fe (ORGANIC PHASE)

Mn (ORGANIC PHASE)

Mg (ORGANIC PHASE)

K (ORGANIC PHASE)

Na (ORGANIC PHASE)

Zn (ORGANIC PHASE)

REMAINDER TO ION CHROMATOGRAPH FOR ION ANALYSIS

CAP., LET STAND 24 HOURS

TO A. A. FOR:

Ag (AQUEOUS PHASE)

Ca (AQUEOUS PHASE)

Cd (AQUEOUS PHASE)

Cu (AQUEOUS PHASE)

Fe (AQUEOUS PHASE)

Mg (AQUEOUS PHASE)

Mn (AQUEOUS PHASE)

Na (AQUEOUS PHASE)

Zn (AQUEOUS PHASE)

TO A. A. FOR ALL OTHER METALS (AQUEOUS PHASE)

NOTES:

1. * LAMARRE WITH AUTOCLAVE MUST BE CLEANED IN ELECTROLYTIC UNIT PRIOR TO USE

2. ** H2O2 MUST BE UNSTABILIZED
APPENDIX C

CHEMICAL REACTIONS USED TO CONSTRUCT THE LOG f(O₂)-pH DIAGRAM, FIGURE 20.

Reaction, Equilibrium Constant (at 230°C), and Source:

a) \(5\text{CuFeS}_2 + 2\text{SO}_4^{=} + 4\text{H}^+ = 4\text{FeS}_2 + \text{Cu}_5\text{FeS}_4 + 2\text{H}_2\text{O} + 3\text{O}_2\)
   \[\text{Log } K = -84.24 \quad \text{Source: See note at end of list.}\]

b) \(\text{FeS}_2 + \text{H}_2\text{O} = \text{FeS} + \text{H}_2\text{S} + \frac{1}{2}\text{O}_2\)
   \[\text{Log } K = -25.24 \quad \text{Source: Barner and Scheuerman, 1978}\]

c) \(\text{FeS}_2 + \text{H}_2\text{O} = \text{FeS} + \text{HS}^- + \text{H}^+ + \frac{1}{2}\text{O}_2\)
   \[\text{Log } K = -30.63 \quad \text{Source: Barner and Scheuerman, 1978}\]

d) \(\text{H}_2\text{S} = \text{HS}^- + \text{H}^+\)
   \[\text{Log } K = -7.194 \quad \text{Source: Helgeson, 1969}\]

e) \(5\text{CuFeS}_2 + 2\text{H}_2\text{S} + \text{O}_2 = 4\text{FeS}_2 + \text{Cu}_5\text{FeS}_4 + 2\text{H}_2\text{O}\)
   \[\text{Log } K = 41.74 \quad \text{Source: See note at end of list.}\]

f) \(\text{H}_2\text{S} + \frac{3}{2}\text{O}_2 = \text{SO}_4^{=} + 2\text{H}^+\)
   \[\text{Log } K = 61.11 \quad \text{Source: Garrels and Christ, 1965}\]

g) \(\text{HS}^- + \frac{3}{2}\text{O}_2 = \text{SO}_4^{=} + \text{H}^+\)
   \[\text{Log } K = 68.28 \quad \text{Source: Garrels and Christ, 1965}\]

h) \(2\text{O}_2 + \text{H}_2\text{O} + \text{Ag}_2\text{S} + \text{CO}_2 = \text{Ag}_2\text{CO}_3 + \text{SO}_4^{=} + 2\text{H}^+\)
   \[\text{Log } K = 48.97 \quad \text{Source: Helgeson, 1969}\]

i) \(2\text{Ag} + \text{H}_2\text{S} + \frac{3}{2}\text{O}_2 = \text{Ag}_2\text{S} + \text{H}_2\text{O}\)
   \[\text{Log } K = 25.27 \quad \text{Source: Barner and Scheuerman, 1978}\]

ej) \(2\text{Ag} + \text{H}^+ + \text{HS}^- + \frac{1}{2}\text{O}_2 = \text{Ag}_2\text{S} + \text{H}_2\text{O}\)
   \[\text{Log } K = 31.21 \quad \text{Source: Helgeson, 1969}\]

k) \(2\text{Ag} + \text{SO}_4^{=} + 2\text{H}^+ = \text{Ag}_2\text{S} + \text{H}_2\text{O} + (3/2)\text{O}_2\)
   \[\text{Log } K = -37.47 \quad \text{Source: Helgeson, 1969}\]

NOTE: Log K values calculated from the Van't Hoff expression using data from Crerar and Barnes (1976) and from Barner and Scheuerman (1978).