GEOLOGICAL STUDY ON THE ORE DEPOSITS IN THE SUR LIPEZ DISTRICT, BOLIVIA

ASAHIKO SUGAKI, HIROTOMO UENO, NOBUTAKA SHIMADA,
ARASHI KITAKAZE, KENICHIRO HAYASHI,
ORLANDO SANJINES V. and OSCAR VELARDE V.

ABSTRACT

Geology of the Sur Lipez district located at most southern portion of a mineralization belt along the Eastern Cordillera of Bolivian Andes consists of the Ordovician, Cretaceous, Tertiary and Quaternary systems, and dacite stocks. There are many polymetallic ore deposits of hydrothermal fissure filling type such as the San Antonio de Lipez, Buena Vista, Escala, Esmoraca, Candeleria de Santa Isabel, Bolivar, Santa Rosa, Moroco, Trapiche, and Villarruer in the district. They occur in the dacite stock, volcanic complex and Quehua formation of Miocene. Ore from the mines such as San Antonio de Lipez, Buena Vista and Escala consists of a lot of ore minerals such as pyrite, sphalerite, galena, arsenopyrite, chalcopyrite, marcasite, pyrrhotite, hematite, magnetite, argentite, jalpaite, electrum, native silver, stibnite, realgar, orpiment, greenockite, aikinite, boulangerite, semseyite, jamesonite, bournonite, tetrahedrite, tennantite, famatinite, stephanite, polybasite, pyrargyrite and fizelyite with gangue minerals such as quartz, braite, siderite, calcite, chlorite, sericite and kaolinite. Minerals indicating low temperature formation such as realgar, orpiment, stibnite, silver sulfosalts and antimony sulfosalts and siderite occur. No wolframite and tourmaline which are common minerals from the polymetallic tin deposits in the Eastern Cordillera appear.

Homogenization temperature and salinity in NaCl equivalent concentration of liquid inclusion in quartz and sphalerite from San Antonio de Lipez (Systema 1 and 2) and Buena Vista (Once) mines are as follows; 157° to 317°C and 1.2 to 16.1 wt %, and 160° to 305°C and 4.4 to 5.8 wt %, respectively.

INTRODUCTION

A lot of polymetallic ore deposits such as tin, tungsten, silver, lead, zinc, antimony, and bismuth are found in the Eastern Cordillera of Bolivian Andes and their distribution is shown as a mineralization belt along the Cordillera as Figure 1 (Clark *et al.*, 1976; Claure and Minaya, 1979). Tin deposits are ranged from north to south as belt-like form as seen in the figure. There is shown a zoning of mineralization from tin zone of center portion in the belt to lead-zinc zone via antimony zone of the outer portions. Among them, the ore deposits in the La Paz, Potosi, Oruro and Quechisla districts have been investigated by us in 1978, 1979, 1981 and 1983, and the results of our studies have been already published (Sugaki *et al.*; 1981a, b, c, d, 1983a, b, 1984, 1985a, b). Field survey of the ore deposits in the Sur Lipez district (Figure 2) have been carried out during July to August in 1983. There are many silver-lead-zinc deposits such as San Antonio de Lipez, Buena Vista, Escala, Esmoraca, Candelaria de Santa Isabel, Boliver, Santa Rosa, Moroco, Trapiche and Villarruer mines in the district. They are hydrother-

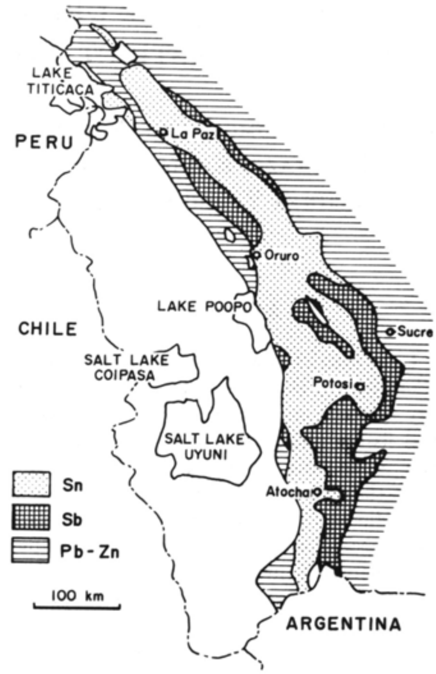

FIGURE 1. TIN (Sn), ANTIMONY (Sb) AND LEAD-ZINC (Pb-Zn) MINERALIZATION ZONES FOUND IN THE EASTERN CORDILLERA OF BOLIVIAN ANDES (AFTER CLAURE AND MINAYA, 1979).

mal shallow seated deposits filled up fissures developing in dacite stock, volcanic complex and acidic tuff (Quehua formation) of Miocene. Many of them have been mined out as silver ore from the age of the Spanish colony, and now are being explored by COMIBOL (Corporacion Minera de Bolivia). Ores from these mines are principally composed of pyrite, sphalerite, galena, arsenopyrite, marcasite, chalcopyrite, pyrrhotite, realgar, orpiment, stibnite, famatinite, boulangerite, bournonite, semseyite, polybasite, pyrargyrite, stephanite, tetrahedrite in association with quartz, barite, siderite, sericite and kaolinite as gangue minerals. There is found no tungsten mineral in the district. Small amounts of tin minerals such as cassiterite, stannite and franckeite are microscopically observed in the ore from the Candelaria de Santa Isabel mine, but ores from all the other mines in the district contain no tin minerals. As characteristic minerals from the mines in the Sur Lipez district, there are silver minerals such as argentite, polybasite, pyrargyrite, stephanite, jalpaite and fizelyite, antimony sulfosalt minerals such as bournonite, boulangerite, semseyite, tetrahedrite and famatinite, and arsenic sulfide minerals such as realgar and orpiment. The geological and mineralogical data obtained by our filed and laboratory studies on the ore deposits in the Sur Lipez district are described in this paper.

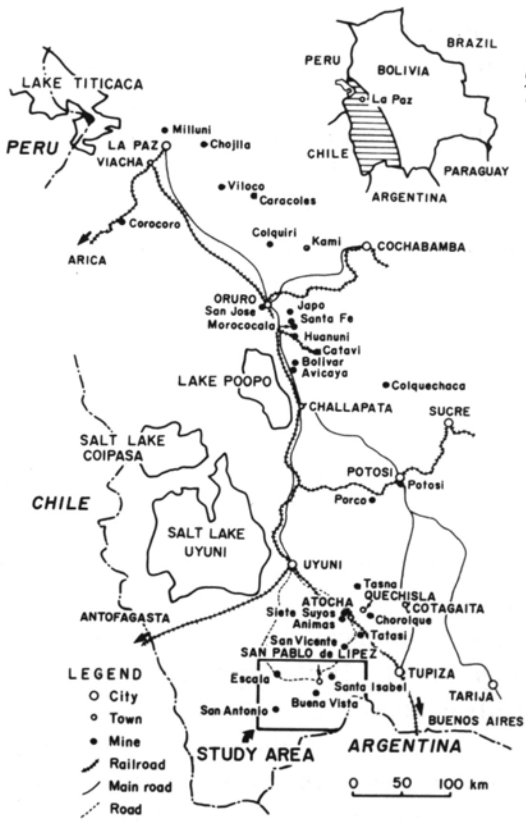

FIGURE 2. LOCATION MAP OF THE SUR LIPEZ DISTRICT.

San Pablo de Lipez which is a central town, about 200 population, in the district is situated at about 100 km southwest from Atocha of the Quechisla district, approximate 140 km southeast from Uyuni and about 55 km north from the border with Argentina. To visit to the Sur Lipez district, there are two ways from La Paz by train and car. That is, we can arrive at Uyuni or Atocha via Oruro from La Paz for 11 or 14 hours respectively by train, and then can visit to San Pablo de Lipez from Atocha or Uyuni by car driving 100 or 180 km, respectively. But the way between them is no good road. We can also visit to the district by car driving 1,100 km through Oruro, Potosi, Cotagaita and Atocha from La Paz for about 2 or 3 days. There is another way to San Pablo de Lipez by car using the road running parallel to the railway via Challapata and Uyuni 670 km from Oruro for 2 days, 960 km from La Paz for 2 or 3 days, but the way between Challapata and San Pablo de Lipez, 590 km, is uneven and sandy bad road.

The climate of the Sur Lipez district is annually divided into dry and wet seasons which are obviously distinguished. Dry season is from April to October, and rainy season, November to March. Total amounts of rain are about 400 mm per year at San Pablo de Lipez. However, it almost falls during rainy season and sometimes floods as cutting off traffic road. The humidity in general is as low as 10 to 20% in the dry season, and 50 to 60% in the wet season (Montes de Oca, 1982). Accordingly, there is conspicuously dry condition except rainy time of the wet season. Thus, our field works have been done during the dry season of winter time. During field survey in July to August, temperatures were about −15° to −20°C at early morning or night and about 15°C at daytime. Daily temperature change, about 30° to 35°C was very hard.

Topography

The Sur Lipez district corresponds to the western margin of most southern portion in the Eastern Cordillera, and consists of mountain and hill lands which have elevations from 4,000 to 6,000 m. Topography of the district is roughly classified into two portions of northern and southern areas. The northern area of the district generally shows gentle hilly topography from 4,000 to 4,400 m elevation, and mainly consists of Ordovicain, Tertiary and Quaternary systems as seen in Figure 3-A. However, the southern area near border with Argentina is composed of steep eroded mountain lands from 4,500 to 6,000 m consisting of Miocene volcanic complex (Figure 3-B). In this area, there are found some peaks such as Mts. Santa Isabel (5,616 m above sea level), Bonete (5,619 m), Morokho (5,681 m) and Lipez (5,929 m) which consist of Miocene dacite stocks.

Rivers in the northern area of the district in general run to the direction of northwest and then north to flow into the salt lake Uyuni. For example, the rivers Llajta Mayu and Mina Blanca near the San Antonio de Lipez mine run to northwest and north cutting deeply Mts. Lipez and Trinidad, respectively, and flow together to the river Grande de Lipez via the river Salada and the rivers Lipez and Galera, respectively. The river Grande de Lipez directly flows into the salt lake Uyuni. Also, the river Buena Vista near the Buena Vista mine runs to northwest, and flow together to the river San Pablo running north side of the town of San Pablo de Lipez, and then becomes to the river Galera. Many of the rivers before flowing together to the river Grande de Lipez dry up because river water gets into underground in the dry flat land of the northern area.

Meanwhile the river San Antonio and its branches eroding deeply the mountains in the southern area of the district near the border with Argentina run to east and then flow together to the river San Juan which runs roughly to north and northeast, and then becomes the rivers Camblaya, Piloya and Pilcomaya running to east and southeast. They finally flow into South Atlantic Ocean as the rivers Parana and La Plata.

Geology

The Geology of the Sur Lipez district is mainly composed of Ordovician, Cretaceous, Tertiary and Quaternary systems (Ahlfeld and Branisa, 1960 ; Claure and Minaya, 1979). The geological map of the area is shown in Figure 4 based on the data by Ahlfeld and Schneider-Scherbina (1964), Kussmaul *et al.* (1975) and JICA (Japan International Cooperation Agency) and MMAJ (Metal Mining Agency of Japan) (1982, 1983). The Ordovician system which is a basement of the district appears locally in the central and eastern portions of the district. The Cretaceous system is also found in very limited area of eastern portion in the district. The Tertiary formations are exposed widely from the northern to southern areas in the district. Intrusive dacitic rocks are found as stock into

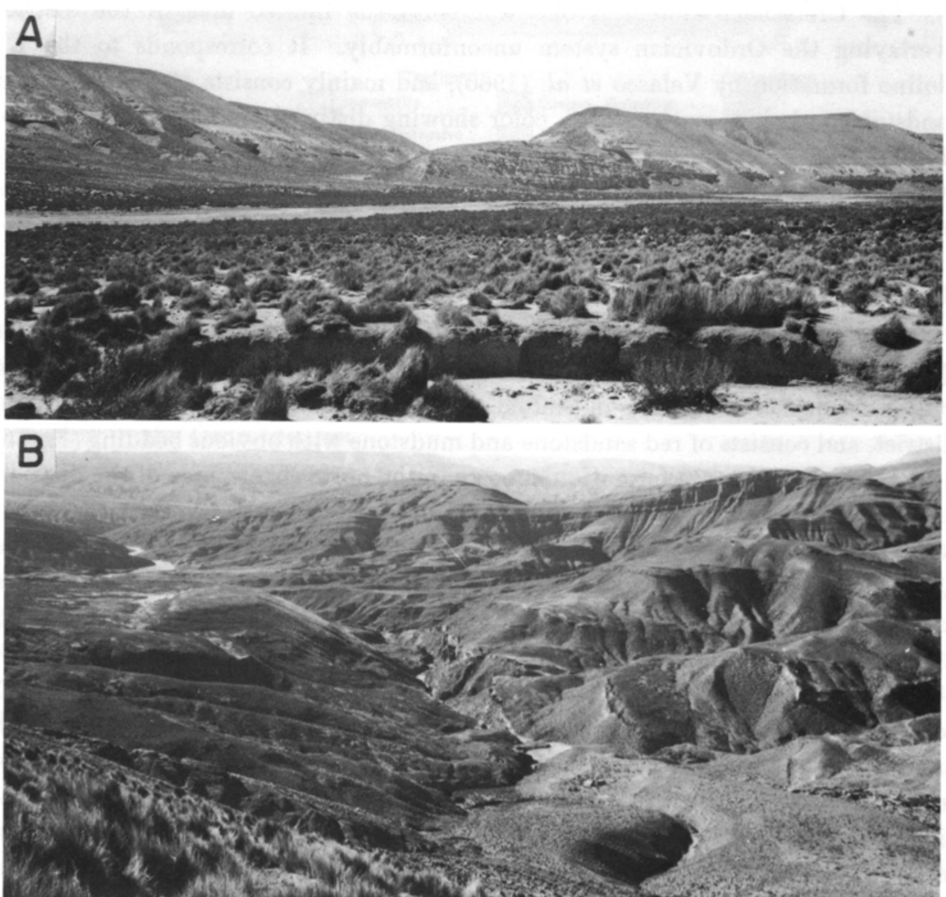

Figure 3. Topography of the Sur Lipez district.
A. A view of Tertiary mountain range.
B. Gentle sloped mountains of the Quehua formation at the San Antonio de Lipez.

Teriary formation at many places.

1. Ordovician system

The Ordovician system consists mostly of slate, sandstone and their alternation distinctly folded with axes of the NW-SE direction. It also is frequently cut by fault. Slate is black in color and shows obvious bedding with distinctly slaty cleavage. It consists microscopically of quartz and sericite, 2 to 20 μm in size, carbonaceous and clayey matters. Sedimentary lamination is found in it. Sandstone is a massive and hard rock of gray color with bedding. It is composed of quartz with sericite and clayey materials. The Ordovician system is unconformably covered with Cretaceous and Tertiary formations.

2. Cretaceous system

The Cretaceous system is only found in the limited area of the district overlaying the Ordovician system unconformably. It corresponds to the El Molino formation by Velasco *et al.* (1966), and mainly consists of coarse-grained sandstone and shale with reddish color showing distinctly cross bedding. Also, thin layer of limestone, calcareous sandstone and green sandstone appear partly. It shows gentle folding, and is covered with the Tertiary formation unconformably.

3. Tertiary system

The Tertiary system is composed of the Potoco, San Vicente, Rondal and Quehua formations, volcanic complex and ignimbrite in ascending order. The Potoco formation distributes in limited area of the north or eastern portions in the district, and consists of red sandstone and mudstone with obvious bedding (Figure 3-A). The San Vicente formation appears in the northeastern area of the district, and is mainly composed of red sandstone and conglomerate. Also, the Rondal formation mainly consists of basalt lava, about 30 m thick. Meanwhile the Quehua formation, about 100 m thick, widely distributes in the district, and is mainly composed of pyroclastics of dacite lava, dacitic tuff, tuff breccia and agglomerate with roughly horizontal bedding. According to Kussmaul *et al.* (1975), the K-Ar ages for biotite from dacitic tuff of the Quehua formation are 17.0 to 22.9 Ma. The volcanic complex which is mainly composed of dacite and andesite lavas and their pyroclastic rocks appears at the Santa Rosa mining area in central portion of the district, and overlays on the Rondal and Quehua formations unconformably. The Quehua formation and volcanic complex around the mines are affected by hydrothermal alterations such as chloritization, kaolinization and sericitization. Ignimbrite (Fernandez *et al.*, 1973), about 200 m thick, unconformably overlays on the Ordovician and Quehua formations and volcanic complex. It mainly consists of dacitic to rhyodacitic ignimbrite and tuff.

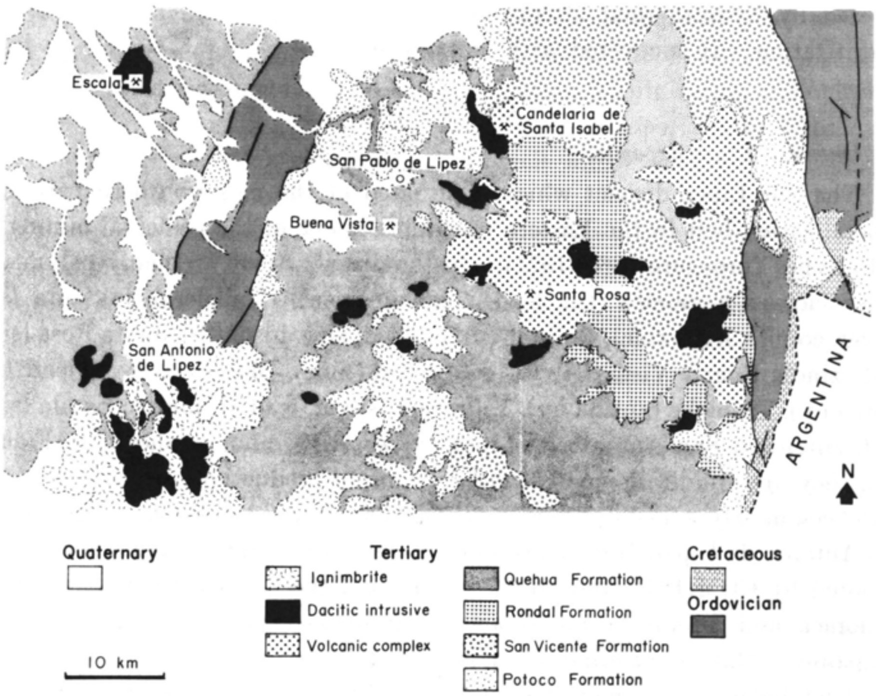

FIGURE 4. GEOLOGICAL MAP OF THE SUR LIPEZ DISTRICT.

Ignimbrite mainly appears around San Antonio de Lipez and Mt. Bonete in the southern parts of the district. According to Kussmaul *et al.* (1975), the K-Ar ages for biotite from ignimbrite are 7.1 and 9.7 Ma, corresponding to the Morococala formation in the Oruro district.

4. *Quaternary system*

The diluvial sediments composed of cobble, pebble, sand and silt distribute in the northwestern area of the district, and appear as terrace deposits of flat land surface in about 4,000 m elevation. Also moraine sediments consisting of cobble, pebble, sand and silt are found in narrow area of the mountain lands in the southern part of the district. The alluvial deposits distribute in narrow area along the rivers as gravel, sand and silt.

5. *Intrusive rocks*

Intrusive dacite occurs as a lot of small stocks formed central bodies of Mts. Lipez, Bonete and Santa Isabel etc. It is massive and grayish white in color, and has quartz, biotite, hornblende, orthoclase and plagioclase as phenocrysts in groundmass consisting of fine grained aggregate of quartz, feldspar, biotite and glass. At San Antonio de Lipez and Santa Isabel mines, dacite Stock is strongly affected by hydrothermal alterations such as sericitization, kaolinization and chloritization. It is covered with ignimbrite.

Ore Deposits

1. Outline of ore deposits

The Sur Lipez district which is situated at the most southern part of the mineralization belt in the Eastern Cordillera is one of the principal mining area in Bolivia (Turneaure 1960, 1971). In the district, there are many polymetallic mines such as Esmoraca (tin, lead, zinc, tungsten), Candeleria de Santa Isabel (silver, copper, lead, zinc), Bolivar (silver, lead, zinc, bismuth), Santa Rosa (silver, lead, zinc), Buena Vista (silver, gold, lead, zinc), Moroco (silver, lead, zinc, antimony), Trapiche (antimony), Villarruer (silver, lead, bismuth), Escala (silver, lead, zinc) and San Antonio de Lipez (silver, lead, zinc) as shown in Figure 5. But, they are middle to small scales for mining productions and many of them have been mostly mined out during period of the Spanish colony. At present, the San Antonio de Lipez, Buena Vista and Escala mines among them are being only explored by COMIBOL and on the other hand the Candelaria de Santa Isabel, Esmoraca and Villarruer mines are being worked in small scale by private companies. But, other mines are now closed.

They belong to ore deposits hydrothermally filled up fissures developed in the Miocene dacitic tuff (Quehua formation), volcanic complex and dacite stocks etc. The ores from the mines investigated consist of many ore minerals such as pyrite, sphalerite, galena, arsenopyrite, chalcopyrite, marcasite, pyrrhotite, hematite, magnetite, cassiterite, argentite, jalpaite, stibnite, greenockite, electrum, native silver, realgar, orpiment, aikinite, boulangerite, semseyite, jamesonite, bournonite, tetrahedrite, tennantite, famatinite, polybasite, stephanite, pyrargyrite, fizelyite and franckeite with gangue minerals such as quartz, barite, siderite, calcite, chlorite, sericite, saponite and kaolinite. They have been produced by mineralization in intimate relation to activity of dacite. In the chapter, ore deposits of the San Antonio de Lipez, Buena Vista, Escala, Candeleria de Santa Isabel and Santa Rosa mines and ores from them, especially mineral assemblages with fluid inclusion data, are described as below.

1. San Antonio de Lipez mine

The San Antonio de Lipez mine which is at about 35 km southwest of San Pablo de Lipez (Figure 5), is located at northeastern foot of Mt. Lipez (5,929 m above sea level, Figure 6-A). It has been actively mined as silver deposits in the age of the Spanish colony, but now is being only explored by COMIBOL (Figure 6-B). The grade of ores from the mine is 200 to 240 g/t Ag, 1.2 to 2.6% Pb and 0.5 to 3.4% Zn. High grade silver ore, 1,000 to 5,000 g/t, sometimes occurs in the Systema 1 vein (JICA and MMAJ, 1983).

Geology around the mine mainly consists of Miocene dacite stock and pyroclastic rock of the volcanic complex (JICA & MMAJ, 1982, 1983). The dacite stock in the mine is strongly altered by sericitization, kaolinization and chloritization as its original texture is not observed under microscope. In this case, quartz only remains as phenocryst, and other minerals almost change to fine crystal aggregate of sericite, kaoline or chlorite.

Ore deposits of the San Antonio de Lipez mine are silver bearing quartz veins developed in the dacite stock and pyroclastic rocks of the volcanic complex. Two main veins as Systema 1 and 2 are now being explored. Their arrangement at the Mesa de Plata level is shown in Figure 7. The veins which have many parallel small veins and branches in general run to the direction of N80° to 90°E dipping of 60° to 70°S.

Systema 1 vein, which has several parallel and branch veins, strikes N80° to 90°E and dips 60° to 70°S. Its scale is about 200 m long and 0.5 to 1 m, sometimes up to 3 m wide. It principally consists of quartz accompanied by pyrite, marcasite, sphalerite, galena, hematite and barite (Figure 8-A, B and D), and generally forms crustified banding as seen in Figure 8-D. They sometimes associate with small amounts of chalcopyrite, arsenopyrite, tetrahedrite, magnetite, greenockite, aikinite, native silver, argentite, polybasite, pyrargyrite and stephanite etc. The outer portion of the vein mainly consists of quartz, chlorite and sulfide minerals with silver minerals. Meanwhile its inner portion is principally composed of barren quartz, barite and siderite.

Argentite which is one of the principal silver minerals from the mine is only found microscopically in association with sphalerite, galena, native silver,

FIGURE 5. LOCATION MAP OF MINES IN THE SUR LIPEZ DISTRICT.

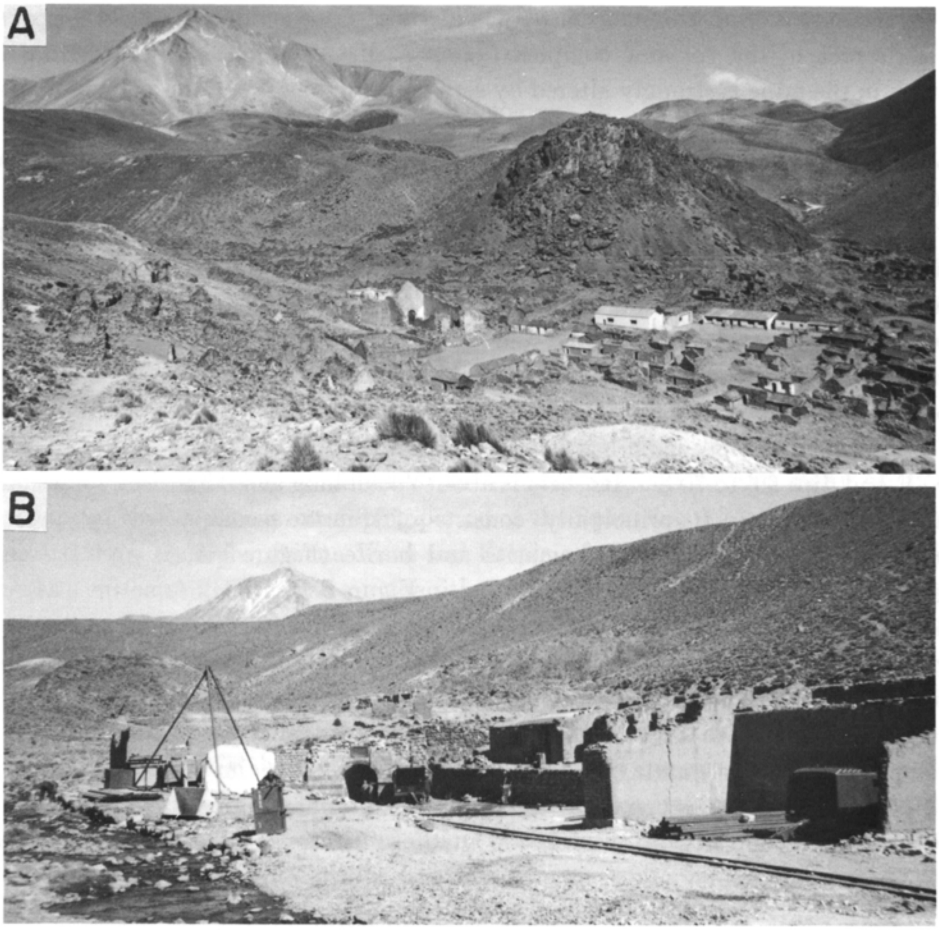

FIGURE 6. SCENERY OF THE SAN ANTONIO DE LIPEZ MINING AREA.
A. A distant view of the San Antonio mine with a background of Mt. Lipez (5,929 m).
B. A view of the Mesa de Plata section.

polybasite, aikinite and quartz (Figure 9-A, B). Native silver appears as an irregular form, 0.05 to 0.1 mm in size, enclosed in quartz and associating with galena and argentite (Figure 9-B). Pyrargyrite usually occurs as a fine grained crystal showing subgraphic texture in galena associating with tetrahedrite (Figure 9-D). Also, silver sulfosalt minerals such as polybasite, pyrargyrite and stephanite associate with each other or galena, tetrahedrite and marcasite (Figure 9-C). Tetrahedrite which contains 5 to 8% Ag commonly assembles with galena, pyrargyrite, chalcopyrite, sphalerite and marcasite. It occasionally occurs as fine grained inclusion in galena with pyrargyrite. Sphalerite from the vein has 3.0 to 6.0 mole % FeS. Very small amounts of greenockite are only found as aggregate of fine grained crystal enclosed in galena. Hematite appears as aggregate of

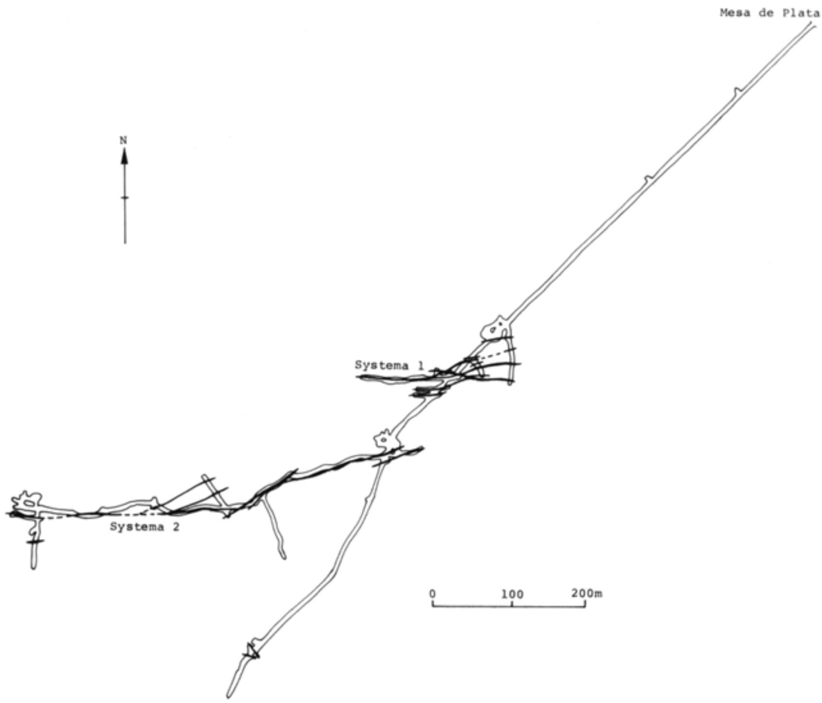

FIGURE 7. ARRANGEMENTS OF THE VEINS AT THE MESA DE PLATA LEVEL IN THE SAN ANTONIO DE LIPEZ MINE.

lamellar crystal, 0.1 to 1 mm long, in assemblage with galena, sphalerite and quartz, sometimes magnetite and barite. Clay minerals such as chlorite, kaolinite, sericite and saponite occur as crustified band at the outer portion of the vein.

Systema 2 vein which has some branches runs to the direction of N70° to 90° E dipping of 60°-65°S, and has 0.3 to 1 m in width. It is mainly composed of quartz, barite, hematite, galena and sphalerite in association with small amounts of magnetite, pyrite, marcasite, arsenopyrite, chalcopyrite, native silver, argentite, pyrargyrite, polybasite, stephanite, tetrahedrite and aikinite. It often shows a crustified banding structure as same as Systema 1 vein (Figure 8-C). Argentite, native silver and aikinite closely associate with each other and galena, sphalerite and quartz. Pyrargyrite assembles with chalcopyrite, stephanite, polybasite, tetrahedrite, galena and marcasite, and is occasionally found as inclusion, less than 10 μm in size, in galena with tetrahedrite. Tetrahedrite which contains 4 to 9 wt% Ag is commonly accompanied by pyrargyrite and galena. Sphalerite contains 0.2 to 1.3 wt% Fe (0.3 to 2.3 mole % FeS) and 0.6 to 1.2 wt % Cd.

Quartz from the veins in the mine microscopically has a lot of fluid inclusions of two phases, liquid and vapor. Their homogenization temperatures and salin-

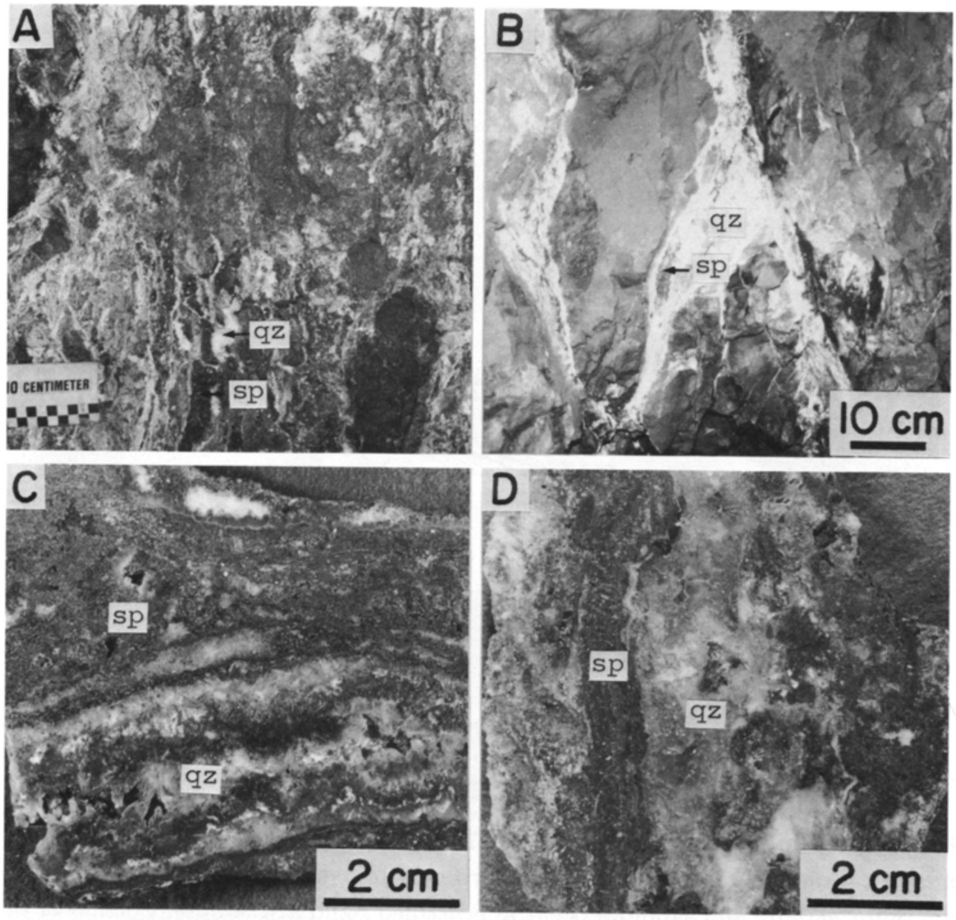

FIGURE 8. ORE VEINS OF THE SAN ANTONIO DE LIPEZ MINE AND ORE SPECIMENS.
A. Sphalerite (sp)-quartz (qz) vein, Systema 1 vein, Mesa de Plata level.
B. Sphalerite (sp)-quartz (qz) vein, Systema 1 vein, Mesa de Plata level.
C. Crustified banding of quartz (qz) and sphalerite (sp), Systema 2 vein, 0 level (Sample No. 8371360).
D. Sphalerite (sp) and quartz vein, Systema 1 vein, 0 level (8371355).

ities in NaCl equivalent concentration are 161° to 290°C and 6.1 to 16.1 wt% NaCl for the Systema 1 vein, and 157° to 317°C and 1.2 to 12.0 wt % NaCl for the Systema 2 vein, respectively. Meanwhile, their values reported by JICA and MMAJ (1983) were 149° to 298°C and 0 to 18.9 wt % NaCl. Both the data are in good accordance with each other.

Crystallization sequence of ore and gangue minerals obtained from the data on occurrence and mineral assemblage and paragenesis is shown in Figure 10. It indicates that quartz, hematite and pyrite were crystallized at early stage of mineralization. Meanwhile sulfide minerals such as chalcopyrite, sphalerite, galena, arsenopyrite, argentite, native silver, aikinite and greenockite were principally produced at middle stage of the mineralization. After them silver bearing sulfosalt minerals such as tetrahedrite, pyrargyrite, polybasite and stephanite were crystallized in association with galena, marcasite and chalcopyrite. At late stage of the mineralization barite with quartz and marcasite were precipitated. Clay minerals such as chlorite, kaolinite, sericite and saponite were crystallized at the early to middle stages of the mineralization as crustified bands in quartz.

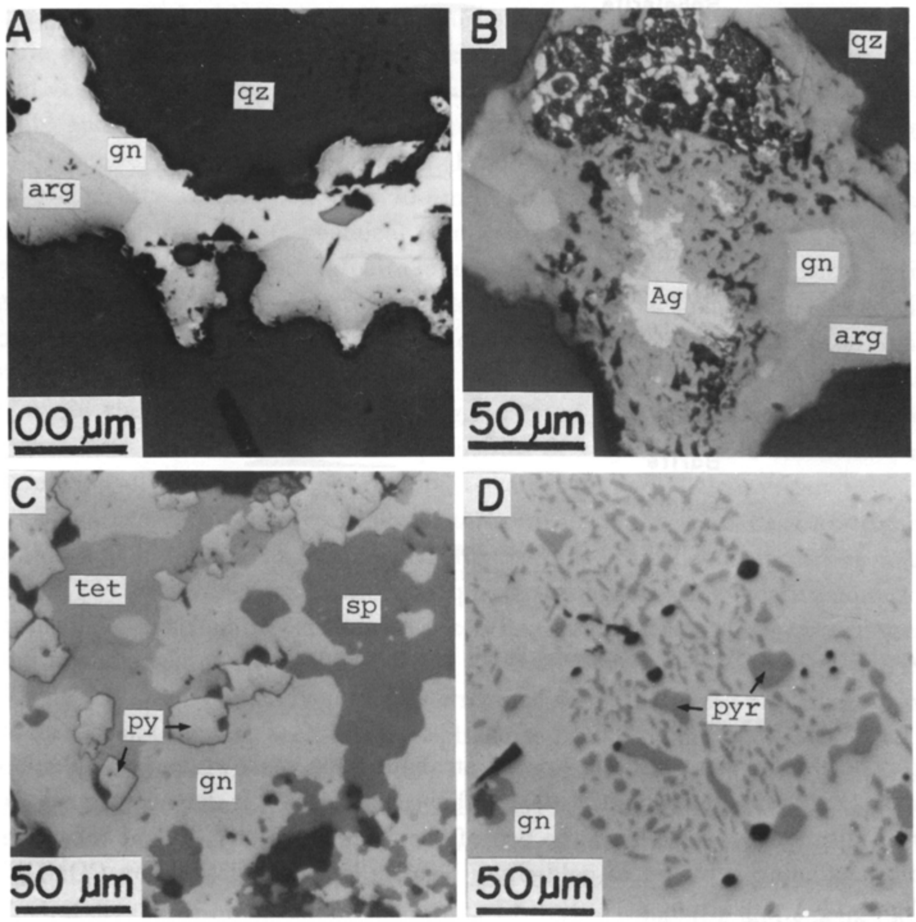

FIGURE 9. PHOTOMICROGRAPHS OF ORES FROM THE SAN ANTIONIO DE LIPEZ MINE.

A. Argentite (arg) and galena (gn) included in quartz (qz), Systema 1 vein (84033185).

B. Native sliver (Ag) and galena (gn) with argentite (arg) in quartz, Systema 1 vein (84033185).

C. Intimate association of tetrahedrite (tet), galena (gn), sphalerite (sp) and pyrite (py), Systema 1 vein (84033183).

D. Fine grained pyrargyrite (pyr) showing subgraphic texture in galena (gn), Systema 1 vein (84033183).

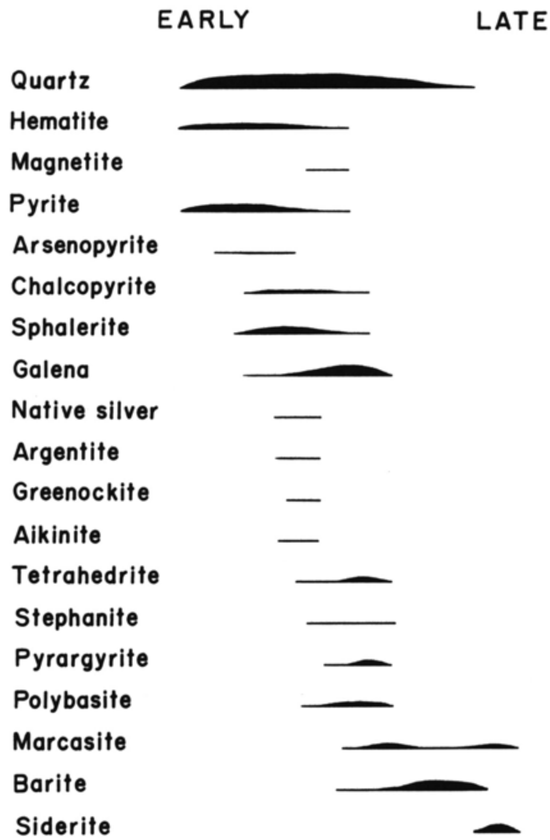

FIGURE 10. MINERALIZATION SEQUENCE OF MINERALS FROM THE SAN ANTONIO DE LIPEZ MINE.

Siderite were formed at the latest stage of the mineralization.

2. *Buena Vista mine*

The Buena Vista mine is located at about 5 km southwest of San Pablo de Lipez (Figure 5) and about 4,400 m above sea level. It has developed as a silver-antimony deposit from the age of the Spanish colony, but at the present time it is being explored as gold-silver bearing lead-zinc deposit by COMIBOL (Figure 11-A, B).

Geology around the Buena Vista mine consists of the Quehua formation of Miocene (JICA and MMAJ, 1982). It is mainly composed of massive and gray colored dacitic tuff with phenocrysts and fragments of quartz, plagioclase, biotite and hornblende, and pumice. Dacitic tuff as country rock of the vein is strongly altered by sericitization, and changes its color from gray to grayish white or white in range of about 20 to 30 cm wide at both sides of the vein.

Ore deposits of the Buena Vista mine are of vein type developed in the Quehua formation. The veins such as San Pablito and Once are composed of several parallel veins and their branches as shown in Figure 12 (−50 m level).

The San Pablito vein runs to the direction of N70° to 75°W dipping 70°to 75° N, and extends to about 700 m long with 10 to 40 cm, sometimes up to 80 cm wide. High grade ore with 1.2% Cu, 33.0% Pb, 27.2% Zn and 610 g/t Ag was produced from the vein (JICA and MMAJ, 1982). The vein is principally composed of aggregate of coarse grained pyrite, sphalerite, galena and quartz associated with small amounts of chalcopyrite, arsenopyrite, electrum, argentite, jalpaite, famatinite, tetrahedrite, tennantite, bournonite, fizelyite, boulangerite and semseyite etc. (Figure 13-B). Pyrite, sphalerite and quartz are found as granular form, 0.5 to 3 mm in size. Galena occurs as granular aggregate in interspaces of pyrite and sphalerite with minor amounts of chalcopyrite, tetrahedrite, bournonite, semseyite and rarely electrum (Figure 13-C, D). Electrum only appears microscopically as inclusion, 5 to 70 μm in size, in pyrite and sometimes galena and chalcopyrite, and its chemical composition is $Au_{0.90-0.95}$ $Ag_{0.05-0.10}$. Minor amounts of argentite and jalpaite are also found in sphalerite with pyrite. Semseyite occurs as granular form enclosed in galena accompanying by pyrite, bournonite, tetrahedrite and sometimes chalcopyrite (Figure 13-C). Bournonite, tetrahedrite, chalcopyrite and semseyite intimately associate with each other, and fill up in the interspace of granular aggregate of pyrite, sphalerite and galena (Figure 13-C and D). Very small quantities of tennantite and famatinite are microscopically found with bournonite, tetrahedrite and chalcopyrite.

The Once vein which corresponds to extension of the San Pablito vein has parallel and branch veins as shown in Figure 12. It is also composed of coarse grained pyrite, sphalerite, galena and quartz associated with small amounts of tetrahedrite, bournonite, semseyite, fizelyite, boulangerite, realgar, orpiment, stibnite and arsenopyrite (Figure 13-A). Tetrahedrite, bournonite, semseyite and fizelyite are microscopically found as irregular form, 0.1 to 0.3 mm in size, intimately associating with each other. Sphalerite from the vein has 0.6 to 1.1 wt % Fe (0.8 to 2.0 mole % FeS) and 0.0 to 0.3 wt % Cd. Boulangerite microscopically appears as aggregate of very fine acicular crystals assembling with semseyite, bournonite and fizelyite. Orpiment and realgar fill up interspace of granular aggregate of pyrite, sphalerite, galena and quartz, and sometimes appear as euhedral crystal of prismatic form in druse of pyrite, sphalerite and galena in the vein. Occurrence of such arsenic sulfides as orpiment and realgar is very rare from polymetallic deposits in the Eastern Cordillera (Ahlfeld and Munoz, 1955), although they are thought to have been crystallized at late stage of the mineralization. Stibnite only occurs as aggregate of acicular crystal in veinlet cut the vein.

The homogenization temperature and salinity of fluid inclusions in quartz and sphalerite from the Once vein are 170° to 305° and 4.4 to 5.8 wt % NaCl,

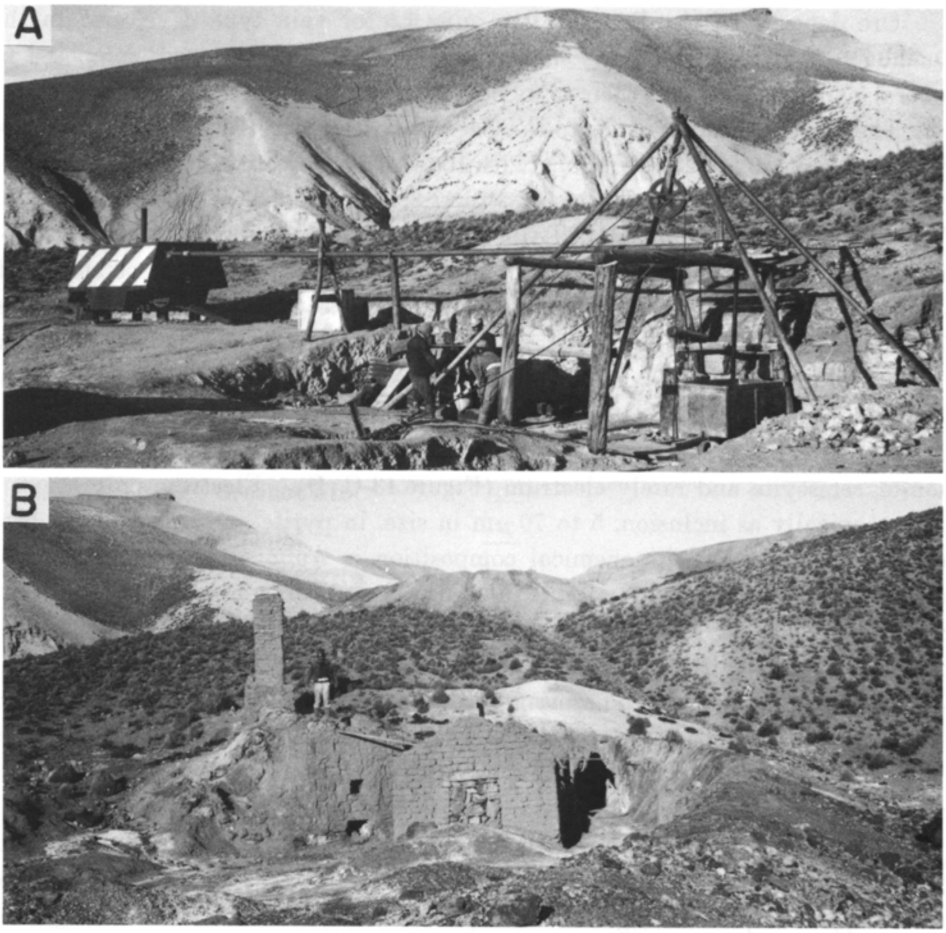

FIGURE 11. SCENERY OF THE BUENA VISTA MINE.
A. A view of the B1 shaft of the Buena Vista mine and the Quehua formation.
B. Old mine office of Spanish Colonial age.

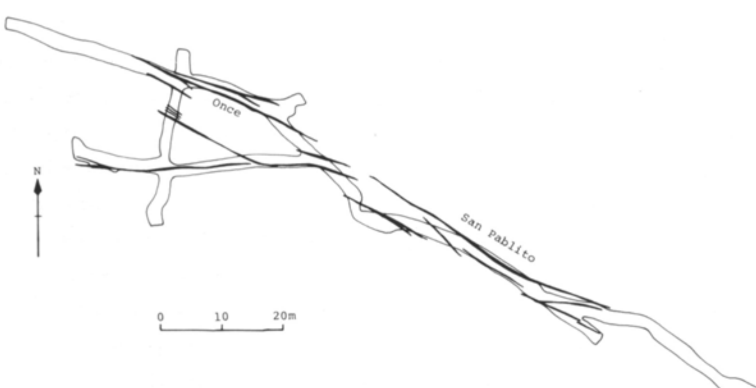

FIGURE 12. VEIN ARRANGEMENT AT THE −50 LEVEL OF THE BUENA VISTA MINE.

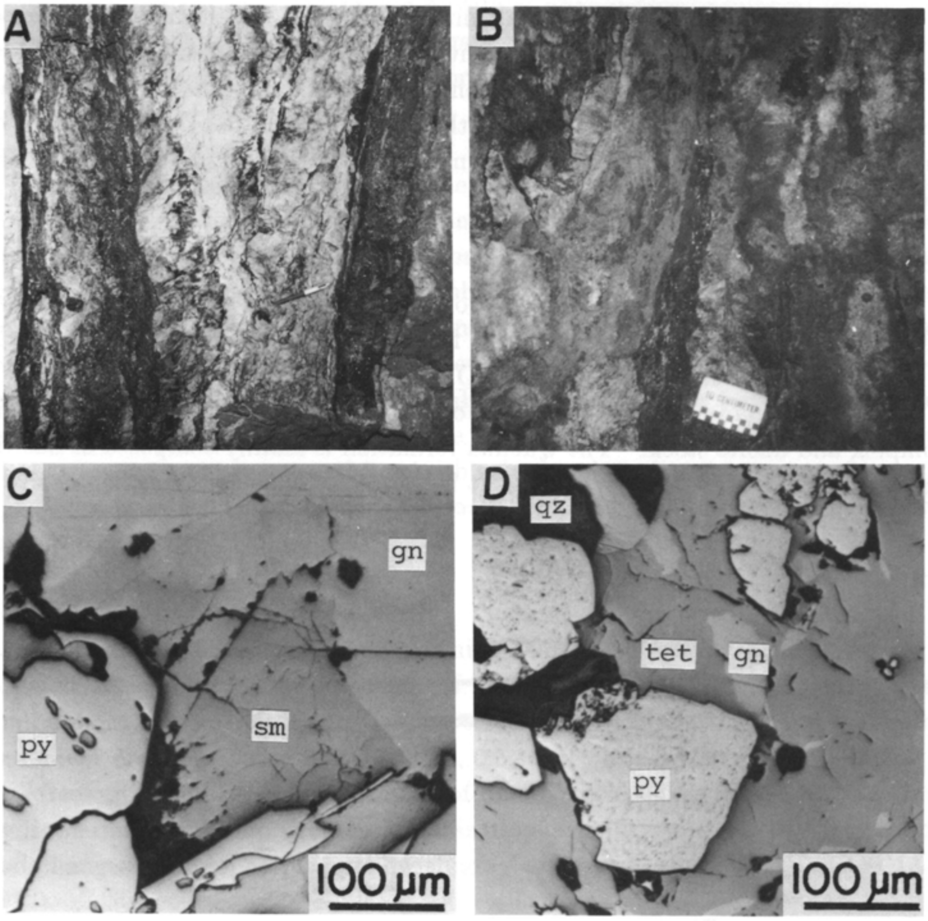

FIGURE 13. ORE VEINS OF THE BUENA VISTA MINE AND PHOTOMICROGRAPHS OF ORE.
A. Galena-sphalerite vein (gray) occurring in altered dacitic tuff, Once vein, −40 level.
B. Galena-sphalerite vein (gray) embedded in altered dacitic tuff, San Pablito vein, −40 level.
C. Semseyite (sm) at the boundary between galena (gn) and pyrite (py), San Pablito vein, 0 level (Sample No. 8380319).
D. Tetrahedrite (tet), galena (gn) and pyrite (py) assemblage with quartz (qz), San Pablito vein, 0 level (8380319).

respectively.

From the data on occurrence, assemblage and paragenesis of minerals, the sequence of the mineralization formed the ore and gangue minerals is considered as shown in Figure 14. Pyrite, sphalerite and quartz were crystallized at the early stage of the mineralization. Electrum was formed at early to middle stages of mineralization associating with pyrite, sometimes galena and chalocopyrite. Meanwhile, galena, chalcopyrite and arsenopyrite were precipitated at the middle stage of the mineralization. Sulfosalt minerals such as tetrahedrite, bournonite, semseyite, boulangerite, fizelyite, tennantite and famatinite were crystallized at late stage of mineralization. Also, arsenic sulfide minerals such as realgar and orpiment were produced at late stage of the mineralization to fill up interspace or druse of pyrite and sphalerite aggregate in the vein. Finally, stibnite veinlets cut the whole vein.

3. Escala mine

The Escala mine is situated at about 30 km west of San Pablo de Lipez (Figure 5). The mine has been worked from the age of the Spanish colony, but is now being only explored by COMIBOL.

Geology around the mine consists of Miocene Quehua formation, volcanic complex and dacite stock. The Quehua formation is mainly composed of dacitic tuff with nearly horizontal bedding. It has a lot of pumiceous fragments, 3 to 5

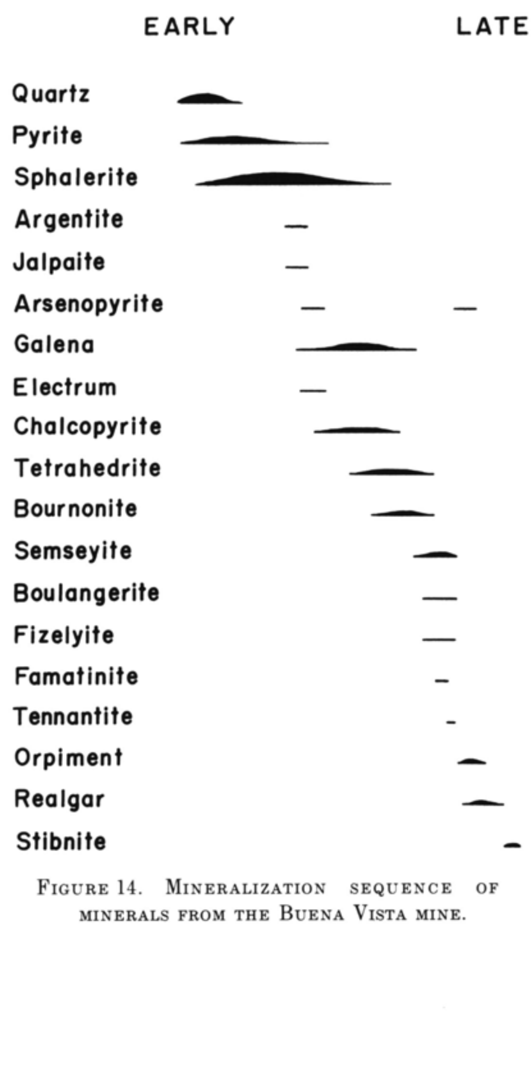

FIGURE 14. MINERALIZATION SEQUENCE OF MINERALS FROM THE BUENA VISTA MINE.

mm in size, and quartz, feldspar and biotite as phenocrysts or mineral fragments. Its matrix consists of fine grained aggregate of quartz, feldspar, biotite, accidental fragments and glass. The volcanic complex and dacite stock often suffer so strongly hydrothermal alterations such as sericitization and koalinization that their original textures disappear.

There are many parallel veins in the Escala mine. They fill up fractures, 10 to 40 cm wide, of strike N55°to 60°W developed in dacite stock and pyroclastic rocks of the volcanic complex. Ores from the mine show crustified banding, and are principally composed of galena, sphalerite, pyrite, marcasite, arsenopyrite, quartz and siderite associated with minor amounts of chalcopyrite, pyrrhotite, tetrahedrite, jamesonite and semseyite etc. As silver bearing minerals, tetrahedrite which contains 5 to 7 wt % Ag only occurs as granular form in galena and marcasite with chalcopyrite. Semseyite appears as radial aggregate of prismatic form, 0.2 to 0.7 mm long, assembling with galena, sphalerite, marcasite and quartz. Sphalerite from the mine contains 5.5 to 10.8 wt % Fe (9.6 to 18.6 mole % FeS) and up to 1.7 wt % Cd.

4. Candelaria de Santa Isabel mine

Candelaria de Santa Isabel mine which belongs to Compania Lipez Minera is situated at about 15 km northeast of San Pablo de Lipez and located at southeastern slope of Mt. Santa Isabel (5,146 m). This mine products lead, zinc and silver ores containing 2 to 15% Pb, 0.5 to 31% Zn and 60 to 270 g/t Ag.

Geology around the mine consists of dacite stock which strongly suffered by hydrothermal alteration such as kaolinization, silicification and carbonitization and changed its color to pale yellowish gray to grayish white (JICA and MMAJ, 1982).

Ore veins developed in altered dacite stock generally strike to the direction of N70° to 80°W dipping to north. They have 20 to 70 cm width. The veins principally consist of sulfide minerals such as pyrite, sphalerite, galena, arsenopyrite, marcasite and chalcopyrite associated with minor amounts of tetrahedrite, bournonite, jamesonite, semseyite, pyrargyrite, cassiterite, stannite and franckeite. Quartz and calcite also occur as gangue minerals. Pyrite and sphalerite occur as aggregate of euhedral or subhedral crystals closely associating with galena and quartz, sometimes chalcopyrite, arsenopyrite and marcasite. Galena usually appears as a band consisting of its granular aggregate, or fills up interspaces of aggregate of pyrite and sphalerite. It assembles with semseyite, jamesonite and marcasite, and namely franckeite. Galena sometimes contains fine grained inclusions, 5 to 20 μm in size, of bournonite, tetrahedrite and pyrargyrite. Minor amounts of cassiterite occurs as aggregate of fine crystal, 10 to 20 μm in size, associating with sphalerite, pyrite and stannite. Tetrahedrite, bournonite and pyrargyrite assemble with pyrite, sphalerite, marcasite and galena, and sometimes jamesonite and franckeite. They are also found as fine inclusions in galena with pyrite and sphalerise.

5. Santa Rosa mine

Santa Rosa mine is located at about 10 km southeast from San Pablo de Lipez. It has been worked at Spanish colony as silver mine, but now closed. According to JICA and MMAJ (1982), geology around the mine mainly consists of andesite, dacite and their pyroclastic rocks of the volcanic complex. They are so strongly affected by hydrothermal alteration as to show pale gray to grayish white in color. Ore vein occurs in the volcanic complex. It strikes N50°W to N75°E and has 0.1 to 1.6 m in width. The ore from the mine contains 1.1% Pb and 400 g/t Ag and is principally composed of sulfide minerals such as galena and sphalerite with small amounts of pyrite, hematite, quartz and tetrahedrite. Galena appears as granular aggregate associated with sphalerite, tetrahedrite, pyrite and quartz. As a silver bearing mineral, tetrahedrite is only found in the ore.

Ore Minerals

Ore and gangue minerals occurred from the San Antonio de Lipez, Buena Vista, Escala, Candelaria de Santa Isabel and Santa Rosa mines in the Sur Lipez district are listed up in Table 1. The kinds of minerals and their relative amounts in each mine are also shown in Table 2.

Pyrite, sphalerite and galena are found as most common minerals from all of the mines in the district. Marcasite, chalcopyrite and arsenopyrite are also found as essential ore minerals from the San Antonio de Lipez, Buena Vista, Escala and Candelaria de Santa Isabel mines. Pyrrhotite appears as fine inclusion in pyrite and sphalerite from the Escala and San Antonio de Lipez mines. Arsenic sulfide minerals such as orpiment and realgar which are very rare in Bolivia occur as a product at late stage of mineralization from the Buena Vista mine. Stibnite appears as a veinlet cut the vein at latest stage of the mineralization in the Buena Vista mine.

Silver sulfide minerals such as argentite and jalpaite which are very rare from the polymetallic deposits in the Eastern Cordillera are found in the ore from the San Antonio de Lipez and Buena Vista mines. Electrum is only observed microscopically as fine grained inclusion in pyrite, galena and chalcopyrite in the ore from the Buena Vista mine. Its chemical composition is $Au_{0.90-0.95}Ag_{0.05-0.10}$. Native silver occurs in high grade ore from the San Antonio de Lipez mine, and associates with argentite, galena, sphalerite and aikinite.

Also, silver sulfosalt minerals such as pyrargyrite, polybasite, stephanite and fizelyite are found in the ore from the San Antonio de Lipez and Candelaria de Santa Isabel mines. They assemble with each other and galena, tetrahedrite, sphalerite and bournonite. Pyrargyrite also appears as fine grained inclusion

TABLE 1. ORE AND GANGUE MINERALS OCCURRING FROM THE MINES IN THE SUR LIPEZ DISTRICT.

Mineral name	Chemical formula	Mineral name	Chemical formula
Pyrite	FeS_2	Bournonite	$CuPbSbS_3$
Marcasite	FeS_2	Jamesonite	$FePb_4Sb_6S_{14}$
Arsenopyrite	$FeAsS$	Boulangerite	$Pb_5Sb_4S_{11}$
Pyrrhotite	$Fe_{1-x}S$	Semseyite	$Pb_9Sb_8S_{21}$
Chalcopyrite	$CuFeS_2$	Franckeite	$FePb_6Sb_2Sn_2S_{14}$
Galena	PbS		
Sphalerite	ZnS	Cassiterite	SnO_2
Greenockite	CdS	Hematite	Fe_2O_3
Stannite	Cu_2FeSnS_4	Magnetite	Fe_3O_4
Famatinite	Cu_3SbS_4		
Tetrahedrite	$(Cu,Ag,Fe,Zn)_{12}Sb_4S_{13}$	Quartz	SiO_2
Tennantite	$(Cu,Ag,Fe,Zn)_{12}As_4S_{13}$	Barite	$BaSO_4$
Orpiment	As_2S_3	Siderite	$FeCO_3$
Realgar	AsS	Calcite	$CaCO_3$
Stibnite	Sb_2S_3		
Native silver	Ag	Kaolinite	$Al_2Si_2O_5(OH)_2$
Electrum	(Au,Ag)	Sericite	$KAl_2Si_3AlO_{10}(OH)_2$
Argentite	Ag_2S	Chlorite	$(Mg,Fe,Al)_{12}(Si,Al)_8O_{20}(OH)_{16}$
Jalpaite	Ag_3CuS_2	Saponite	$(Ma,Fe,Al)_3(Si,Al)_4O_{10}(OH)_2$
Aikinite	$CuPbBiS_3$		
Polybasite	$(Ag,Cu)_{16}Sb_2S_{11}$		
Stephanite	Ag_5SbS_4		
Pyrargyrite	Ag_3SbS_3		
Fizelyite	$Ag_2Pb_5Sb_8S_{18}$		

associating with tetrahedrite and bournonite in galena from the San Antonio de Lipez mine. Tetrahedrite occurs as one of principal silver bearing minerals in the ores from all the mines in the district. Sulfosalt minerals such as bournonite, jamesonite, boulangerite, semseyite, famatinite and tennantite are found in the ores from the San Antonio de Lipez, Buena Vista, Escala and Candelaria de Santa Isabel mines.

Hematite occurs as a principal mineral associating with sulfide and silver sulfosalt minerals in the veins of the San Antonio de Lipez mine. Small amounts of tin minerals such as cassiterite, stannite and franckeite are only found microscopically in the ore from the Candelaria de Santa Isabel mine in association with sphalerite, quartz, pyrite and chalcopyrite.

As gangue mineral, quartz occurs as an essential mineral in intimate association with ore minerals from all of the mines in the district. Barite is found as a common gangue mineral from the San Antonio de Lipez mine. Meanwhile clay minerals such as kaolinite, sericite, chlorite and saponite appear as crustified bands in the vein of San Antonio de Lipez mine. Siderite is also found as essential gangue mineral as late stage product of mineralization at the San Antonio de Lipez and Escala mines.

SUMMARY

1. Geology of the Sur Lipez district consists of the Ordovician, Cretaceous, Tertiary and Quaternary systems, and intrusive igneous rocks as dacite stock. The Ordovician system is mainly composed of slate, sandstone and their alterna-

TABLE 2. ORE AND GANGUE MINERALS FROM THE MINES IN THE SUR LIPEZ DISTRIHT AND THEIR AMOUNTS.

	San Antonio de Lipez	Buena Vista	Escala	Candelaria de Santa Isabel	Santa Rosa
Pyrite	◯	◯	◯	◯	○
Marcasite	◯		◯	◯	
Arsenopyrite	∘	○	◯	○	
Pyrrhotite		∘	∘		
Chalcopyrite	∘	∘	∘	◯	
Galena	◯	◯	◯	◯	◯
Sphalerite	◯	◯	◯	◯	◯
Greenockite	∘			∘	
Stannite				∘	
Famatinite		∘			
Tetrahedrite	○	○	○	○	○
Tennantite		∘			
Orpiment		○			
Realgar		○			
Stibnite		○			
Native silver	∘				
Electrum		∘			
Argentite	∘	∘		∘	
Jalpaite		∘			
Aikinite	∘				
Stephanite	∘	∘			
Pyrargyrite	○			∘	
Polybasite	○				
Fizelyite		∘		∘	
Bournonite		○		○	
Jamesonite		∘	○	○	
Boulangerite		∘			
Semseyite		∘	∘	∘	
Franckeite				∘	
Cassiterite				∘	
Hematite	◯	∘			
Magnetite	∘				
Quartz	◯	◯	○	◯	○
Barite	◯				
Siderite	○		○		
Kaolinite	○				
Sericite	○				
Chlorite	○				
Saponite	○				
Calcite				○	

Size of the circles in the table indicates comparative amouts of minerals from the mines.

tion folded distinctly. It is unconformably covered with the Cretaceous and Tertiary systems. The Cretaceous system only appears in the limited area, and mainly consists of coarse grained red sandstone and shale.

Meanwhile, the Tertiary system covers wide area in the district, and is composed of the Potoco, San Vicente, Rondal and Quehua formations and volcanic complex and ignimbrite in ascending order. The Potoco formation consists of red sandstone and mudstone with obvious bedding. The San Vicente formation is composed of red sandstone and conglomerate. The Rondal formation mainly consists of basaltic lava. The Quehua formation widely appears in the district, and is mainly composed of pyroclastic rocks of dacitic tuff, tuff breccia and agglomerate. The volcanic complex mainly consists of dacite and andesite lavas, tuff breccia and massive tuff. Also, ignimbrite is mainly composed of rhyodacitic ignimbrite and tuff. The Quehua formation and volcanic complex around the mines are affected by hydrothermal alteration such as chloritization, kaolinization and sericitization, but ignimbrite is not altered.

2. Dacite often occurs as stock into the volcanic complex and Quehua formation, and it sometimes forms a central core of Mts. Lipez, Bonete and Santa Isabel etc. At San Antonio de Lipez and Santa Isabel, it in part suffers strongly hydrothermal alteration of sericitization, kaolinization and chloritization. Ore deposits such as San Antonio de Lipez, Escala and Candelaria de Santa Isabel etc. often occur in such altered dacite stock and pyroclastics of the volcanic complex.

3. In the Sur Lipez district, there are many polymetallic deposits of silver, gold, lead, zinc, antimony, tin, tungsten and bismuth etc. such as the San Antonio de Lipez (silver, lead, zinc), Buena Vista (silver, gold, lead, zinc), Escala (silver, lead, zinc), Esmoraca (tin, lead, zinc, tungsten), Candelaria de Santa Isabel (silver, copper, lead, zinc), Bolivar (silver, lead, zinc, bismuth), Santa Rosa (silver, lead, zinc), Moroco (silver, lead, zinc, antimony), Trapiche (antimony) and Villarruer (silver, lead, bismuth) mines. They are hydrothermal fissure filling type and occur in the dacite stock, volcanic complex and Quehua formation of Miocene. Ores from the mines such as San Antonio de Lipez, Buena Vista and Escala consist of many ore minerals such as pyrite, sphalerite, galena, arsenopyrite, chalcopyrite, marcasite, pyrrhotite, hematite, magnetite, argentite, jalpaite, electrum, native sliver, stibnite, realgar, orpiment, aikinite, boulangerite, semseyite, jamesonite, bournonite, tetrahedrite, tennantite, famatinite, stephanite, polybasite, pyrargyrite, fizelyite with gangue minerals such as quartz, barite, siderite, calcite, chlorite, sericite and kaolinite. It is characteristic to occur a lot of low temperature minerals such as marcasite, stibnite, famatinite, realgar, orpiment, antimony and silver sulfosalt minerals, barite, siderite and kaolinite from the mines in the district as described above. Also appearance of famatinite, realgar and orpiment suggests that mineralization was carried out under high sulfur and arsenic activities at some stages.

4. The ore deposits of the San Antonio de Lipez mine are vein type in the dacite stock and volcanic complex altered hydrothermally. The veins, 0.3 to 1 m wide, principally consist of quartz, pyrite, marcasite, sphalerite, galena, hematite and barite associated with small amounts of chalcopyrite, arsenopyrite, tetrahedrite, magnetite, aikinite, native silver, argentite, polybasite, pyrargyrite and stephanite, and gangue minerals of chlorite, sericite and kaolinite. Native silver appears as irregular form, 0.05 to 0.1 mm in size, assembled with galena and

argentite. Silver sulfosalt minerals such as polybasite, pyrargyrite and stephanite commonly occur as granular form in association with galena, tetrahedrite, marcasite and galena. They are also found as fine grained inclusion in galena.

5. The ore veins of the Buena Vista mine occur in the Quehua formation. They principally consist of pyrite, sphalerite, galena and quartz accompanied by small amounts of chalcopyrite, arsenopyrite, electrum, argentite, jalpaite, famatinite, orpiment, realgar, stibnite, tetrahedrite, tennantite, bournonite, fizelyite, boulangerite, semseyite and siderite. Pyrite, sphalerite and quartz were formed at early stage of mineralization, and galena and tetrahedrite associated occasionally with chalcopyrite, bournonite, semseyite, boulangerite and fizelyite were crystallized at slightly later stage than that of pyrite and sphalerite. Electrum, 5 to 70 μm in size, appears as inclusion in pyrite, galena and chalcopyrite microscopically. Orpiment and realgar fill up the interspace of granular aggregate of pyrite, sphalerite, galena and quartz. Stibnite is found as aggregate of acicular crystal as veinlet which cuts the vein.

6. Ore deposits of the Escala mine also are a fissure filling type developed in dacite stock. The ore from the mine is principally composed of galena, sphalerite, pyrite, marcasite, arsenopyrite, quartz and siderite associated with minor amounts of chalcopyrite, pyrrhotite, tetrahedrite, jamesonite and semseyite.

7. Ore veins of the Candelaria de Santa Isabel mine embedded in dacite stock and volcanic complex are composed mainly of pyrite, sphalerite, galena, arsenopyrite, marcasite, chalcopyrite and quartz associated with small amounts of tetrahedrite, bournonite, jamesonite, semseyite, pyrargyrite. Minor amounts of tin minerals such as cassiterite, stannite and franckeite are also found in association with pyrite and sphalerite.

8. Ore veins of the Santa Rosa mine occur in volcanic complex, and mainly consist of galena and sphalerite with small amounts of pyrite, hematite, quartz and tetrahedrite. As a silver bearing mineral, tetrahedrite is only found in the ore.

9. It is characteristic to occur low temperature minerals such as silver sulfosalts, argentite, stibnite, realgar, orpiment and famatinite from the mines in the district, although small amounts of high temperature mineral as cassiterite appears. However, no wolframite and tourmaline are found in the ores from the mines.

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