

Characteristics of some silver-, and base metal-bearing,
epithermal deposits of Mexico and Peru

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This report is preliminary and has not been reviewed for conformity with
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Introduction

Lithotectonic, mineralogical, and geochemical data on two silver- and base metal-bearing deposits from Peru and two from Mexico are compiled to facilitate comparisons with other epithermal deposits. Silver and base metal-bearing deposits of Mexico and Peru constitute an important portion of the world silver production derived from shallow, vein-type deposits hosted in volcanic rocks. Although these deposits are generally similar to epithermal deposits of Nevada and Colorado in the western United States, they have some important differences. Because of this, data on the geological attributes of these deposits are very useful for developing models of ore formation that can be used in mineral exploration. The data collected for this compilation are presented in the following pages in summaries of the important characteristics of each deposit. This compilation, which shows the complexities in the geology of epithermal ore deposits in Mexico and Peru, serves as a basis for further comparisons among epithermal deposits throughout the world. The case studies provide data useful to geologists and explorationists interested in developing models of ore formation to be used in exploration for mineral deposits of this type. The deposits described in this report are the Guanajuato district of Guanajuato, Mexico, the Pachuca-Real del Monte district of Hidalgo, Mexico, the Colqui district of Lima, Peru, and the Julcani district of Huancavelica, Peru.

Although many characteristics of the geology and geochemistry of this type of deposit were considered, the most important criterion for choosing these deposits was that they have substantial quantities of precious- and base-metal mineralization. Additional criteria for selecting the deposits were that they be hosted primarily by calc-alkaline volcanic rocks of intermediate to silicic composition and that they be younger than Tertiary in age. Many deposits in Mexico and Peru and other parts of Central and South America were excluded because the literature describing the districts is not readily available. Furthermore, many districts have not been examined in detail or the information available is of limited geological scope. The four districts that are compiled in this report were chosen because they are described in abundant literature dating from early mining reports on the general geology and mineralogy to very recent data on detailed geochemical and mineralogical studies. They were chosen as being fairly typical, classic examples of near-surface, low-temperature vein deposits as described by Lindgren (1928) in his treatise on ore deposits (Mineral deposits, McGraw-Hill, 1049 p.). These deposits are similar in aspects of their geology and geochemistry to many of the famous, epithermal silver mining districts in Colorado and Nevada including Creede, Colorado, Tonapah, Nevada, and the Sunnyside Mine of the Eureka district, Colorado, and, in the special case of Julcani, to Summitville, Colorado, and Goldfield, Nevada. The characteristics that distinguish them include overall size, production and alteration assemblage. The information documented in each summary will be used in a forthcoming series of papers on the comparative anatomy of precious and base metal deposits in North and South America.

Discussion

The districts covered in this report all contain substantial amounts of base metal sulfides and sulfosalts as well as economically important quantities of silver and gold. In most of the districts mining began during the Spanish colonial period. One of the first districts to be discovered by the Spaniards was Pachuca-Real del Monte, which was found in 1522 shortly after the arrival of Cortez in Mexico. Similarly, Guanajuato was discovered by Spanish packers or prospectors in 1548. Both of these districts had their reputations built on the large quantity of silver that was mined in those early days. Colqui was also mined originally for silver, (Colqui comes from the Quechua word for silver) although today primarily lead and zinc ore is mined. Julcani is unique to this group because it was initially famous for the gold ores extracted from the center of the district (the Tentadora area); today (1984) it is the second largest producer of silver in Peru and a major source of bismuth.

Guanajuato is by far the largest of the four districts, having a surface extent of 22 kilometers northwest by 9 kilometers northeast and a vertical extent of at least 700 meters. Pachuca-Real del Monte is next in size, extending over 11 kilometers west by 8 kilometers north and having a vertical range of up to 600 meters. Julcani and Colqui have similar areal extents of 5 northwest x 3 km northeast and 8 northeast x 2 northwest, respectively. They also have similar vertical extents of mineralization, 450 meters for Julcani and 400-480 meters for Colqui.

The age of mineralization at Guanajuato has been dated at 27.4 ± 0.4 to $30.7 \text{ my} \pm 0.3$ based on potassium-argon measurements on late adularia in the veins. This age is considerably older than the dates derived by potassium-argon measurements for the other districts. Muscovite, admixed with silver-gold ore, yielded ages of $10 \pm 0.5 \text{ my}$ and $10.6 \pm 0.5 \text{ my}$ for the mineralization at Colqui. Similarly, the host volcanic unit at Julcani was dated at $10.13 \pm 0.08 \text{ my}$ by K-Ar measurements on muscovite. Pachuca-Real del Monte has not been dated by isotopic methods but field relations suggest an age of Miocene/Pliocene or younger, which puts it at about the same age as the ores at Colqui and Julcani. The ore deposits all appear to have formed within a couple of million years after extrusion of the host.

The predominant host for the districts are calc-alkaline volcanics, consisting of andesite rhyodacites and rhyodacites. However, at Guanajuato, the mineralization extends down into the underlying Eocene/Oligocene conglomerate and Mesozoic sediments and at Colqui the volcanic sequence includes minor amounts of siliceous and calcareous sediments. Calderas have not been identified in any of the four districts although the mineralization at Julcani is localized at an eruptive center. At the other districts mineralization took place along major faults or fault systems related to uplift or doming.

The appearance of alunite, which indicates acid sulfate alteration, and the presence of substantial amounts of gold in addition to silver at Julcani distinguishes it from the other three districts which are dominantly Ag-bearing and have a K-silicate mineral stable in the environment of ore deposition. Pachuca also had considerable amounts of gold ores which have been mined (Erickson, Pers. Comm., 1984). The presence of enargite and

the associated alunite-quartz-pyrite alteration at Julcani (Petersen and others, 1977) highlight its similarity to acid-sulfate alteration type districts such as Summitville, Colorado, and Goldfield, Nevada. Noble and Silberman (1984) consider Julcani to be the Ag-analog of the Au-rich, acid-sulfate alteration districts exemplified by Goldfield, Nevada.

Guanajuato, Colqui and Pachuca-Real del Monte, are similar mineralogically and geologically in most aspects to such well-studied classic epithermal districts as Creede, Colorado and Sunnyside, Colorado. The presence of muscovite instead of potassium feldspar as a stable vein mineral distinguishes Colqui from the epithermal deposits of Nevada and Colorado. This distinction may be important in defining the geochemical environment of the ore at Colqui. Guanajuato and Pachuca-Real del Monte are distinguished from the deposits of Colorado and Nevada on the large volume of ore produced at each of those districts. The ore produced from the combined Pachuca-Real del Monte districts is valued at over 3,760 million dollars (1973 constant dollars) whereas that from Guanajuato is valued at about 2,950 million dollars (1973 constant dollars). The famous Comstock Lode, at Virginia City, Nevada which produced ore valued at approximately 1,120 million dollars is the only deposit in Colorado and Nevada to come near the Mexican districts in value of production.

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I. Geologic characteristics of the Guanajuato district.

DISTRICT: Guanajuato, State of Guanajuato, Mexico (Lat. 21°02'N, 101°15'W)

MAJOR MINES AND VEINS: Las Torres, Rayas, Cata, Mellado, Sirena and Valenciana mines; Veta Madre vein system, Sierra vein system and La Luz vein system.

COMMODITIES MINED: Au, Ag, Pb, Cu, Zn, and very minor Hg

PRODUCTION: Total production to 1979 is estimated at 113,400 kilograms of Au, and 28,353,000 kilograms of Ag. For the year 1933, 50,780 kilograms of Ag, 935 kilograms of Au, 4680 kilograms of Pb, and 45 kilograms of Cu were produced. For the years 1968-1975 and 1977 to 1979 826,600 kilograms of Ag, 6805 kilograms of Au, 366,400 kilograms of Pb and 737,300 kilograms of Cu were mined. Skillings (1982) reports production through 1981 estimated at 32,000 metric tons of Ag and 140 metric tons of Au.

AGE OF ORE: K-Ar ages on late adularia (post-ore) in the vein systems range from 27.4 ± 0.4 m.y. to 29.2 ± 2.0 m.y. (Veta Madre) and from 28.3 ± 5.00 m.y. to 30.7 ± 0.3 m.y. (Sierra) (Gross, 1975).

REGIONAL PETROTECTONIC SETTING: The area is underlain by Mesozoic and Cenozoic rocks. The Mesozoic rocks (Esperanza Fm.) are composed of marine sedimentary rocks and lavas which have been folded and intruded by Cretaceous dikes and stocks of intermediate to felsic composition. The Mesozoic rocks are overlain unconformably by a flat-lying Eocene conglomerate (Guanajuato Fm). The conglomerate is in turn overlain by at least 2300 meters of extrusive volcanic rocks which range in age from lower Oligocene (37.0 ± 3.0 m.y.) to middle Oligocene (32.1 ± 1.0 m.y.) Dikes of various composition cut the lavas and are probably the feeders to overlying flows and tuffs.

The Oligocene volcanics include a volcanoclastic sandstone (Losero Fm), air-fall and ash flows of rhyolite (Bufa Fm), andesite tuff with basal volcanoclastic shale and sandstone (Calderones Fm), porphyritic andesite flows interbedded with andesitic tuff (Cedro Fm) and welded ash flow tuff (Chichindaro Fm). Cretaceous to early Tertiary diorite and granite (La Luz Complex) intrude the Esperanza Fm but are not observed to cut Tertiary rocks. Quartz monzonite, monzonite and diorite dikes may be related to the La Luz Complex. Younger dikes are related to the Calderones Fm (porphyritic andesitic dikes), Cedro Fm (andesitic dikes) and Chichindaro Fm (rhyolite dikes).

The district lies on the NE flank of a NW trending regional anticline. There are 3 sets of major faults in the area. The oldest trends NE to E and is pre-ore (weakly mineralized). The intermediate faults trend NW and are pre-ore and ore-stage (3 systems: the Sierra, the Veta Madre and the La Luz; all are strongly mineralized). The youngest set which trends NE, is post-ore.

ORE HOST AND AGE OF HOST: All rocks that outcrop in the district are mineralized except the youngest formation (Chichindaro) although the Chichindaro Fm is also pre-ore.

<u>Formation</u>	<u>Thickness</u>	<u>Age</u>
Chichindaro	more than 25m	Middle Oligocene (32.1 ± 1.0 m.y., K-Ar)
Cedro	100-640m	Middle Oligocene (by strat. position)
Calderones	200-250m	Oligocene (by strat. position)
Bufo	360m	Early Oligocene (by K-Ar method, 37.0 ± 3 m.y.)
Losero	10-50m	Early Oligocene (by strat. position)
Guanajuato	at least 1500m	Late Eocene to early Oligocene (by fossils)
Esperanza		Triassic to Jurassic (by strat. position)

ASSOCIATED VOLCANICS: See above

ALTERATION: Pre-ore stage propylitic alteration is widespread and consists of chlorite-pyrite-montmorillonite and rare epidote as a pervasive alteration of the rock groundmass. Pre-ore potassic alteration is restricted to an inner, more veinward zone and is primarily a adularia-sericite-illite quartz alteration of the rock groundmass. The potassic alteration is only located in areas of intense fracturing of vein walls. Argillic alteration is associated with the ore-stage fluids and consists of kaolinite and halloysite within and adjacent to the veins; montmorillonite occurs farther from the veins. Argillization is restricted to a halo around ore shoots and passes upward into a sericite and/or illite cap above the ore shoots.

EXTENT OF ORE: The ores are contained within 3 major vein systems. The largest has a surface extent of more than 15 km in length; the others extend for about 10 km (maximum). The ore shoots extend irregularly along the veins from the surface (approx. 2400 meters above sea level) down to at least 1700 m.a.s.l. The ore bodies have been divided into Upper (surface to 2100 m.a.s.l.), Lower (2200 m to 1700 m.a.s.l.) and Deep (<1700 m.a.s.l.).

VEIN MINERALOGY:

Ore: electrum, acanthite, polybasite, aquilarite, naumannite, sphalerite, galena, pearceite, Ag-metal, Au-metal, rare proustite-pyrargyrite, chalcopryrite

Gangue: chlorite, adularia, illite, melahalloysite, montmorillonite, halloysite, kaolinite, sericite, quartz, pyrite, guanajuatite, calcite, fluorite, laumontite, hematite, dolomite, siderite and rare epidote and pyrrhotite. Conspicuously absent minerals: barite, rhodochrosite

ASSEMBLAGES:

- (1) pyrite - sphalerite - galena - chalcopryrite - tetrahedrite
- (2) pyrite - acanthite, polybasite, pyrargyrite, chalcopryrite (very rare), electrum, silver, and gold.

Deposition of assemblage 1 preceded deposition of assemblage 2. Ag and Au are often associated with adularia, calcite and sericite, in fact, as adularia increases in a vein, Ag values increase (Kamilli, pers. comm., 1983). Sphalerite rarely occurs with silver minerals.

CHARACTER AND TEXTURE OF ORE: The ore occurs as dark gray, crenulated, hair-like stringers, as poorly defined bands up to 20 cm-wide and as irregular pods in veins up to several centimeters in diameter. Some open-space filling occurs with vugs lined with concretionary quartz layers, masses of dark gray material and crystals of ore minerals.

EVIDENCE FOR SUPERGENE PROCESSES: A variety of oxidation and alteration products have been reported.

PARAGENESIS:

- 1: quartz (milky-white, rarely amethystine + calcite ± nontronite ± chlorite ± pyrite ± adularia ± montmorillonite
- 2a: pyrite + sphalerite + galena + chalcopryrite + tetrahedrite + quartz (amethystine)
- 2b: Pyrite + acanthite + polybasite + pyrargyrite + chalcopryrite + electrum + quartz (amethystine)
- 3: quartz (rarely amethystine) + calcite ± pyrite ± adularia ± siderite ± dolomite

The earliest (1) and latest (3) stages consist chiefly of gangue minerals and minor Au and Ag. Most ore minerals were deposited during stage 2a and 2b; 2a is base-metal dominant whereas 2b is Ag-rich.

MINERALOGICAL AND CHEMICAL ZONATION: There are two schools of thought:

- 1) Mineralogy of Upper and Lower (middle) ore horizons (Stage 2), as described by Buchanan (1978), consists of acanthite + adularia + pyrite + electrum + chalcopryrite + quartz; Deep ore horizons consists of chalcopryrite + galena + sphalerite + adularia + quartz + acanthite. Buchanan, (1978) believes that there were 2 fluids.
- 2) Upper, Lower and Deep ores horizons have essentially the same minerals (Stage 2), which were deposited in the same order but in varying proportions (common fluid for all ore types). Minor quantities of Au and Ag minerals are associated with sericite + adularia + quartz (Gross, 1975).

FLUID INCLUSION DATA:

STAGE & MAJOR PHASES	INCL. HOST PHASE	TEMPERATURE OF HOMOGENIZATION RANGE	BEST EST.	#	TYPE	INCLUDED PHASES	EVIDENCE FOR BOILING
<u>Las Torres Mine:</u>							
PRE-ORE	calcite	231->360		11	*PS		4,5
ORE Ag-stage	quartz calcite	231->360	230	281	P,PS*	very rare occurrences of halite & sylvite phylosilicate	1-5
ORE Post-Ag	quartz calcite	225->360 228->360	230 230	110	P,PS*		1-7
<u>Rayas mine</u>							
Above deep > 1700 m.a.s.l.	quartz	258-360		22	*		
< 1700 m.a.s.l.	quartz	261-385		17		Halite	
	sphalerite	282		1			

(Data from Buchanan, 1979)

* boiling

Evidence for Boiling

P: primary
PS: pseudosecondary

1. Inclusions aligned in bands P:
2. Highly shredded ore and gangue
3. Uneven argillic alteration in vein, uneven banding
4. Variable liq/vapor ratios;
5. Wide range in homogenization temperature
6. Varying salinities
7. Inclusions spatially related to silver deposition

Analyses of fluids leached from ore and gangue minerals in parts per million,

<u>Stage</u>	<u>Salinity(ppm)</u>	<u>Ca :Na :K :Mg</u>	<u>Error</u>
Pre-Ore	29,200	96 :2 :2 :0	10%
Ore-stage			
Bufa host	5,260	63 :9 :26 :2	"
Losero host	26,000	66 :11 :15 :7	"
Post-silver	6,910	95 :2 :2 :5	"

	<u>Cu</u>	<u>As</u>	<u>Sb</u>	<u>Mn</u>	<u>Pb</u>	<u>Au</u>	<u>Ag</u>	<u>Fe</u>	<u>Bi</u>	<u>Zn</u>	<u>Ca</u>	<u>Na</u>	<u>K</u>
Pre-Ore													
Ave(1)	100	0.7	2.9	0.9	600	0.1	1.2	2.4	4.7		10840	232	197
Ore-stage													
Bufa host													
Ave(5)	11.5	0.1	1.4	0.07	57.7	0.02	11.5	4.7	22.5	61.4	1006	149	410
Losero host													
Ave(1)	59.8	.96	2.8	0.2	158.3	0.02	11.8	1.5	59.0	7.2	5918	1013	1355
Post-silver													
calcite													
Ave(3)	5.9	.07	.35	.03	19.7	0	0.6	0.97	7.0	0.5	2039	52	52

STABLE ISOTOPE DATA: No data.

PROPOSED SOURCE OF HYDROTHERMAL FLUIDS: No data.

TRACER DATA FOR SOURCE OF METALS: No data.

GEOPHYSICAL EVIDENCE: No data.

SUMMARY: The fracture systems were permeable throughout most of their lengths, with the fractures partially filled with breccia fragments and gouge. Precious and base metal and sulfur rich solutions rose up the fractures filling open spaces and partially replacing the breccia with Au and Ag and perhaps major amounts of base metal sulfides. The precious metals were sparsely distributed throughout the quartz vein filling (Gross, 1975) and if deposited, base metal sulfides were restricted to the deepest parts of the ore deposit.

Boiling was common in these solutions above the deeper levels at a temperature of 230°C. Based on an average total dissolved solid content of 29,200 ppm, the boiling depth (hydrostatic) was at about 330 meters (Haas, 1976) below the paleosurface. Since the ores were at least 600 meters below the paleosurface, hydrostatic conditions could not have prevailed and lithostatic pressure release is proposed as the mechanism responsible for boiling. Boiling can result in a pH rise, a temperature drop, a rise in concentration of metal complexes, and a rise in fO₂. Many combinations of these factors may promote base metal deposition at the level of boiling.

At Guanajuato, quartz deposition, possibly a function of adiabatic temperature drop of rising solutions, ceased at 2350 meters above sea level. This could have resulted from 1) mixing with cool and dilute groundwater or 2) depletion of silica due to quartz precipitation at depth due to boiling. Calcite, opal and jasper are deposited above the 2350 meter level in the ore deposits.

Wall rock alteration resulted in a zonal pattern of inner intense potassic alteration surrounded by a propylitic halo. Alteration is more intense and the potassic grade localized in areas of greater fracture permeability. After the pre-ore stage mineralization, the altered host rocks were refractured. Fractures formed along pre-existing veins as well as in previously unfractured rock. Most fractures in propylitically altered rocks were tight or gouge-filled whereas fractures in the potassically altered rocks were open and free of gouge.

Ore-stage solutions rose up the various isolated stockwork (fractured) areas to the paleosurface. The solutions, with $T_h = 230^\circ\text{C}$ and an average salinity of 5260 ppm would boil at 340 meters below the paleosurface (Haas, 1976), assuming hydrostatic pressure prevailed. The shallow ore shoots may have formed as a result of simple boiling. Evidence for this is limited to: a) the samples from the upper horizon contain fluid inclusion evidence of boiling, b) boiling under hydrostatic conditions, leading to a pH rise and deposition of metals, is a commonly observed feature of hydrothermal systems. Thus, the assumption that the base of the upper horizon ore shoots is at the boiling level is supported by the physical condition.

Boiling may also explain the presence of lower horizon ore shoots. 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 occurs both above the level of boiling (due to calcite and adularia precipitation) and below the level (due to quartz, calcite and adularia precipitation). As the sealing occurs above and below the boiling level, the fractures at depth remain open and filled with ore stage solutions, however, fluid movement is essentially stopped. If the cap fractures as a result of regional tectonism, hydro fracturing, etc., 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. The "flashing" will cause a rise in pH, in $f\text{O}_2$, a drop in $f\text{CO}_2$, a drop in temperature and lead to precipitation of metal sulfides, adularia, quartz, calcite and sericite. Thus, the lower horizon area can be mineralized over a vertical interval of 340 meters using this process. The main ore shoot at Las Torres has a vertical extent of 330 meters.

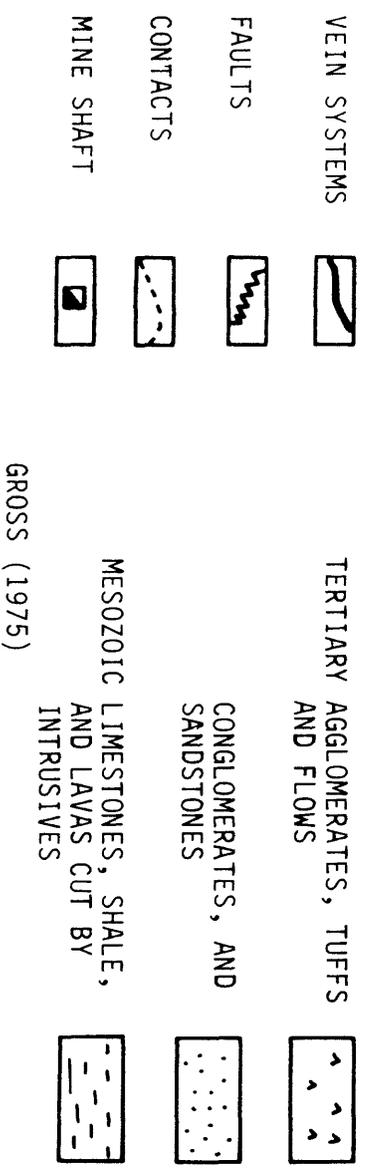
Immediately after flashing, the solutions will rise up the newly-opened channels to the paleosurface. This process repeats itself - boiling, self-sealing, fracturing, flashing, boiling, self-sealing, fracturing. During flashing and boiling, volatiles are partitioned into the vapor phase. If the vapors condense at a higher level in the system a low pH liquid will result. This liquid reacts with the walls and forms minerals stable at low pH. These occur around the ore shoots as a halo or cap of argillic and phyllic alteration. Since they occur where the vapors are trapped (margins of ore shoots), the margins of the system have the low pH alteration assemblage, not the center.

After the ores accumulated, the salinity of the solution increased while metal content and H_2S content dropped. Since T_h was still 230°C or warmer, the solutions were boiling but had little metal to precipitate so calcite, quartz and minor fluorite were deposited late in the mineralization history.

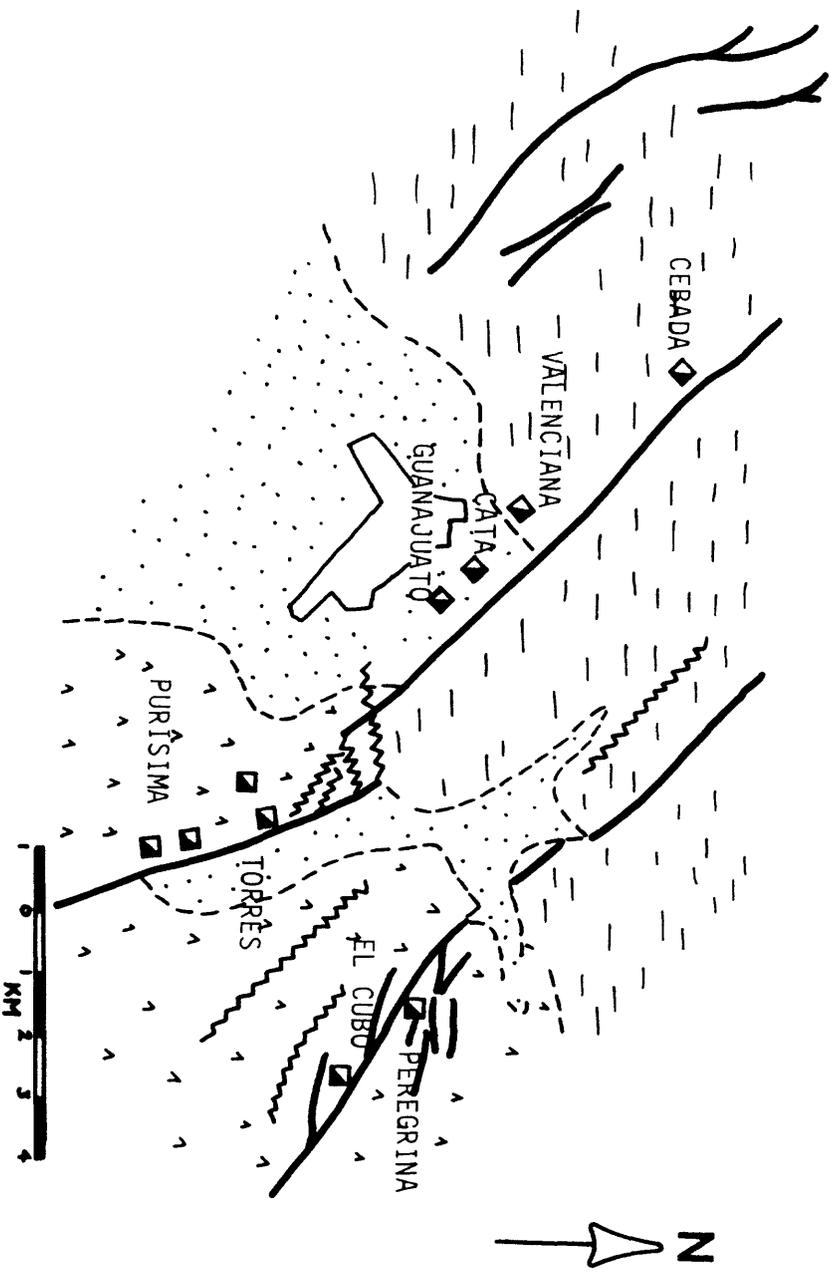
References

- Botsford, C.W., 1909, Geology of the Guanajuato district, Mexico: the Engineering and Mining Journal, pp. 691-694.
- Buchanan, L. J., 1979, The Las Torres Mine, Guanajuato, Mexico, Ore Controls of a fossil geothermal system: Unpub. PhD thesis, Colorado School of Mines, 138p.
- Gross, W.H., 1975, New ore discovery and source of silver-gold veins, Guanajuato, Mexico: Econ. Geol., v.70, pp 1175-1189.
- Haas, J.L., 1976, Thermodynamic properties of the coexisting phases and thermochemical properties of the NaCl component in boiling NaCl solutions: USGS Bull. 1421-B, 71 pp.
- Petruk, W. and Owens, D., 1974, Some mineralogical characteristics of the silver deposits in the Guanajuato Mining District, Mexico: Econ. Geol., v. 69, pp 1078-1085.
- Randall, T.A., 1979, Structural setting, emplacement of Veta Madre ore bodies using the Sirena and Rayas Mines as examples, Guanajuato, Mexico: in Nev. Bur. Mines and Geol., Ridge, J.D., Ed., Rept. 33.
- Skillings, D.N., 1982, Fresnillo-Major Mexican Silver Producer, Skillings Mining Review, October 23, 1982, p. 6-8.
- Wandke, A. and Martinez, Juan, 1928, The Guanajuato Mining district, Guanajuato, Mexico: Econ. Geol., v. 23, pp. 1-44.

GEOLOGY OF THE GUANAJUATO DISTRICT, MEXICO



GROSS (1975)



II. Geologic characteristics of the Pachuca-Real del Monte district,

DISTRICT: Pachuca-Real Del Monte District, Hidalgo, Mexico
(~Latitude 20° 07'N, Longitude 98° 45'W)

MAJOR MINES AND VEINS: East system veins of the Pachuca area: Viscaina, Altagracia, Santa Ana (No. 5, No. 2, Noreste), Camilia (No. 6, Noreste), Maravilas-Pabellon, Paricutin, Rosario Viejo. East system veins of the Real del Monte area: Moran, Viscaina-Tapona-Monte, Santa Gertrudis-Pinta-Regla. North system veins of Real del Monte: Dios te Guie, Colon-La Rica-Alfredo, Santa Ines, Salvadora-San Luis-Santa Brigida-Resquicio-W1-W2-W3, Cabrera-Escobar-Reina, Purisma.

ORE: Ag, Au and trace amounts Pb, Zn, Cu, Hg

PRODUCTION: Total production is estimated at roughly 40,000,000 kilograms of Ag and 187,000 kilograms of Au since the early 1600's. Data on specific years indicate that for the year 1933, 161,300 kilograms of Ag, 880 kilograms of Au, 4500 kilograms of Pb, and 910 kilograms of Cu were produced. Other estimates indicate that from the beginning of mining (Spanish colonial period) to 1963, 35,000,000 kilograms of Ag, 176,000 kilograms of Au were extracted and that for the years 1968-1975, and 1977-1979, an additional 1,000,000 kilograms of Ag, 5730 kilograms of Au, 6,500,000 kilograms of Pb, 13,700,000 kilograms of Zn and 9,000,000 kilograms of Cu were produced.

AGE OF ORE: Later than early Miocene.

REGIONAL PETROTECTONIC SETTING: The veins occur within rocks of Miocene-Pliocene age that range in composition from basaltic andesites to rhyolites and consist mainly of flows and flow breccias and lesser amounts of tuff and volcanoclastic rocks. Intrusive rocks include several eroded rhyolite-dacite domes and a host of east-west-trending dikes ranging in composition from andesite to rhyolite. Regional unconformities and thin but persistent clastic beds occur at the tops of some formations. The volcanic rock in the district is estimated to be about 2,270 meters thick. Rock units are flat-lying to gently dipping and are offset by east-west trending, south-dipping normal faults with some areas of north-south trending vertical faults. Some east-west trending reverse and wrench faults are present. Most faults came into being prior to and partly during deposition of ore. Only minor wrench faulting and reactivation of some normal faults took place after ore deposition.

ORE HOST AND AGE OF HOST: Calc-alkaline volcanics of the Tezuantla, Cerezo, Vizcaina, Santa Gertrudis, Real del Monte, and Pachuca Formations. The age of the host is estimated by stratigraphic relations to be Miocene to Pliocene.

ASSOCIATED VOLCANICS: (Listed from youngest to oldest.)

Tezuantla Fm. = rhyolite-rhyodacite flows and tuffs

Cerezo Fm. = rhyolite-rhyodacite flows and tuffs

Vizcaina Fm. = andesite-dacite flows, minor flow breccias and tuff
basal volcanoclastic member

Santa Gertrudis Fm. = andesite-dacite flows, minor flow breccia,
basal discontinuous volcanoclastic member

Real del Monte Fm. = andesite-dacite flow breccias, minor flows,
basal discontinuous volcanoclastic member

Pachuca Fm. = andesite-dacite flows and flow breccias, basal volcano-
clastic member.

ALTERATION: Wall rock alteration is divided into five assemblages, the distribution and intensity of which are related to fracture density and vertical position in the mineralized system. Wall rock in and adjacent to ore-bearing veins and larger fractures are characterized by adularia-chlorite-pyrite alteration. Away from veins, wall rocks dissected by minor fractures are propylitically altered. Above ore bodies, fault zones are characterized by illite-calcite-chlorite-pyrite alteration. Massive, unfractured rocks above and below the ore bodies are characterized by hematite-magnetite-chlorite alteration.

EXTENT OF ORE: The veins range in length from 1,300 to 3,000 meters, in average width from 3 to 10 meters and in maximum vertical extent from 450 to 660 meters. All ore occurs within a vertical interval of 1,000 meters. The ore is concentrated in highly fractured areas in faults. Irregular pods or lenses are erratically distributed along veins and separated from each other by narrow low grade vein segments or by unmineralized fault gouge. Ore bodies terminate upwards by pinching out (above the ore bodies, the faults are simple slip-planes and contain a few stringers of quartz and calcite.) Downward, the veins may pinch out to below minimum mining width, pinch out completely, horsetail, or they may continue at depth or even get wider but the Ag/Au values drop.

VEIN MINERALOGY:

Ore: galena, sphalerite, argentite, chalcopyrite, polybasite, stephanite, tetrahedrite (rare), Ag-wire

Gangue: quartz (some amethystine), johansennite-rhodonite, adularia, calcite, pyrite, prehnite, epidote, illite and kaolinite, fluorite, dolomite, barite (very minor)

Conspicuously absent minerals: proustite and pyrargyrite

CHARACTER AND TEXTURE OF ORE: The ore consists of 1) angular rock fragments; 2) massive vein material (gangue) which cements rock fragments and 3) vuggy veinlets which vary in width from less than a millimeter to over 0.5 meter. The dominant mode of occurrence of sulfide minerals is as a replacement of preexisting vein and wall-rock minerals.

EVIDENCE FOR SUPERGENE PROCESSES: Chalcocite, covellite, malachite, Ag-chlorides and bornite, limonite, mn-oxides, bromides, minor Au and Ag-metal and anglesite are found occasionally as supergene replacements of other sulfides.

PARAGENESIS: The first minerals deposited in the vein were a cloudy, fine-grained quartz, johansennite-rhodonite and adularia. These were followed in time by a clear, coarse-grained quartz, prehnite, epidote and minor sphalerite. This was followed by more sphalerite, along with galena, chalcopyrite, argentite, illite-kaolinite, and increasing amounts of calcite. Pyrite occurs throughout the paragenetic sequence but is in abundance only just after deposition of the second type of quartz.

MINERALOGICAL AND CHEMICAL ZONATION: The highest silver grades are encountered in middle mine levels; silver values decrease with depth for at least 160m below the bottom of the cutoff grade of ore. Hg-halos have been used as a guide for mineral exploration. Base-metal sulfides are much more abundant, especially at depth, in the veins of the north system than in those of the east system. The base sulfides tend to be disseminated in the wall rocks of the north system more than in those of the east system.

NUMBER OF PERIODS OF HYDROTHERMAL ACTIVITY: One period of vein mineral deposition (Bastin, 1948 and Drier, 1976).

FLUID INCLUSION DATA: 95% of sampled inclusions were simple two-phase gas-liquid inclusions. Multiphase inclusions contained NaCl crystals, and some contained an unidentified sulfide(?) phase in addition to liquid and gas and NaCl. The three-phase inclusions (l, g, NaCl) occurred with two-phase l-v inclusions in which the v-l ratio was large suggesting they trapped a boiling fluid.

First melting temperature of ice (T_m) = -0.25°C to -3.5°C with errors ranging from $+0.25$ to $\pm 1.0^\circ\text{C}$ depending on inclusion size, $T_{mave} = -0.88^\circ\text{C}$ (107)

Temperature of homogenization (T_h) = 210°C to $305^\circ\text{C} \pm 2^\circ\text{C}$ (372)
Subdivided on the basis of mineral, the T_h average values are as follows:

<u>mineral</u>	<u>#</u>	<u>temperature</u>
cloudy quartz	(136)	$262^\circ\text{C} \pm 27^\circ\text{C}$
clear quartz	(251)	$247^\circ\text{C} \pm 9^\circ\text{C}$
sphalerite	(3)	$225^\circ\text{C} \pm 4^\circ\text{C}$

Quartz-calcite stringers from above the veins give the following ranges:

$T_m = -0.25^\circ\text{C}$ to -1.0°C with $T_{h_{ave}} = -0.58^\circ\text{C}$ (25)

$T_h = 180^\circ\text{C}$ to 250°C with $T_{h_{ave}} = 200^\circ\text{C}$ (136)

STABLE ISOTOPE DATA:

δD (inclusion fluid) = -90.00‰ (1 sample)

δO^{18} (adularia with very minor quartz) = $+5.00\text{‰}$

$\delta O_{H_2O}^{18}$ (calculated at 250°C) = -6.2

O'Neil and Silberman (1974) concluded in their isotopic study that the water/rock ratio was less than one.

PROPOSED SOURCE OF HYDROTHERMAL FLUIDS: Dominantly meteoric fluids; the shift in δO^{18} to heavier values may result from interaction of meteoric water with the heavier country rock and groundwater.

TRACER DATA FOR SOURCE OF METALS:

Isotopic composition of Pb in Galena:

Sample #	8/4	7/4	6/4
PCH-PR-400	18.712	15.692	38.654
STD DEV. (1 SIGMA)	0.505	0.016	0.013

Cumming, Kesler and Krstic (1979) suggest that lead was contributed from Precambrian basement sources to Cenozoic magmas passing upwards through the basement.

SUMMARY: The Pachuca-Real del Monte district occurs wholly within a calc-alkaline volcanic rock sequence of probable Miocene-Pliocene age. The ore deposits occur in veins and are localized in dilatant zones in faults, which occur at fault intersections or where faults undergo changes in strike or dip. Orebodies terminate laterally and upward where the dilatant zones pinch out; they terminate downward due to a decrease in grade.

Veins appear to have formed beneath a cover of 400 to 500 meters of pre-ore volcanic rock, as indicated by the presence of fluid inclusions indicative of boiling and by stratigraphic reconstruction.

Veins are composed of angular rock fragments (50%), fine-grained cloudy quartz + adularia + johansennite (20%-30%), coarse-grained clear quartz + adularia + prehnite (10%-30%), pyrite + galena + sphalerite + chalcopryrite + argentite (1%-3%), and calcite. Cloudy quartz + adularia + johansennite were deposited between 320°C and 250°C , clear quartz + adularia + prehnite were deposited at about 250°C . Sulfides and calcite

were deposited between 250°C and 200°C and quartz-calcite stringers above veins were deposited at about 200°C. During deposition of clear quartz, the geothermal gradient in the veins was low and may have approximated an adiabatic gradient. The temperature in the veins was probably regulated by the hydrostatic pressure at the highest point in the veins.

Freezing temperature determinations showed that the salinity of the hydrothermal fluids was below 0.4 molal NaCl-KCl equivalent. Salinity determinations coupled with mineral dissociation reactions in the system $K_2O-Na_2O-CaO-Al_2O_3-SiO_2-H_2O-Cl-S-Ag-O_2$ reveal that the pH of the hydrothermal fluids was about 5.8 and that total dissolved silver in solution was about 1 to 100 ppb.

Wall-rock alteration occurred in fractured and otherwise permeable rock. Adjacent to the veins, the alteration minerals are adularia, albite, quartz, calcite, epidote, chlorite, prehnite, and pyrite. Above the veins alteration minerals are calcite, illite, quartz, and pyrite. The wall-rock alteration adjacent to the veins was probably accomplished by potassium metasomatism and reduction of iron from Fe^{3+} to Fe^{2+} . Wallrock alteration above the veins was accomplished by H^+ metasomatism and the introduction of sulfur.

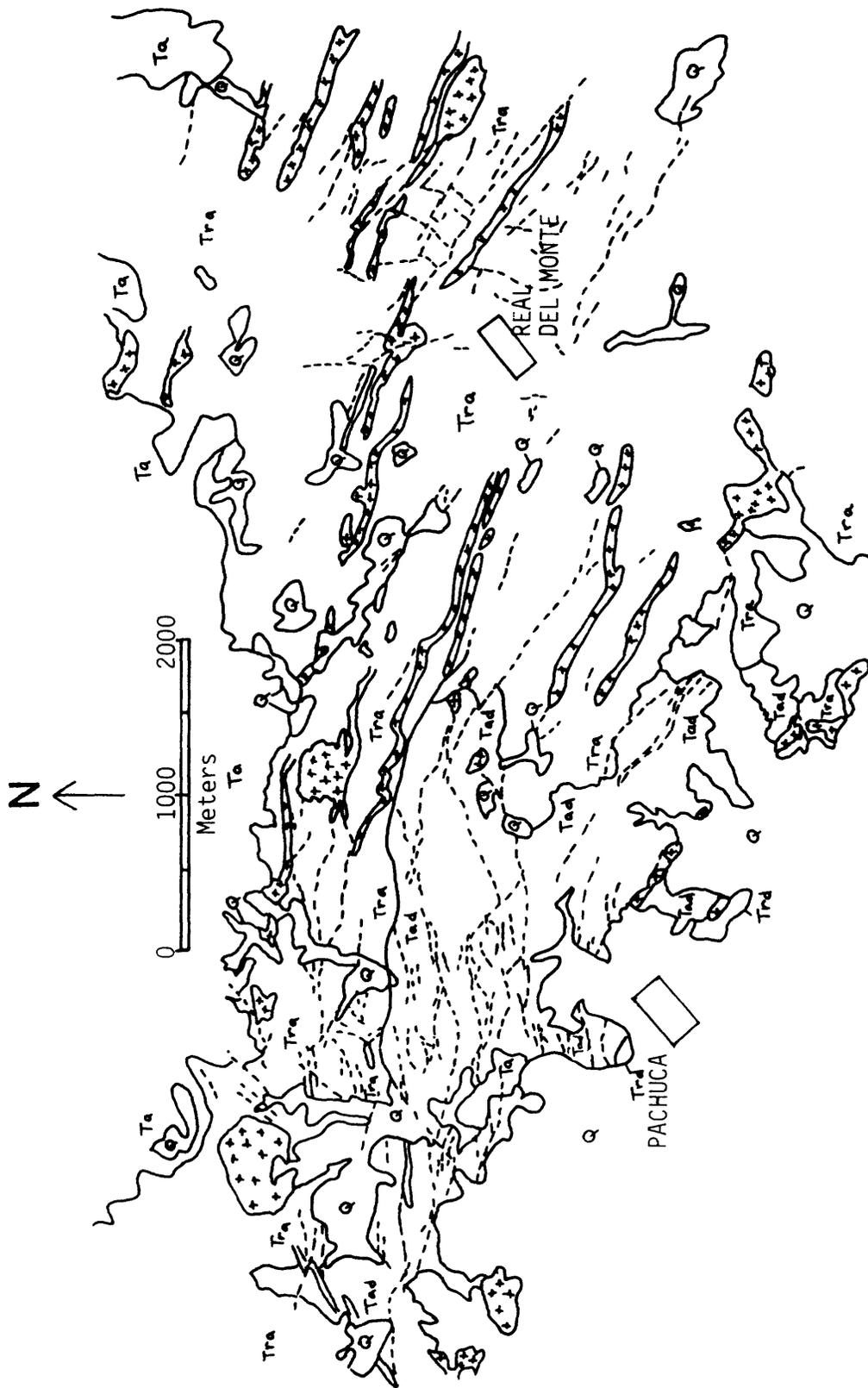
References

- Bastin, E. S., 1948, Mineral relationships in the ores of Pachuca and Real del Monte, Hidalgo, Mexico: *Econ. Geol.*, v. 43, p. 53-65.
- Bastin, E. S., 1948, Mineral relationships in the ores of Pachuca and Real del Monte, Hidalgo, Mexico - a discussion of the reply: *Econ. Geol.*, v. 43, p. 525.
- Cumming, G. L., Kesler, S. E., and Krstic, D., 1979, Isotopic composition of lead in Mexican Mineral Deposits: *Econ. Geol.*, v. 74, p. 1395-1407.
- Drier, J. E., 1976, The Geochemical environment of ore deposition in the Pachuca-Real del Monte District, Hidalgo, Mexico: unpublished Ph.D thesis, The University of Arizona, 115 p.
- Drier, J.E., 1982, Distribution of wall rock alteration and trace elements in the Pachuca-Real del Monte district, Hidalgo, Mexico: *Mining Engineering*, p. 699-704.
- Geyne, A. R., Fries, C., Jr., Segerstrom, K., Black, R. F., and Wilson, I. F., 1963, *Geology and Mineral deposits of the Pachuca-Real del Monte District, state of Hidalgo, Mexico*: Consejo de Recursos Naturales no Renovables Pub. 5E, 203p.
- Gomez, A. C., Ramos, S. C., and Patino, P. M., 1978, Estudio de termometria de oclusiones fluidas y halos de mercurio en el area Prosperidad, distrito de Pachuca-Real del Monte, Hidalgo: Consejo de Recursos Minerales, VII Seminario Interno sobre exploracion geologico-minera, p. 643-674.

Kapadia, A. H., and Valverde, J., 1978, Avance del programa evaluativo distrito de Pachuca y Real del Monte, estado de Hidalgo, Mexico: Gerencia de evaluation y contractos, p. 572-576.

O'Neil, J.R. and Silberman, M.L., 1974, Stable isotope relations in epithermal Au-Ag deposits: Econ. Geol., v. 69, p. 902-909.

Wisser, E., 1948, Mineral relationships in the ores of Pachuca and Real Del Monte, Hidalgo, Mexico a reply: Econ. Geol., v. 43, p. 280-292.



GEOLOGY OF THE PACHUCA-REAL DEL MONTE DISTRICT, MEXICO

- Q Quaternary alluvium
 - Trc Tertiary intrusives, dikes and stocks
 - Tra Olivine andesite, andesite, dacite lavas
 - Tad Rhyolite, andesite and dacite flows of Cerezo, Vizcaina, and Santa Gertrudis Fms.
 - Trd Andesite and dacite flows of Real del Monte, Pachuca, and Corteza Fms.
 - Tr4 Rhyolite and dacite flows of Santiago Fm.
- Contacts
 - Mineralized faults

Adapted from Geyne, Fries, Black, and Wilson (1963)

III. Geologic characteristics of the Colqui district,

Lima, Peru

DISTRICT: Colqui District, Department of Lima, Peru
(Lat. 11°33'03"S Long. 76°27'48"W; Elev. 4400 m.s.n.m.)

MAJOR MINES/VEINS: Finlandia, Colqui, San Juan-Lourdes, Vermouth, Maria Teresa, Pfo-Pfo, Yau-Yau, Quinarcán, Gaby, Ivonne, Cobre, Sin Nombre, El Camino, and Río Bravo veins.

ORE: Mainly Pb, Zn, lesser amounts of Ag, Au, Cu, Cd

PRODUCTION: Intermittently active since Spanish colonial time. 30,000 metric tons of Ag-ore were extracted from the Colqui vein during the period from 1924 to 1929.

For the years 1962, 1964, 1965 and 1968-1973, 65,695 kilograms of Ag (2,112,160 troy ounces), 1160 kilograms of Au (37,298 troy ounces), 20,936 metric tons of Pb, 33,486 metric tons of Zn, 912 metric tons of Cu, and 193 metric tons of Cd were mined (Kamilli and Ohmoto, 1977, and Inst. Nac. de Invest. Fomentos Min., 1962, 1964, 1965).

AGE OF ORE: 10 ± 0.5 my; 10.6 ± 0.5 my (K-Ar age on hydrothermal muscovite in silver-gold ore) (Kamilli and Ohmoto, 1977).

REGIONAL PETROTECTONIC SETTING: The Colqui district is in the Tertiary volcanic belt of Peru. To the west is the coastal batholith and to the east a miogeosynclinal sequence. The local stratigraphic sequence consists of lava flows and tuffs, basalts and minor limestone units. A number of stocks are present in the district. They include a quartz norite, a hornblende-biotite andesite porphyry with oligoclase phenocrysts, and a highly altered andesite porphyry with andesine phenocrysts. Dikes in the district parallel the vein system. One has been described as a highly altered hornblende-andesite porphyry. The district was subjected to medium intensity folding (Petersen and Diaz, 1972). The main fold trends north-south and plunges north. There are two principal fault systems; one trends east-northeast, the other north-south.

LOCAL TECTONIC SETTING: The exclusive locus of mineralization is a system of en-echelon vertical faults and tension fractures (Petersen and Diaz, 1972).

ORE HOST AND AGE: Tertiary Finlandia Fm; and Tertiary Lourdes Fm;

ASSOCIATED VOLCANICS: Six formations are present in the Colqui District, the Usho, Lourdes, Finlandia, and Colqui Superior, Colqui Medio, and Colqui Inferior Formations. The Lourdes and Finlandia Fms host the ore. The overlying Usho Fm is composed of massive andesitic lava flows and tuffs. The Lourdes consists of andesitic and dacitic porphyry lavas and lithic tuffs, and basal siliceous and calcareous sediments. The Finlandia Fm is primarily massive lava flows and tuffs. Basalt flows

with plagioclase phenocrysts make up the Colqui Superior while the Colqui Medio is made up of thinly stratified lithic tuffs with clasts of porphyritic andesite, and cryptocrystalline volcanic rock. Thin beds of limestone are also found within the unit. The lowermost Colqui Inferior unit consists of massive crystal tuffs with subhedral to anhedral andesine crystals and embayed quartz.

ALTERATION ASSEMBLAGES, TIMING AND DISTRIBUTION: The area has undergone hydrothermal alteration which is most intense in the vicinity of the veins. In general, the tuffs are the most severely altered rocks in the district, the lavas less altered and the stocks altered least of all. Close to the Finlandia vein propylitic alteration gives way to intermediate argillic and quartz-sericite alteration, but there are no well defined zones around the vein. Other wall-rock specimens which show more characteristics of argillic alteration contain relicts of mafic minerals completely altered to chlorite + magnetite + epidote + calcite or siderite. Magnetite and pyrite commonly have coronas of hematite or are completely replaced by that mineral.

EXTENT OF ORE: The Finlandia vein in the Colqui district extends a distance of 400-480 meters vertically and 700 meters horizontally. The entire vein system extends over a surface area 8 km NE by 2 km NW. Depth of mineralization is estimated at somewhat greater than 1,000 meters, based on evidence of boiling and data of Haas (1971).

VEIN MINERALOGY:

Ore: sphalerite, galena, chalcopyrite, tetrahedrite, electrum, argentite, proustite-pyrargyrite, pearceite-polybasite, cinnabar stibnite

Gangue: quartz, pyrite, marcasite, kaolinite, siderite, barite, rhodochrosite, and muscovite. Conspicuously absent minerals include enargite, pyrrhotite, bornite and K-feldspar.

CHARACTER AND TEXTURE OF ORE: Most minerals exhibit banded colloform or crustiform textures. Quartz ranges from fine-grained chalcedonic crusts to coarse euhedral crystals. Muscovite is crustiform and crystallized in small radiating clusters. Pyrite is sometimes fractured and infilled with other sulfides and sulfosalts. No textures indicating replacement have been observed.

EVIDENCE FOR SUPERGENE PROCESSES: No data.

PARAGENESIS: Mineralization took place in seven stages (Kamilli and Ohmoto, 1977). The primary criteria for distinguishing stages (Stage II excepted) are the textures and relative proportions of the more common minerals rather than the presence or absence of particular minerals.

Stage I: Euhedral milky quartz, minor bands of disseminated galena, sphalerite, and muscovite, along with minor amounts of pyrite, chalcopyrite and tetrahedrite.

Stage II: (high silver and gold values in places) Ubiquitous fine-grained quartz, pyrite and muscovite, other fine-grained minerals such as kaolinite, sphalerite, galena, chalcopyrite, argentite, tetrahedrite, proustite-pyrargyrite, pearceite-polybasite, electrum and siderite.

Stage III: Coarse euhedral quartz, milky and rarely amethystine.

Stage IV: Predominant ore in the Finlandia vein. Sphalerite, galena, minor chalcopyrite, tetrahedrite, quartz and muscovite.

Stage V: Primarily milky quartz, with significant amounts of chalcopyrite, pyrite and lesser amounts of tetrahedrite, siderite, galena, sphalerite and muscovite.

Stage VI: Sphalerite and galena, also quartz, pyrite, chalcopyrite, tetrahedrite, siderite may also be present.

Stage VII: Reddish brown to light green sphalerite, barite and galena. Other late minerals include quartz, siderite and cinnabar.

MINERALOGICAL AND CHEMICAL ZONATION:

Regional: The Colqui district exhibits a mineralogical zoning that is centered in the area of the Cobre vein, which has a high proportion of chalcopyrite. Westward from the Cobre, the mineralization changes from copper to lead-zinc, silver and finally mercury. The Finlandia, San Juan-Lourdes and Vermouth veins are principally sphalerite- and galena-bearing. In the western part of the district the Colqui and Maria Teresa veins have been mined principally for silver. At Pariamina at the southwestern margin of the district, there are several small fractures that contain cinnabar. To the east of the Cobre vein is the Pfo-Pfo vein, which contains galena, pyrite, tetrahedrite and sphalerite, and appears to be transitional between the lead-zinc and the silver zones. The bonanza silver-gold ore shoots of the Finlandia vein are an exception to this zoning pattern.

Local: The Finlandia vein consists of Pb-Zn mineralization with the Au-Ag mineralization localized in bonanza shoots.

Stage II has a strong vertical zonation; the top is represented by a band of fine-grained quartz, pyrite and muscovite. Further downward, tetrahedrite, electrum, proustite-pyrargyrite and other gold-silver minerals appear.

Stage IV does not show mineralogical zonation above the shallowly plunging part of the Finlandia vein - Fault 3 intersection. Below this intersection the amount of sphalerite and galena drops sharply in bulk proportion and total volume. The richest Pb-Zn ore in the Finlandia Vein is to the west of the intersection of the vein with Fault 3.

NUMBER OF PERIODS OF HYDROTHERMAL ACTIVITY: No data

FLUID INCLUSION DATA: Temperatures of homogenization quartz and sphalerite decreased with time (stages I-VII) from ~299°C to 140°C (317 samples). Stage II fluid inclusions trapped a boiling solution. The salinities (equiv. wt. % NaCl) from quartz and sphalerite also decreased with successive stages from a bimodal distribution of ~13.0 wt. % NaCl and <.5 wt. % NaCl to about 6 wt. % NaCl (215 samples). The leach analyses show that salinities (calculated) range from 1.8 wt % to >7.2 wt. % NaCl (19 samples).

CHEMICAL COMPOSITION DATA:

Kamilli and Ohmoto (1977):

Atomic absorption analyses of water leached from quartz

<u>Element</u>	<u>Amount in ppm</u>	<u>No. of samples</u>
Na**	6000 \pm 600 to 26,000 \pm >1,000	(17)
K	600 \pm 300 to 5,300 \pm 1,000	(14)
Ca	600 \pm 300 to 5,500 \pm 2,200	(8)
Mg	\leq 40 to 2,000 \pm 800	(8)
Mn	\leq 340 to \leq 1,200	(8)
Cl (calc)	11,000 to 42,000	(8)

Tsui and Holland (1979):

Laser microprobe analyses of single fluid inclusions in quartz

<u>Element</u>	<u>Amount (ppm)</u>	<u>No. sample</u>
Na**	5000 \pm 250 to 28,000 \pm 1400	10
Ca	160 to 3,200	10
Mg	6 to 200	10
Mn	<2 to 110	10
Cu*	<1 to 300	10

* may have been some Cu contamination

** some inclusions contained dawsonite

STABLE ISOTOPE DATA:

Mineral	$\delta_{\text{qtz}}^{18}\text{O}/\text{oo}$	$\delta_{\text{H}_2\text{O}}^{18}\text{O}/\text{oo}$	$\delta_{\text{H}_2\text{O}}^{\text{D}}/\text{oo}$	$\delta\text{S}^{34}\text{O}/\text{oo}$
Quartz	-0.6 to 15.5 (43)	-8.4 to +3.0	-71 to -107 (13)	-
Sphalerite	-	-	-48 to -57 (4)	-1.4 to -1.5 (20)
Qtz + Sph	-	-	-50 to -100 (2)	-
Galena	-	-	-	-4.0 to -1.3 (18)
Pyrite	-	-	-	-3.5 to -0.4 (18)
Chalcopyrite	-	-	-	-0.6 to -0.5 (2)
Barite	-	-	-	14.0 to 14.2 (2)

The calculated temperatures from $\delta^{34}\text{S}$ and sphalerite and galena pairs range from 217° to 333°C.

PROPOSED SOURCES OF HYDROTHERMAL FLUIDS: Several lines of evidence including fluid inclusion thermometry, and stable isotope data indicate that two distinct hydrothermal fluids took part in the mineralization (Finlandia Vein). One is interpreted as meteoric and the other as a sedimentary formation (connate) water.

SOURCE TRACER DATA: No data.

GEOPHYSICAL EVIDENCE: No data.

MODEL OF ORE DEPOSITION:

Kamilli and Ohmoto (1977) suggest the following model as being a reasonable interpretation of the geochemical data.

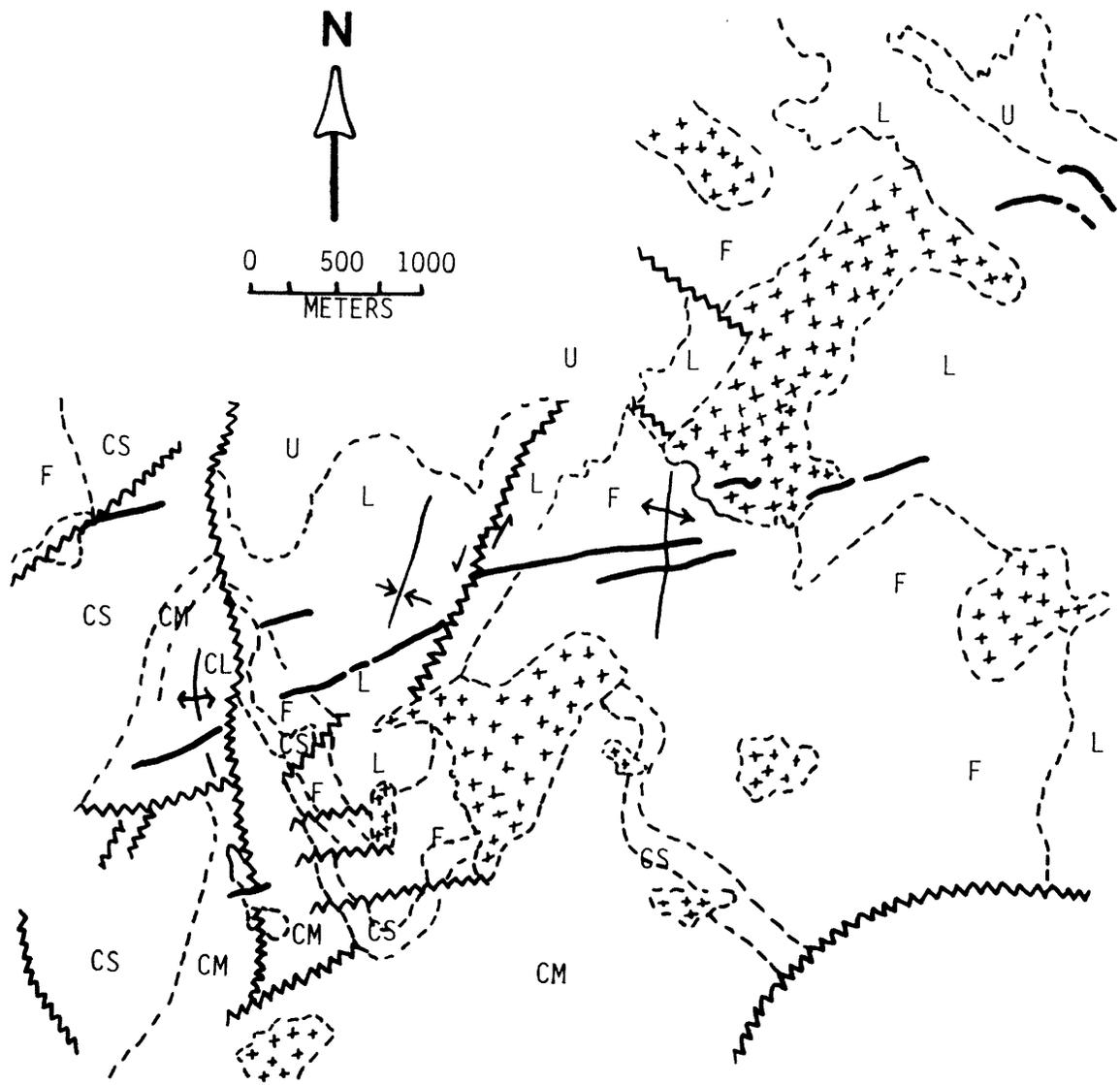
Given a source of heat, presumably a cooling magma at depth, (or one or more local stocks), available ground water or formation water would be caught up in a hydrothermal convection system which would grow with time as the magma cooled and heated an increasingly large volume of country rock. The formation waters would tend to circulate continuously, while large quantities of meteoric water would descend, periodically, into the system via the relatively open fractures in the upper levels of the volcanic pile to flood the system. The influx of large amounts of meteoric water could be due to anomalously high amounts of precipitation at specific intervals, or renewed tectonic activity and fracturing.

The increase in salinity of the low-salinity fluid inclusion population going from stage I to stage II mineralization, but not in the fluid inclusion population with high salinities, suggests that the low-salinity fluids were actually involved in boiling and were responsible for the bonanza silver-gold deposition. This is consistent with Taylor's

(1974) suggestion that most epithermal silver and gold orebodies were deposited from meteoric-hydrothermal solutions because the low-salinity fluids of stages I, II and III at Colqui have δD values ($= -100^{\circ}/\text{oo}$), indicative of a meteoric origin.

References

- Instituto Nacional de Investigacion y Fomentos Mineros, 1962, 1964, 1965, 1970, 1971, Anuario de la Industria, Minera del Peru, Boletín No. 26, 28, 29, 34, 35.
- Kamilli, R.J. and Ohmoto, H., 1977, Paragenesis, Zoning, Fluid Inclusion and Isotopic Study of the Finlandia Vein, Colqui District, Central Peru: Econ. Geol., v. 72, no. 6, p. 950-982.
- Nolan, T.B., 1933, Epithermal precious-metal deposits, in Ore deposits of the western states (Lindgren vol.): New York, Am. Inst. Mining Metall. Petroleum Engineers, p. 623-640.
- Peterson, V., and Diaz, N., 1972, Geología de la region Minera Colqui, Huarochiri, Lima: Soc. Geol. del Perú Bol., v. 42, p. 5-20.
- Taylor, H.P., 1974, The application of oxygen and hydrogen isotope studies to problems of hydrothermal alteration and ore deposition: Econ. Geol., v. 69, p. 843-883.
- Tsui, T.F. and Holland, H.D., 1979, The analysis of fluid inclusions by laser microprobe: Econ. Geol., v. 74, p. 1647-1653.



GEOLOGY OF THE COLQUI DISTRICT, PERU

VEIN		INTRUSIVES	
FAULT		USHO FM	
CONTACT		LOURDES FM	
FOLD AXES		FINLANDIA FM	
		UPPER COLQUI	
		MIDDLE COLQUI	
		LOWER COLQUI	

Adapted from Petersen and Diaz (1972)

IV. Geologic characteristics of the Julcani district, Huancavelica, Peru

DISTRICT: Julcani, Department of Huancavelica, Peru
(Latitude 12°54'30"S, Longitude 74°47'W)

MAJOR VEINS AND MINES: Mimosa mine (Barbara, Gaby, Mimosa, San Demetrio, A, Porvenir, P.R. 620, Carmen, Castilla, Hada, San Pedro, Apollo 11 and 705 veins.) Herminia mine (Docenita, Aro 2NW, 3NW, Esperanza, 504, Luz 82, 435-Teresa, San Jose, Santo Domingo and 4NW veins). Also Tentadora, Estella, Lucrecia, Sacramento, Rita, Manto and Acchilla mines.

ORE: Ag, Bi, Pb, Cu, Au and minor W

PRODUCTION: The area has been worked since Spanish colonial times, although production data is limited. Recent reports suggest that 1.816 billion kilograms of Ag - Bi - Pb - Cu ores were extracted during the years 1952-1977. In addition, there is an estimated 908 million kilograms of ore reserves (1977) and 2.724 billion kilograms of prospective ore (1977). For the years 1962, 1964, 1965, 1970 and 1971, 159,871 kilograms of Ag, 343 kilograms of Au, 6.96 million kilograms of Pb, and 4.58 million kilograms of Cu were produced. The district was initially famous for the gold ores which were extracted from the upper parts of the Tentadora section in the center of the district. The minor amounts of Au left in the district are not presently economic. Tungsten was first reported in 1901 by Gandolini (wolframite in pyritic veins of the Tentadora section). Julcani is now (1984) a major producer of Ag and Bi.

AGE OF ORE: The ores are younger than the enclosing volcanics which are dated at $10.13 \pm .08$ m.y. (Noble et al. 1972). The core of the district, the Tentadora area is oldest (but undated). At Herminia the ore post-dates the alunitic alteration (9.99 ± 0.30 to 9.74 ± 0.29 m.y.) of the enclosing volcanics. However, all the ores predate adularia-bearing alteration assemblages that formed 9.6 to 9.3 m.y. ago (Noble and Silberman, 1984).

REGIONAL PETROTECTONIC SETTING: The oldest rocks in the region are shales and sandstones of undetermined age, belonging to the lower Paleozoic Excelsior Group defined by McLaughlin (1924). These are unconformably overlain by upper Paleozoic and lower Triassic (?) clastic sedimentary rocks and limestones. These are overlain towards the flanks of the regional anticline by units including the upper Triassic and Jurassic limestones of the Pucará Group, Lower Cretaceous sandstones and shales of the Goyllarisquizga Group and lower to middle Cretaceous limestones of the Chulec Formation. The Cenozoic is represented by two groups of volcanic and sedimentary rocks: the Rumichaca Group (intercalated volcanics and sediments) and pyroclastic rocks of the Julcani volcanic center. The regional structure is dominated by an asymmetric, faulted N-S-trending anticline defined by the upper Permian and Mesozoic sediments. Two regional N-trending longitudinal faults displace the eastern limb of the anticline.

LOCAL TECTONIC SETTING AND ORE CONTROLS: The Julcani mining district is located at the central part of the Julcani volcanic center. This consists of pyroclastic rocks, lavas, endogenous domes and dikes that cut or overlie the previously described units. The volume of the early pyroclastics is estimated at 2 km³ by Noble and Silberman (1984). Early workers in the area envisaged an underlying and surrounding intrusive phase of quartz monzonite porphyry. Noble and Silberman (1984) have documented that the main stage of volcanic activity was short-lived. In the latter part of the main volcanic stage or after it, a system of tourmalinized breccia dikes was injected into the central part of the district, in a crude radial pattern (Shelnutt, 1980). Three late dikes cut the breccia dikes. Upward doming of magmas of the Julcani volcanic center, and perhaps reactivation of the Lircay faults, fractured the volcanic rocks, producing a large number of tension fractures and normal faults that served as channelways for the mineralizing hydrothermal fluids. Magmatic activity continued episodically throughout the period of fracturing, hydrothermal alteration and mineralization. Areas northwest and north of Julcani have pyroclastic rocks that are both younger and lithologically distinct from the pyroclastic rocks of the Julcani Center. The young pyroclastics are dated at 6.8 ± 0.3 my (Noble and Silberman, 1984).

ORE HOST AND AGE OF HOST: The ore is hosted by rocks of the Julcani volcanic center which consist of calc-alkaline, silica-rich, rhyodacitic and dacitic pyroclastics, rocks and lavas (Noble and Bowman, 1976). The volcanics are dated (K-Ar) at 10.13 ± 0.08 by Noble et al. (1972).

ASSOCIATED VOLCANICS: The early pyroclastic phase is represented by scattered remnants of rhyodacite tuff, tuff breccia, and pyroclastic breccia (ranging from base-surge deposits to ash flows). The pyroclastic activity was followed closely by the emplacement of endogenous domes of dacitic and rhyodacitic composition. Short lava flows and major talus aprons border the domes. The rocks of the main stage of volcanism are rhyodacites and dacites. They contain phenocrysts (25-40%) of andesine, with lesser amounts of quartz, biotite, apatite and Fe-Ti oxides. Minor local amounts of hornblende and clinopyroxenes are present in dacites of the later dome phase. The magmas are characterized by very high f_{O_2} and f_{S_2} values and the local presence of phenocrystic anhydrite (Drexler, 1982, and Drexler and Noble, 1983).

ALTERATION: Some rocks in the area have undergone the same degree of pervasive propylitic alteration regardless of relative age, while some of the later dikes have undergone less alteration than the lavas they crosscut. Radiometric studies indicate that the alteration was accompanied by introduction of K₂O and possibly Rb (Scherkenbach, 1978; Scherkenbach and Noble, 1984). The core of the district, the Tentadora area, is characterized by pyrite-sericite-quartz alteration. The margins of the district and the central part at depth contain advanced argillic alteration (quartz-alunite-pyrite) dated at 9.99 ± 0.3 , 9.77 ± 0.29 , and 9.74 ± 0.29 my (hypogene alunite) by Noble and Silberman (1984). Later alteration events included a pre-ore kaolinite alteration of alunite-bearing rocks. The assemblages

quartz + K-feldspar + muscovite and quartz-K-feldspar-kaolinite are found toward the margins of the district (Wilson, 1979). Minor pyrophyllite is present locally in the veins. After deposition of the ore minerals emplacement of the Bulolo dike, late fluids locally formed adularia-bearing alteration assemblages at about 9.6 to 9.3 my ago (Noble and Silberman, 1984).

EXTENT OF ORE: The district extends for over 5 x 3 kilometers and has a vertical extent of 450 meters.

VEIN MINERALOGY:

Ore: galena, orpiment, realgar, Ag-sulfosalts, Pb-sulfosalts, enargite, Au-metal, chalcopryite, wolframite, sphalerite, bismuthinite, tennantite-tetrahedrite, semseyite, aramayoite, andorite, bournonite.

Gangue: quartz, pyrite, arsenopyrite, siderite, barite and stibnite. Conspicuously absent minerals include Mn-bearing minerals.

CHARACTER AND TEXTURE OF ORE: Replacement textures are common throughout the district. Quartz and sulfides occur as crustiform minerals in the vugs; the ore is banded in the veins.

EVIDENCE FOR SUPERGENE PROCESSES: No data

PARAGENESIS: The minerals were deposited in Stages I (earliest) through IV (Petersen et al., 1977). Stage I consists of pyrite; Stage II of enargite, followed in order by barite, Ag, tetrahedrite-tennantite, sphalerite-1, chalcopryite, bismuthinite, galena, bournonite, stibnite, andorite, aramayoite and semseyite; Stage III consists solely of sphalerite-2 and stage IV of siderite. This has been described by Petersen et al. (1977), in detail for the Herminia mine in the district. Other mines examined have a similar paragenetic sequence with respect to major sulfides, although varying amounts of the sulfosalts may or may not be present. The major stage (II) can be viewed as minerals deposited from a single pulse of fluid since there is an absence of distinct or well defined time-planes.

The above describes the Herminia Mine. In general, the mineralogy varies from mine to mine on the district. For example, the Mimosa System can be described paragenetically from oldest (I) to youngest (IV) as follows:

- I pyritic ore
- II barite, enargite, Ag-bearing sulfosalts (Td-Tn), sphalerite, chalcopryite, bismuth, galena and boulangerite
- III late sphalerite 2
- IV siderite

As shown, the predominant minerals in Stage II change from one hydrothermal system to another within the Julcani Center.

Pyrite-Au-tungsten mineralization could not be precisely correlated with any of the four mineralization stages. Peterson *et al.* (1977) suggest that the Py-Au-W ores were deposited by the same solutions that deposited either stage I or stage II. A similar uncertainty clouds correlation of the orpiment, realgar and Pb sulfosalts observed on the outermost fringes of the zoning sequence. Although Petersen *et al.* (1977) correlated them with the Stage II fluids, no specific evidence was given as to why this correlation was made.

MINERALOGICAL AND CHEMICAL ZONATION :

Regional: The ores of the Mimosa Mine are zoned vertically, while those of the Herminia Mine are zoned laterally. In general, the pyritic gold-tungsten and enargite-pyrite ores occur close to the center of the Julcani district, whereas the galena, lead sulfosalt, orpiment and realgar ores are on the fringes of the known mineralized area. Between these two zones most of the main-stage mineralization occurred. This area is where the tetrahedrite and tennantite, which contain most of the Ag-values, were deposited. Goodell and Peterson (1974) and Petersen *et al.* (1977) show that a monotonic increase in Pb/Cu values occur along the "apparent" path of mineralizing solutions throughout the Julcani District, except in Tentadora. They propose using the behavior of Pb/Cu as an indicator of position within a zoning sequence of a particular stretch of vein. They suggest that under "special conditions" the ratio may be directly related to the differentiation of a hydrothermal solution along its path. They observe that subsidiary solution paths exhibit greater rates of change of ratio values versus distance than major paths.

They also studied changes in Ag/Cu, and Ag/Pb in Herminia, Carmencita and Mimosa. When plotted against log Pb/Cu, the ratios define a broad band of values. Ag/Pb and Ag/Cu pass through a maximum in Herminia reflecting the area of high silver values which are there.

In Carmencita, both Ag/Cu and Ag/Pb are less than at Herminia. In Mimosa, Ag/Pb is less while Ag/Cu is greater. The vertical or lateral displacement of the curves relative to each other may provide an indication of differences in bulk chemistry of the solutions or depositional regimes. The Carmencita curves may correspond to the latter half of the Herminia curves suggesting that ore may be found at depth and to the south of Carmencita.

Further examination of Ag/Cu, Ag/Pb, Pb/Cu ratios with respect to a number of mines in the district suggests that hydrothermal solutions emanated from the pyritic gold-tungsten zone and flowed in three directions simultaneously - south, southeast and north.

Local: The Sr content of barite in the central zone of the Herminia Mine is 8.8%; the margins of the zone decrease to 3.8 to 4.0%.

NUMBER OF PERIODS OF HYDROTHERMAL ACTIVITY: Noble and Silberman (1984) suggest that volcanic, structural and hydrothermal conditions provide evidence for at least 6 and perhaps 8 distinct, high-level, magmatic events. They point out that one of those may have driven hydrothermal system(s) that deposited all or part of the ore body.

FLUID INCLUSION DATA:

Homogenization temperatures (Th):

320°C - 365°C for the Mimosa mine; 325°C for the Herminia mine (G. Salazar, pers. comm. to U. Petersen, 1972).

190° to 210° for the Herminia mine (J. Benavides, oral comm., 1981 to D. C. Noble)

165° to 275° and 5-12 equiv. wt.% NaCl equivalent (median = 12 wt%) for the Herminia mine on secondary inclusions in quartz phenocrysts from the quartz-alunite-pyrite alteration (Bruha and Noble, 1983).

STABLE ISOTOPE DATA: Measurements (Petersen, 1972) of S^{34}/S^{32} on barite-enargite and barite-tennantite pairs yielded temperatures of 340° to 315°C. (No discussion of possible disequilibrium was included in the reference).

TEMPERATURE OF DEPOSIT FROM OTHER SOURCES: Distribution of As and Sb in enargite and tetrahedrite-tennantite - 325°C to 350°C (Petersen, 1972). (See above) Geologic reconstruction and lack of boiling suggest a temperature of formation at less than or equal to 250°C (Noble and Silberman, 1984).

SUMMARY: Julcani is a complex volcanic center emplaced along the axis of a regional anticline; its location may have been influenced by major longitudinal and transverse faults. An explosive volcanic episode involving pyroclastic rocks and lavas was followed by the intrusion of domes and dikes. These calc-alkaline rocks have been dated at about 10.13 ± 0.08 m.y. Fracturing as the result of the emplacement, alteration of the rocks and mineralization (along the fractures) occurred within a half million years after the emplacement of the domes.

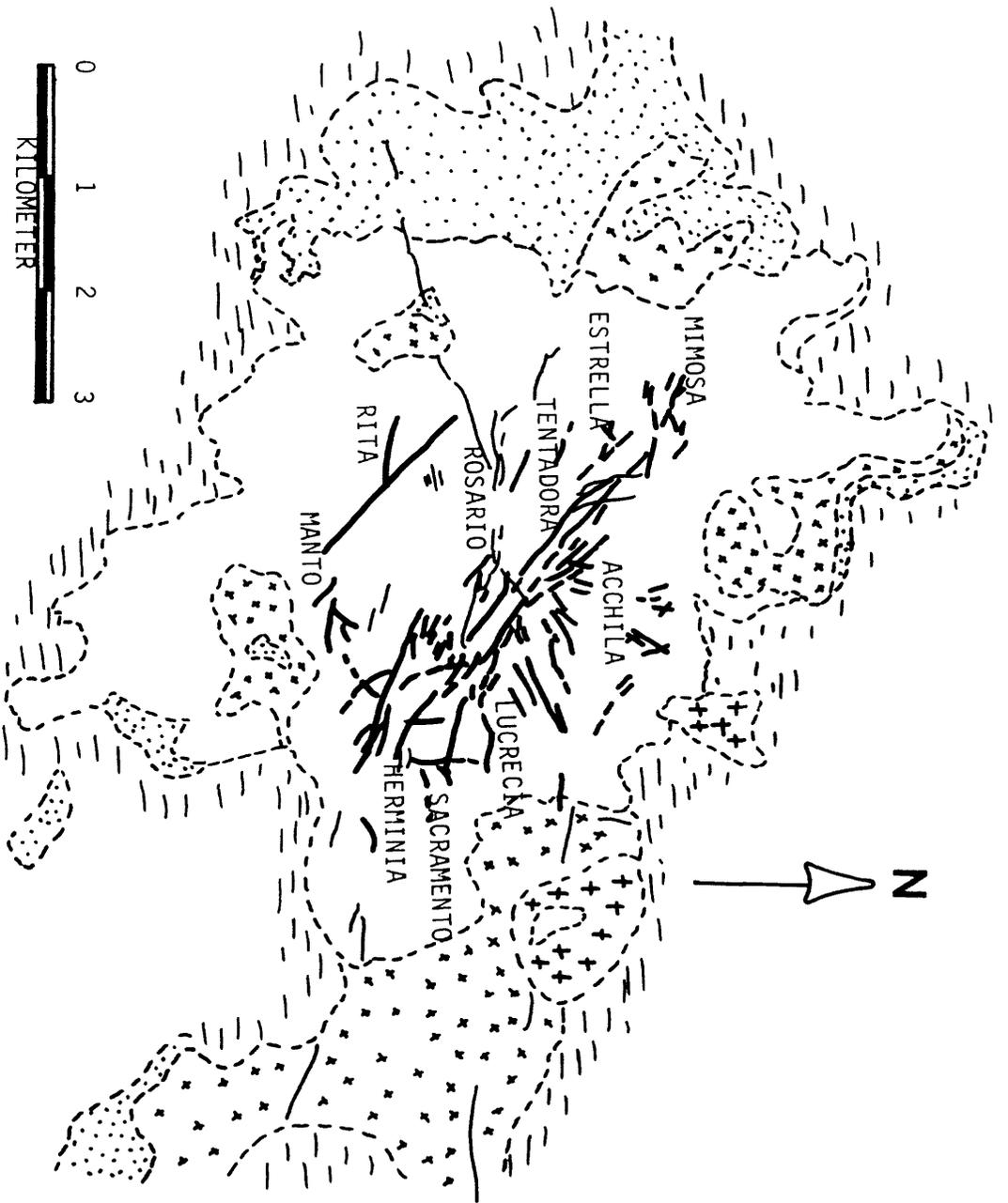
This interpretation is based on radiometric dating by Silberman & Noble, (1984) "Replicate dating of rhyodacite clasts from lower parts of the early pyroclastic sequence and of the Bulolo-Estella dike indicates that the center was magmatically active for less than 0.5 m.y." The Bulolo-Estella dike post-dates all alteration and mineralization. Late fluids (post-mineralization) locally formed adularia-bearing alteration assemblages between about 9.6 and 9.3 my ago further delimit the time of mineralization (Noble and Silberman, 1984). In addition, Noble and Silberman have suggested that this mineralization may be considered the silver analogue of such high-level, high-sulfur systems as Summitville, Colorado, and Goldfield, Nevada.

- Scherkenbach, D.A., 1978, Potassium and rubidium metasomatism related to mineralization at the Julcani district, Peru: Unpub. M.S. thesis, Michigan Technological University, 68 p.
- Shelnutt, J.P., 1980, Intrusive breccias of the Julcani silver district, Peru; Unpub. M.S. thesis, Michigan Technological University, 56 p.
- Wilson, M.L., 1979, Some mineralogical relations in hydrothermally altered dacites, Julcani, Peru: Unpub. M.S. thesis, Michigan Technological University, 60 p.

Several hydrothermal vein systems are identified within the complex (each having a distinctive, though related mineralogy, paragenesis and zoning pattern). Each hydrothermal vein system is possibly related to a number of fluid pulses; although the main stage of mineralization was probably the result of a single pulse.

References

- Bruha, D.T., and Noble, D.C., 1983, Hypogene quartz-alunite + pyrite alteration formed by moderately saline, ascendent hydrothermal solution: Geol. Soc. Amer. Abs. with programs, v. 15, no. 5, p. 325.
- Drexler, J.W., and Noble, D.C., 1983, Highly oxidized sulfur-rich dacite-rhyolite magmas of the Julcani silver district, Peru: Insight into a "productive" magmatic system: Geol. Soc. America Abs. with programs, v. 15, p. 325.
- Drexler, J.W., 1982, Mineralogy and geochemistry of Miocene volcanic rocks genetically associated with the Julcani Ag-Au-Cu-Bi deposit, Peru and Physiochemical conditions of a productive magma body: unpub. Ph.D. Dissert., Michigan Technological University.
- Goodell, P.C., 1974, A typical sulfosalt environment: The mineralogy of the Julcani district, Peru: Mineralogical Record, v. 5, p. 215-221.
- Goodell, P.C., and Petersen U., 1974, Julcani Mining District, Peru: A Study of Metal Ratios; Econ. Geol., v. 69, p. 347-361.
- McLaughlin, D.E., 1924, Geology and physiography of the Peruvian Cordillera, departments of Junin and Lima: Geol. Soc. America Bull, v.35, p. 591-632.
- Noble, D.C., and Bowman, H.R., 1974, Geochemical and field constraints on the depth of differentiation and eruptive history of silicic calc-alkalic magmas related to base and precious metal mineralization, Andes of central peru: Geol. Soc. America Abs. with Programs, v. 8, p. 615.
- Noble, D.C. and Silberman, M.L., 1988, Volcanic and hydrothermal evolution and K-Ar chronology of the Julcani District, Peru: Econ. Geol., in press.
- Noble, D.C., Petersen, U., McKee, E., Arenas M. and Benavides, A., 1972, Cenozoic volcano-tectonic evolution of the Julcani-Huachocolp-Castrovirreyra area, central Peru: Geol. Soc. Amer. Abs with Programs, v.4, p. 13.
- Petersen, U., 1972, Metodos modernos aplicados a la investigacion de yacimientos peruanos, Boletin de la Sociedad Geologica del Peru, Tomo 42, p. 23-35.
- Petersen, U., Noble, D.C., Arenas, M.J. and Goodell, P.C., 1977, Geology of the Julcani Mining District, Peru: Econ. Geol., v.72, No. 6, p. 931-949.



GEOLOGY OF THE JULCANI DISTRICT, PERU

- DIKES
 - VEINS
 - LATE DOMES
 - VOLCANIC ROCKS AND TALUS
 - PYROCLASTIC ROCKS
 - SEDIMENTS
- PETERSEN AND DIAZ (1972)